THE AECL STUDY FOR
AN INTENSE NEUTRON - GENERATOR
(TECHNICAL DETAILS)

Edited

by

G. A. Bartholomew

and

P. R. Tunnicliffe

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PREFACE

The AECL study for an intense neutron-generator has been in progress for two years. Recently the scientific and technical details and the conceptual designs were compiled in a report supporting proposals addressed to AECL's Board of Directors for further work. The compilation is being issued in this form to permit further discussion of the technical aspects. However readers are asked to appreciate that it was written primarily for an AECL audience, and specifically that

- those chapters giving tentative information about costs, the rate of investment and similar items have been omitted or modified
- many references have been made to interim internal reports in order to complete the local documentation, but these references do not imply that the reports themselves can be made generally available.

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Authors and consultants of the various sections are listed in the tables of contents heading each chapter. We are especially grateful to those scientists and engineers from Canadian industry and universities who freely contributed their efforts to this study.

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CONTENTS*

I.	INTRODUCTION	I. 1
II.	THE ING PROJECT IN SUMMARY (modified)	II. 1
III.	ORGANIZATION AND LOCATION (omitted)	III. 1
IV.	RECOMMENDATIONS (omitted)	IV. 1
V.	RESEARCH AND TECHNICAL APPLICATIONS	V. 1
	A. Physics Research	1
	B. Nuclear Power Technology	50
	C. Chemistry and Materials Research	59
	D. Isotope Production	72
	E. Biological and Medical Applications	73
VI.	ACCELERATOR AND BEAM TRANSPORT	VI. 1
	A. Reference Design	1
	B. General Description	12
	C. Source and Preacceleration	30
	D. Injector Linac	34
	E. SOC Stages	37
	F. Radio-Frequency System	91
	G. Control System	118
	H. Beam Transport	126
	I. Shielding and Activation	136
	Appendices	142
VII.	TARGET AND EXPERIMENTAL FACILITIES	VII. 1
	A. Thermal Neutron Facility	1
	B. Resonance Neutron Facility	129
	C. Meson Facilities	143
	D. Fast Neutron Facilities	153
	E. Beam Dump and Irradiation Facility	157
	F. Nuclear Power Technology Facility	158
VIII.	SHIELDING AND ACTIVATION	VIII. 1
	A. Radiation Levels and Tolerances	1
	B. Radiation Production and Attenuation	4
	C. Activation	14
	Appendices	21

* Detailed tables of contents are placed at the beginning of each Chapter.

IX.	SITE, LAYOUT, AND SERVICES	IX.1
A.	Reference Site	1
B.	Layout	10
C.	Buildings	21
D.	Services	46
X.	HAZARDS	X.1
A.	Safety Systems	1
B.	Radiation Hazards	13
XI.	COSTS, MANPOWER AND SCHEDULES (omitted)	XI.1
A.	Cost Estimates	1
B.	Manpower	30
C.	Schedule	40
XII.	COMMERCIAL ISOTOPE PRODUCTION	XII.1
A.	Production of Radioisotopes	1
B.	Isotope Production Facilities	8
XIII.	POSSIBLE FUTURE ADDITIONS AND CONJOINT PROJECTS	XIII.1
A.	Variable Energy	1
B.	Storage Ring	2
C.	Power/Breeder Target	8
D.	ING and Elementary Particle Physics	9
XIV.	LINEAR ACCELERATOR	XIV.1
A.	Introduction	1
B.	Linac Structures	2
C.	Radio Frequency Power Supplies	13
D.	Reference Design (Costs omitted)	25
XV.	COMPETITIVE SYSTEMS	XV.1
A.	Introduction	1
B.	Discussion	2
C.	Summary of Conclusions	9

CHAPTER I

INTRODUCTION

(G.A. Bartholomew, J.C.D. Milton, E.W. Vogt)

A. RESEARCH SCOPE OF ING	I.1
B. ORIGINAL MOTIVATION AND GOALS, THERMAL NEUTRONS	2
C. CHOICE OF SYSTEM	5

I. INTRODUCTION

A. RESEARCH SCOPE OF ING

The Intense Neutron-Generator (ING) provides an opportunity for major new advances in many fields of research and technology. The areas of fundamental research that would derive greatest benefit are solid state physics, nuclear physics, and nuclear chemistry. In applied science ING would provide powerful tools for materials research and would provide many useful radioactive isotopes. Of potentially great significance in the long range power outlook, ING would open the door to methods of electrical breeding of fissile material and, with development of efficient accelerators and associated technology, promises a radical new approach to economic nuclear power. More specifically -

- For solid state physics, ING would provide very intense beams of thermal neutrons which, with neutron scattering techniques, permit major steps forward in studies of structure and of dynamic processes in solids and liquids.
- For nuclear physics, intense beams of thermal neutrons and pulsed beams of resonance and fast neutrons would become available, and in addition, new powerful tools for the examination of nuclear structure would be provided by very intense beams of meson which have, as yet, seen little use as nuclear probes. Further opportunities for fundamental research in nuclear physics result from the strong beams of intermediate-energy protons and neutrons and the intense fluxes of neutrinos.
- For nuclear chemistry, ING would produce radioactive species not now readily available in the neutron-poor and transuranic regions of the mass table.
- In materials science, ING could be a major research tool in studies of liquid metals and structural materials bombarded by high fluxes of energetic neutrons and other particles.
- In the industrial area, ING could produce many new high-grade radioactive materials of commercial value and stimulate the development of many new components and techniques required for accelerator development and maintenance and for other purposes.

For research in the electro-nuclear power area, ING would provide initially only a zero-energy facility but the general experience with that facility should contribute much needed information for larger future programs.

Figure I.1 illustrates the interplay between the many disciplines involved as ING evolves from an initial concept to an advanced system and will serve to keep the various functions in perspective. In this figure, boxes and arrows in full lines represent facilities and functions that form part of the plant now proposed while broken lines denote possible future systems that are described in this report for the purpose of conveying the magnitude of the development potential arising from ING. While Fig. I.1 may help to illustrate the wide fields to which ING contributes, it does not convey closely the major steps forward which ING provides in many of these fields. As an example of the particular advance provided by ING, we next discuss in more detail its impact on research requiring a large flux of thermal neutrons. Consideration of needs in this area determined the initial goals of the ING study and influenced the choice of system to meet these goals.

B. ORIGINAL MOTIVATION AND GOALS, THERMAL NEUTRONS

The original motivation for ING¹ arose from the need for more intense continuous fluxes of thermal neutrons for research applications in neutron physics, (including reactor physics) chemistry and metallurgy. To this motivation from pure research may be added the ever-present requirement for irradiation facilities to meet an increasing demand² for radioactive isotopes. In system planning for ING, research needs were given priority over isotope production, but every attempt was made to accommodate isotope production facilities where these were compatible with the research facilities. These initial neutron-oriented motivations for ING are portrayed in the upper left hand section of Fig. I.1 and discussed in detail in Chapters V.A, V.C, and XII.

The relevant measure of the thermal flux for neutron beam research in any facility is the flux available at the inner end of an experimental beam tube. A pattern that has emerged since reactors were first developed shows a roughly exponential increase of beam-tube flux with time - an order of magnitude every ten years. Figure I.2 shows the fluxes available at the inner (i.e. source) end of the beam tubes for NRX, NRU, and present-generation reactors in the United States and United Kingdom, plotted as a function of commissioning date.

¹ G.A. Bartholomew, et al., An Intense Neutron Generator Based on a Proton Accelerator, AECL-2059 (1964).

² Industrial Radioisotope Economics, IAEA report STI/ DOC 10/ 40 (1965) of findings of the Study Group Meetings on Radioisotope Economics (Vienna, 1964).

FIGURE I. 1

FIG. I.2 Beam Tube Thermal Neutron Flux

Assuming a steady rate of progress in neutron physics research, it would appear from this curve that we should expect requirements for a thermal flux of about $10^{16} \text{ cm}^{-2} \text{ s}^{-1}$ to become urgent by 1973 or 1974. Accordingly, a facility in which this flux is made available in some seven beam tubes, in operation by 1974, is taken as a primary goal of the ING project. As this report will show, such a performance can be achieved in this time scale with ING although not without a strenuous and challenging program of development on many fronts.

The unperturbed flux available in an irradiation facility is one relevant measure of its capability for isotope production. Figure I.3 shows the maximum fluxes available in irradiation positions of several operating reactors as a function of the commissioning date. In many reactors the highest flux is produced in a central moderator, or flux trap, almost entirely surrounded by fuel and essentially inaccessible to beam tubes. The maximum flux in a reactor is therefore not necessarily a good index of its suitability for beam research. On the other hand, a device, such as ING, designed to provide a given beam-tube flux, will in general be able to provide an unperturbed flux of the same magnitude or greater for irradiation purposes. Figure I.3 shows the goal of $10^{16} \text{ cm}^{-2} \text{ s}^{-1}$ places ING at the forefront in available flux for irradiations although the margin over other devices is not as great as that in Fig. I.2. It should be noted however, that Figure I.3 gives no information concerning loading capacity which may differ greatly from one device to another depending on design and total neutron output.

A high flux of thermal neutrons is not the only beam requirement for neutron physics research. Of great importance for many experiments are beams of high purity (free of neutrons of undesired energies), beams especially "tailored" in neutron energy or solid angle³, or beams of pulsed neutrons⁴ meeting various specifications as to energy, peak intensity, pulse width, and repetition rate. As a further goal in the ING study, attention was directed toward supplying as many of these specialized beams as possible in addition to the primary high-flux source.

C. CHOICE OF SYSTEM

The fundamental process for neutron production in ING is the spallation reaction produced by energetic ($\sim 1 \text{ GeV}$) protons in a thick, heavy-element target (lead-bismuth eutectic). In this reaction the protons have sufficiently high energy that they collide with the atomic nuclei in the target long before they are slowed down by collisions with

³ P.A. Egelstaff (ed.), Tailored Neutron Beams, special issue of Reactor Science and Technology, (Journal of Nuclear Energy, Parts A and B) 17, 145 (1963).

⁴ See several papers in Proc. Symp. Pulsed High Intensity Fission Neutron Sources, CONF 650217 (1965).

FIG. I.3 Irradiation Facility Thermal Neutron Flux

the electrons. In a typical nuclear impact the incoming proton knocks several nucleons (called "cascade nucleons") out of the target nucleus, and these carry off perhaps half the energy of the bombarding proton. The other half is shared among the remaining nucleons forming an excited nuclear droplet from which neutrons and protons can "evaporate". Neutrons are favored in the evaporation because the large electric charge of the nucleus gives the protons a much higher effective boiling point. Some of the evaporated neutrons may have sufficient kinetic energy to cause further neutron multiplication by $(n, 2n)$ or (n, f) reactions. The cascade nucleons proceed to produce further events of the same kind until all of the available proton energy is dissipated as heat in the target or carried out of the target as nucleon kinetic energy or electromagnetic radiation. The quantities of primary concern in neutron source design are the neutron yield per incident proton and the heat deposited in the source per liberated neutron. These parameters and their dependence on proton energy, source material, and geometry are discussed in Chapter VII which contains a full description of the thermal-neutron target, associated D_2O moderator, and shield.

The decision to use the spallation process in preference to the customary fission process or some other neutron-producing reaction was influenced principally by the following considerations:

a. Efficiency

The spallation process is more efficient than any other neutron-producing reactions that could be developed into a practical high-flux source by 1974. Here "efficiency" is used to refer to the neutron output per unit of heat deposited in the source. A comparison of efficiencies of the various possible reactions is presented in Table I.C.1. Fusion by the $T + d$ reaction might provide an efficiency even higher than that of spallation but, because there is no prospect of developing a fusion reactor to give the required flux within the time scale, this possibility is not considered further.

In comparing fission and spallation in Table I.C.1 it is necessary to distinguish between total heat produced per neutron and heat liberated in the source per neutron. For the purpose of designing an intense source of neutrons, it is the source itself, that is of critical concern. In a reactor the heat liberated in the fuel and our ability to cool the fuel limit the attainable flux. While not all the heat is deposited in the core - some is carried outside by fast neutrons and γ -radiation - the amount of heat escaping is usually only a few percent of that deposited. No allowance has been made for this escaping heat in deriving the efficiency for fission in Table I.C.1. For the ING spallation target, a significant fraction of the total heat escapes the target and this loss, which eases the local cooling problem significantly, was taken into account in

the efficiency for spallation quoted in Table I.C.1. The escaping heat is easily accommodated in the cooling of the moderator and shield.

Considered as an efficient neutron source, the Pb-Bi target has another advantage over a reactor core, and this is the significantly smaller capture cross-section; the lower neutron absorption in the source itself results in a lower local flux depression.

TABLE I.C.1

EFFICIENCIES OF NEUTRON-PRODUCING REACTIONS

Reaction	Source Properties	Efficiency in Source $n \text{ MW}^{-1} \text{ s}^{-1}$
T(d, n)	$E_d = 200 \text{ keV}$	2.4×10^{15}
$^9\text{Be}(d, n)$	$E_d = 15 \text{ MeV}$	5×10^{15}
W(e, n)	$E_e = 35 \text{ MeV}$	3×10^{15}
fission	Thermal reactor, ^{235}U	3×10^{16}
	Bare fast reactor, ^{239}Pu	6×10^{16}
spallation	$E_p = 1 \text{ GeV}$, Pb-Bi target as in Chapter VII	2.1×10^{17}

b. Prospects for Extension to Higher Flux

Thermal-neutron fluxes considerably in excess of $10^{16} \text{ cm}^{-2} \text{ s}^{-1}$ can in principle be obtained with homogeneous reactors^{5,6}. In practice, capital cost, and burnup and reprocessing charges limit the available total power, while heat-transfer considerations limit the attainable power density. A spherical molten-salt reactor with a graphite moderator could give a flux of $10^{17} \text{ cm}^{-2} \text{ s}^{-1}$ in a central flux trap if the power rating were about 10000 MW and the average power density about 10 MW/l ⁶. Although there is no sharp limit, such performance appears to be near the maximum flux capability for reactors.

⁵ E. Critoph, private communication (1965).

⁶ W.K. Ergen, The Highest Thermal Neutron Fluxes Obtainable from Fission Reactors, 2nd Intl. Conf. Peaceful Uses of Atomic Energy, (Geneva) 10, 181 (1958) and private communication (1966).

FIGURE I. 4

The flux of ING may be increased by increasing the beam current, the limit being set by the power density in the Pb-Bi target, the geometry of the target assembly and the capital and operating costs of the accelerator. Increasing the linear dimensions of the target to that of the neutron migration length in the moderator (~ 100 cm), and increasing the beam current to 6.5 A and distributing it over the target to obtain an average power density of 10 MW/l, one can, in principle, obtain a maximum flux of the order of 10^{18} cm $^{-2}$ s $^{-1}$. Thus it would appear that, in the absence of considerations of cost, the spallation process permits significantly higher maximum fluxes to be obtained than can be reached by a reactor.

c. Research and Development Opportunities

As illustrated in Fig. I.1, ING not only satisfies the initial motivation of high flux, but also provides many other research opportunities in nuclear physics and advanced power technology. It can provide commercially valuable isotopes belonging to the neutron-poor as well as the neutron-rich side of the stability valley. During the system design and development stage, many fields of 'Accelerator Engineering' and 'Materials Science' will be stimulated to develop new products and processes and when ING is in operation, applied research carried out on ING will continue to advance these fields. Looking to the future, (right-hand side in Fig. I.1) there are many possible areas in both pure and applied research that may grow out of technology developed at ING. By comparison, the corresponding diagram for a high-flux research reactor, Fig. I.4, shows that, while such a system may equally well satisfy the initial motivation of high flux, it presents a much smaller prospect for expanded research and development.

CHAPTER II

THE ING PROJECT IN SUMMARY

II.1

(G.A. Bartholomew, P.R. Tunncliffe)

A. SUMMARY DESCRIPTION	2
1. Plant	2
3. Cost	2
B. SUMMARY OF REFERENCE DESIGN	5
1. Accelerator	5
2. Beam-Transport System	7
3. Experimental Facilities	9
C. REFERENCE SITE	15

II. THE ING PROJECT IN SUMMARY

This chapter first summarizes the essentials of the Intense Neutron-Generator plant and associated facilities, a construction schedule, the estimated cost, and the staff required. Second, a short description of the reference design accelerator, beam-transport system and experimental facilities is given. This reference design, which will serve as the basis for further scientific and engineering study, has been used to establish feasibility and to estimate costs.

Construction is envisaged in two stages. Initially a "Basic Machine" providing minimum experimental facilities would be built and brought into operation. Subsequently the "Full Machine", with all facilities of the reference design, would be completed.

Detailed description of the reference design will be found in Chapters VI to X. Chapters XIII to XV discuss possible departures from the reference design and future additions. Chapters V and XII are concerned with applications.

A. SUMMARY DESCRIPTION

1. Plant

Fig. II. 1 illustrates the main features of the ING complex. The Basic Machine is outlined in solid lines; extensions to make the Full Machine are shown by broken lines. The principal areas are:

(a) Electrical-mechanical systems

- Areas 1 - 4: A three-stage Separated-Orbit Cyclotron (SOC) delivering 65 mA of 1-GeV protons in continuous (CW) operation.
- Areas 6 - 8 and 10 - 12: Targets bombarded by the proton beam and their associated experimental facilities.
- Area 9, and other interconnecting channels not numbered: A beam-transport system capable of splitting and distributing the beam to the targets for simultaneous operation of all facilities.

(b) Buildings

- Support and shelter structures for the required foundation and radiation shielding for the accelerator, transport system, targets, and experimental areas (as numbered in a)).
- Area 19: Main control center, offices and laboratory building.
- Areas 5, 13 - 18, 20 - 29: Utilities and auxiliary services.

(c) Reference Site

- Layout as shown in Fig. II. 2 with exclusion area and ample space for future development.

3. Cost

	Basic Machine \$million *	Full Machine \$million *
Construction (direct costs, contingencies, engineering, management)		
With the Separated-Orbit Cyclotron	132	157
With a linear accelerator	126	150
Total annual operating costs, including manpower, materials and electrical power	14	21

* Figures are rounded off to the nearest whole integer in 1966 Canadian dollars.

FIG. II. 1. Outline of Main Features of the ING Complex

B. SUMMARY OF REFERENCE DESIGN

1. Accelerator

The reference design accelerator, a Separated-Orbit Cyclotron¹, is a new type. While no such machine has been built, well established principles are used in its design and there is little doubt of its feasibility. The SOC is also being studied at the Oak Ridge National Laboratory² and the Rutherford High Energy Laboratory³.

Protons produced in an ion source are accelerated by a DC potential to 750 keV, in a 'pre-injector.' They are next bunched by a radio-frequency cavity and accelerated to 10 MeV in a short linear accelerator. They are then injected into the first-stage SOC and thence, through stages -2 and -3, reach the final energy of 1 GeV. The output energies of the three stages are 50, 400*, and 1000 MeV.

In the SOC a number of radial RF cavity resonators accelerate the circulating beam many times per revolution. The cavities have voltages of the order 1 MV and typically the energy gain per revolution may be as high as 30 MeV. The orbit separation is sufficiently large that separate magnets may be used to guide and focus the beam between cavities and alternating-gradient strong-focussing can be used to confine it to a small cross-section and ensure little spill. Thus each SOC stage is an annular array of sector magnets and RF cavities.

A large variety of machine configurations will work, but they become expensive if an attempt is made to accelerate over much more than 2:1 in velocity. The three-stage reference design is the cheapest found satisfactory so far.

Table II.B.1 lists some of the basic parameters of the reference design; full details are given in Chapter VI.

¹ F.M. Russell, Nuclear Instr. Methods 23 229 (1963)

² E.D. Hudson, et al, A Low Energy Separated Orbit Cyclotron, proc First National IEEE Particle Accelerator Conf. (Washington) NS-12 (3), 489 (1965)

³ F.M. Russell, proc IEEE Intl. Conf. Isochronous Cyclotrons (Gatlinburg, 1966), to be published.

* For most design calculations an intermediate staging energy of 300 MeV was chosen. The 400-MeV staging energy requested for meson applications, introduces no new design problems and has little effect on costs; detailed revisions have not been made.

TABLE II. B. 1ACCELERATOR PARAMETERS (SOC)

<u>Ion Source</u>	DC duoplasmatron, current 130 mA		
<u>Pre-injector</u>	DC voltage 750 kV		
<u>Buncher</u>	Frequency 50 MHz		
<u>Injector Linac</u>	Dimensions: 4 m diameter, 5.8 m long		
	RF total power	1.45 MW	
	Energy	10 MeV	
<u>Separated Orbit Cyclotrons</u>	<u>Stage 1</u>	<u>Stage 2</u>	<u>Stage 3</u>
Diameter (ft)	45	85	150
Energy Range (MeV)	10-50	50-300*	300*-1000
Number of Sectors	13	13	33
Orbit turns	17	31	28
RF losses (MW)	1.26	2.50	4.32
Magnet steel (tons)	405	2835	4767
Coil copper (tons)	14	20	40
Magnet power (MW)	0.33	0.62	1.27

*Values from detailed study carried out with 300-MeV staging point (see Ch. IV)

The linac considered as the alternative design* has not been studied in detail at CRNL but an intensive study has been carried out at the Los Alamos Scientific Laboratory for an 800-MeV 1-mA Meson Physics Facility (LAMPF). Parameters shown in Table II. B. 2 are derived from the LAMPF design. Further details will be found in Chapter XIV.

Since the SOC was adopted as the reference design, improvements in linear accelerator structures have significantly reduced RF losses. This together with some clarification of the feasibility of high-efficiency RF amplifiers has reduced the relative advantage of the SOC in power consumption - the principle consideration in selecting the SOC as the reference design.

A final selection cannot be made until questions concerning RF capability for both machines and concerning orbit stability and construction tolerances of the SOC are settled by further study and development work.

* The reference-design linear-accelerator parameters are not optimum. Further study will probably yield a more economical design.

TABLE II. B. 2
ACCELERATOR PARAMETERS (LINAC)

<u>Ion Source</u>	DC Duoplasmatron, current 130 mA	
<u>Pre-Injector</u>	DC voltage 750 kV	
<u>Buncher</u>	Frequency 200 MHz	
<u>Linac Sections</u>	<u>Alvarez Section</u>	<u>Waveguide Section</u>
Length (ft)	600	4200
Energy (MeV)	165	975
Frequency (MHz)	200	800
RF Losses (MW)	6.9	20.9
Magnet Power (MW)	0.5	1.2

2. Beam-Transport System

After leaving the final SOC stage, the beam enters the High Activity Tunnel which acts as a distribution center. The layout of this area is shown in detail in Fig. II. 4. Almost all of the 65-mA beam passes on into the thermal-neutron facility tunnel and thence to the thermal-neutron facility (9 and 12 in Fig. II.1).

Thin meson-producing targets are placed in the beam in the High Activity Tunnel. About 1 mA is split from the main beam and diverted left 90° into another tunnel to form beam-2. This beam is used for meson and fast-neutron physics experiments.

Beam-3, about 0.1 mA, or less as required, is split from the main beam and bent 45° right and delivered to the resonance-neutron time-of-flight facility. A second splitter in beam-3 delivers about 1 μ A to the Advanced Power Technology facility. Secondary beam channels in the high-activity and beam-2 tunnel walls allow beams of mesons, neutrons and if desired, protons, to be extracted into the large experimental hall (7 and 8 in Fig. II.1).

The transport system has a total length of about 1700 feet. The magnet system to guide the beam has not been designed in detail, but preliminary estimates require some 52 quadrupole magnets after stage-3. The interstage transport system will require an additional 16 quadrupoles. The beam-splitting operation will be accomplished by a pulsed electrostatic deflection system which extracts 2-ns bursts of

FIG. II. 4 Beam Transport System

0 10 50 FEET
SCALE

protons from the characteristic beam-microstructure formed by the accelerator and deflects them into the beam-2 and beam-3 transport systems. A preliminary design of the beam splitter requires an overall length of 85 ft and a pulse power of about 1 MW to provide deflection.

The transport system, particularly the high-activity tunnel, requires thick shielding to protect personnel and reduce background in the experimental areas. The high-activity tunnel and beam-2 tunnel have sand walls 35 ft thick. Remote-handling equipment and a hot cell are required.

3. Experimental Facilities

3.1 Thermal-Neutron Facility*

The thermal-neutron facility is a vertical cylindrical reactor-like structure with vertical irradiation tubes and with horizontal beam tubes emanating from a central D₂O moderator vessel. An annulus for cobalt irradiation surrounds the vessel. Neutrons are produced at the center of the moderator by spallation from a lead-bismuth target by the 65-mA proton beam. The target is molten and circulates through a vertical Zircaloy tube passing axially through the moderator vessel. A beryllium annulus surrounding the target provides some neutron multiplication. The proton beam is guided by the beam-transport system to the top of the shield and thence downward into the target. The liquid metal is circulated through an heat-exchanger located below floor level. Fig. II.5 shows a section near the midplane of the vessel; Fig. II.6 shows the target, moderator vessel, shield, and proton beam transport system in elevation. Principal dimensions and other parameters of the thermal-neutron facility are given in Table II.B.3. Full details are given in Chapter VII. Its performance has already been compared to other high-flux facilities in Chapter I.

3.2 Low-Energy Experimental Area*

A bending magnet or beam splitter after the stage-1 SOC will provide a beam to an experimental area 40 ft x 80 ft for nuclear physics experiments with 50-MeV protons.

3.3 Meson Facilities*

A thin target of beryllia or carbon intercepts the main proton beam shortly after it enters the High Activity Tunnel (Fig. II.4). The continuous flux of π -mesons produced by the target is accepted by a secondary transport system (pion-channel) and conducted through the shield to the meson experimental area. Details of this facility are given in Table II.B.4

* Facilities marked with * form part of Basic Machine.

FIG. II. 5. Cross Section of Thermal Neutron Facility

FIG. II. 6. Cross Section Thermal Neutron Target

TABLE II.B.3

CHARACTERISTICS OF THERMAL-NEUTRON FACILITY

Facilities	
5 tangential beam tubes (4 with vertical access)	10 cm diameter
1 through-tube with vertical access	20 cm diameter
1 radial beam tube	10 cm diameter
2 pneumatic carriers	10 cm diameter
45 hydraulic carriers	4 cm diameter
5 vertical thimbles	15 cm diameter
1 cobalt blanket	
Maximum available flux	$10^{16} \text{ n cm}^{-2} \text{ s}^{-1}$
Source Strength	$8 \times 10^{18} \text{ n s}^{-1}$
Target	Diameter 20 cm Pb-Bi eutectic, Zircaloy-2 tube, Nb liner
Beryllium multiplier thickness	20 cm
D ₂ O moderator thickness	100 cm
Shield	Iron, heavy concrete
Shield thickness at beam tube elevation	450 cm iron
Pb-Bi inventory	105,000 lb
Pb-Bi flow rate	4560 lb s^{-1}
Pb-Bi temperature	450°C max., 325°C min.
Proton beam	65 mA, 1 GeV, CW
Beam power	65 MW
Target power	39 MW
Moderator power	16 MW
Shield power	10 MW
Experimental floor area	180 ft x 180 ft
Ceiling height	78 ft

TABLE II. B. 4

MESON AND ENERGETIC NUCLEON FACILITIES

<u>Basic-Machine</u> *	
CW Target (Beam-1)	$0.1 \text{ g cm}^{-2} \text{ Be}$
Pion Channel	2 quadrupole doublets, 3 bending magnets, length 40 ft
Pion Yield	$10^8 - 10^9 \text{ s}^{-1} (300 \pm 14) \text{ MeV } \pi^\pm$ at 40 ft
Shield	35 ft sand
Experimental Floor area	20,200 ft^2
<u>Full-Machine Additional Facilities</u>	
CW Target (Beam-1)	$0.1 \text{ g cm}^{-2} \text{ Be}$
Muon Channel	22 quadrupoles, 4 bending magnets, length ~ 40 ft
Muon Yield	$10^8 - 10^9 \text{ cm}^{-2} \text{ s}^{-1} (300 \pm 14) \text{ MeV } \mu^\pm$ at 100 ft
Pulsed Meson Targets (Beam-2)	$\sim 100 \text{ g cm}^{-2} \text{ C}$
Yields for 1-mA protons	$10^9 - 10^{10} \text{ s}^{-1} (150 \pm 8) \text{ MeV } \pi^\pm$ at 40 ft
	$10^7 - 10^8 \text{ cm}^{-2} \text{ s}^{-1}$ stopped $\mu^\pm$ at 50 ft
Neutron target (Beam-2)	liquid D_2 , $400 \text{ g cm}^{-2} \text{ Bi}$
Yield for 1-mA protons	$5 \times 10^7 \text{ cm}^{-2} \text{ s}^{-1}$ in 14 MeV, at 1000 MeV, at 20 ft
	$5 \times 10^7 \text{ cm}^{-2} \text{ s}^{-1} > 200 \text{ MeV}$ at 50 ft
Experimental floor area	69,700 ft^2

3.4 Meson and Energetic Nucleon Facilities

A second thin transmission target located in the main beam downstream of the beam splitter (Fig. II. 4) is associated with a secondary transport system (muon channel) designed to deliver a continuous flux of μ -mesons to the experimental area.

The beam-2 transport and shield are designed to permit installation of targets and beam channels as required for production and delivery to the experimental area of pulsed beams of π - and μ -mesons or scattered protons.

A beam splitter placed between the SOC stages-2 and -3 and a branch transport system delivering the beam to area 7. Fig. I. 1 could make a 400-MeV proton beam available for meson production in that area.

At the end of the beam-2 tunnel the protons encounter a target for producing fast neutrons, and beyond this the surviving proton beam is deflected to an underground beam dump. The fast-neutron target may consist of lead-bismuth, beryllium, or liquid D_2 depending on the spectrum of neutrons required.

3.5 Resonance Neutron Facility

The resonance-neutron facility uses a heavy-element target (lead) and thin hydrogenous moderator to produce the resonance neutrons. An initial complement of four flight tubes of length 50, 150, 250 and 1000 m are required. This facility gives $3.3 \times 10^{19} \text{ s}^{-1}$ peak neutron intensity in 2.4-ns bursts at frequencies up to 10^4 Hz .

3.6 Advanced Power Technology Target

The facility for electrical breeding studies consists of a target assembly surrounded by an iron shield 6 ft thick and an experimental area 55 ft by 40 ft.

3.7 Other Experimental Facilities

Facilities for radiation-damage studies will be provided in the beam dump at the end of beam-2.

Facilities for studying effectiveness of proton and π -meson beams for medical purposes can be allocated a position along beam-2.

Experimental facilities for testing new concepts in accelerator components could be established at various locations in the accelerating system.

C. REFERENCE SITE

The reference-design site is located within the borders of the AECL property at Chalk River. It is about half way between the existing laboratory and the town of Deep River close to the Ottawa River shore on the old Mattawa Road. The site provides:

- Reasonable access to existing facilities at CRNL.
- Bedrock for the accelerator foundations.
- An exclusion area and remoteness from large population centres necessary for protection of the public without extensive containment and active-waste disposal provisions.
- Easy access ~200 MW of electrical energy with satisfactory characteristics.
- Remoteness from important radio communication centres.
- Space for future expansion and for the alternative linear accelerator.

The cost estimates are based on this specific site; revisions would be necessary for any other.

CHAPTER V

RESEARCH AND TECHNICAL APPLICATIONS

A. PHYSICS RESEARCH	V.1
1. Thermal Neutrons (G.A. Bartholomew, B.N. Brockhouse R.A. Cowley, G.Dolling, J.W. Knowles, J.C.D. Milton, J.M. Robson)	3
1.1 Introduction	3
1.2 General Advantages of High Neutron Fluxes	3
1.3 Applications in Solid- and Liquid-State Physics	5
1.3.1 Solids	8
1.3.2 Liquids	10
1.4 Applications in Nuclear Physics	10
1.4.1 Neutron Capture γ -Rays	11
1.4.2 Photo-Excitation Experiments	13
1.4.3 Fission Experiment	16
1.4.4 Zero-Energy n-n Scattering	18
1.4.5 Beta-Decay of the Free Neutron	20
1.4.6 Very Cold Neutrons	21
2. Resonance Neutrons (G.A. Bartholomew, J.C.D. Milton, C.H. Westcott)	22
2.1 Fundamental and Statistical Resonance Parameters	22
2.2 Neutron Capture γ -Rays	23
2.3 Spin Measurements with Polarized Neutrons	24
2.4 Fission Experiments	25
2.5 Nuclear Data for Reactor Development	26
3. Future Extensions (Storage Ring) (G. Dolling, G.A. Bartholomew)	26
4. Energetic Nucleons (R.L. Clarke, W.G. Cross, G.C. Hanna, J.C.D. Milton, J.M. Robson)	28
4.1 The Nucleon-Nucleon Force	29
4.1.1 Nucleon-Nucleon Scattering	29
4.1.2 Single-Pion Production in Nucleon- Nucleon Collisions	30
4.1.3 Reactions Producing Two Pions	32
4.1.4 Bremsstrahlung from p-p and n-p Scattering	32

4.2	Nuclear-Structure Experiments	33
4.2.1	Optical Model	33
4.2.2	Direct-Interaction Inelastic Scattering	34
4.2.3	Quasi-Elastic Scattering	34
4.2.4	Charge-Transfer Reactions	35
4.2.5	Pick-Up Reactions	35
4.2.6	Cluster Ejection	36
4.2.7	Multiple-Nucleon Emission	36
4.2.8	Pion Emission from Nucleon Bombardment of Nuclei	37
4.2.9	Fragmentation and Fission	37
4.2.10	Experiments with Neutrons in the <14 MeV Range	38
4.3	Properties of ING Beams of Importance to Intermediate Energy	39
4.3.1	Intensity	39
4.3.2	Homogeneity	39
4.3.3	Energy Variation	40
4.3.4	Polarization	40
5.	Pions and Muons (J.C.D. Milton, E.P. Hincks, R.L. Clarke, M. Bercovitch)	42
5.1	Experiments with Pions	43
5.2	Experiments with Muons	45
6.	Neutrinos (J.C.D. Milton)	47
B.	NUCLEAR POWER TECHNOLOGY	50
1.	The Reactor Physics of Electrical Breeding (C.H. Millar)	50
2.	Areas of Research (C.H. Millar)	56
3.	Accelerator Development (P.R. Tunncliffe)	57
C.	CHEMISTRY AND MATERIALS RESEARCH	59
1.	Chemistry Research (T.A. Eastwood)	59
1.1	Nuclear Chemistry	59
1.1.1	Decay Scheme Studies	59
1.1.2	Fission and Spallation Reactions	60
1.1.3	Spallation and Fragmentation	63
1.1.4	Thermal- and Resonance-Neutron Cross Sections	64
1.2	Chemical Studies of the Heavy Elements	64
1.3	Activation Analysis	66
1.4	Radiation Chemistry	66

2.	Materials Research (O.J.C. Runnalls)	67
2.1	Basic Science	67
2.1.1	Radiation Damage	67
2.1.2	Damage by High Energy Particles	67
2.1.3	Thermal Neutron Scattering	68
2.1.4	Radiation-Enhanced Diffusion	68
2.1.5	Gases in Metals	68
2.2	Power Reactor Materials Studies	69
2.2.1	Irradiation of Crystal Bar Zirconium for Later Thin-Film Electron Microscopy Studies of Defect Aggregates	69
2.2.2	Study of Anisotropic Growth of Zirconium Single Crystals	69
2.2.3	Saturation of Radiation Damage in Zirconium Alloys	69
2.2.4	Structural Changes in Heat Treated Zirconium-Niobium Alloys	70
2.2.5	Effect of Dose Rate on Mechanical Properties of Zirconium Alloys	70
2.2.6	Effect of High Dose Rates on the Defor- mation of Zirconium Alloys	70
2.2.7	Determination of Flux Effect on the Corro- sion Behaviour of Zirconium Alloys	70
2.3	ING Material Studies	70
2.3.1	Lifetime of Beryllium Flux Multiplier	70
2.3.2	Transmutation Reactions	71
2.3.3	Studies of Corrosion Resistant Materials for ING	71
D.	ISOTOPE PRODUCTION (T.A. Eastwood)	72
E.	BIOLOGICAL AND MEDICAL APPLICATIONS (W.G. Cross)	73
1.	Bio-Medical Research	73
2.	Medical Therapy	73
3.	Radiation Dosimetry	74
4.	Beam Requirements	76
5.	Special Facilities	77

V. RESEARCH AND TECHNICAL APPLICATIONS

Very wide research and technical applications can be visualized for a facility with the beam current and energy capability of ING. However, not all applications can simultaneously be satisfied in a single machine - because the accelerator may not have the necessary flexibility, and because the requirements for different applications are sometimes contradictory. Thus, in the planning of the overall system, compromises are necessary between the various prospective users and also between users and accelerator builders. The research and technical applications presented in this chapter are compatible with the accelerator and beam-delivery system described in later chapters, but with the following qualifications:

- The fully developed machine is assumed, although the complete facility will not be realized for some years after start-up. (see Section IX. B).
- The accelerator reference design (Chapter VI) provides staging energies at 10, 50, 300, and 1000 MeV; these were set by cost optimization. A recent request by meson users for an intermediate staging point at 400 MeV instead of at 300 MeV has not yet been incorporated in the reference design. However, since the cost penalty involved is expected to be small (Appendix VI.2), the 400-MeV staging energy has been assumed for the discussions in this chapter. It is also assumed that a splitter and appropriate beam transport will be installed after the 400-MeV stage so that 400-MeV protons will be available in the meson area; this hardware is not included in the reference design.
- Further study may show the advisability of adopting a linac (Chapter XIV) as the accelerator. The consequences for experiments that involve the beam microstructure (50 MHz for the SOC and 200 MHz for the linac) do not appear serious (see for example Section VII. B 4), but delivery of an intermediate-energy beam at 400 MeV may be difficult. The feasibility of installing a splitter part way along the linac structure has not yet been assessed.

A. PHYSICS RESEARCH

The fully developed ING will provide neutrons at energies ranging from a few hundredths of an electron-volt to 1000 MeV, protons at discrete energies of 50, 400, and 1000 MeV with perhaps a variation of 10% downwards from these three values, pions (π^+ , π^- and π^0) and muons (μ^+ and μ^-) at all energies from zero to about 700 MeV, all four types of neutrinos (ν_μ , $\bar{\nu}_\mu$, ν_e and $\bar{\nu}_e$) with the μ -neutrinos peaked around 200 MeV and the e-neutrinos around 1 MeV, beams of monochromatic γ -rays from 1 to 10 MeV (see subsection 1.4.2 below) and a continuous γ spectrum from

0 to 500 MeV (from π^0 decay). In other words it makes available for research all known particles, except electrons, that can be produced with energies below the strange-particle threshold at 1100 MeV, and it makes them available with intensities and purities that in almost all cases are superior to those available on any existing or proposed machine¹.

The facilities for providing these particles, and their likely intensities, are given in Chapter VII. In the present chapter we describe the types of experiments that we expect to see done with ING. Since such description can easily degenerate into meaningless generalities, we also outline specific experiments that would be done if ING were available today. We realize that, by the time ING is constructed, many of these experiments may have been done, or may be no longer interesting. Nevertheless they serve as examples in a general discussion, and illustrate - as no general discussion could - the wealth and breadth of the field that ING can open up. Thus we hope to show how useful ING would be if it existed today and indicate the enthusiasm with which it would be employed; we know no better way than this to predict how useful it will be ten years ahead.

¹ J. C. D. Milton, ING Research Facilities, report AECL-2177 (1965).

A. PHYSICS RESEARCH

1. Thermal Neutrons

1.1 Introduction

Since the discovery of the neutron, thermal neutrons have found many applications in research in the fields of physics and chemistry. The neutron fluxes available from early reactors ($10^{12} - 10^{13} \text{ cm}^{-2} \text{ s}^{-1}$) were immediately applied to produce isotopes for studies of radioactive decay and to give beams for experiments in nuclear and solid-state physics. With the advent of reactors producing fluxes in excess of $10^{14} \text{ cm}^{-2} \text{ s}^{-1}$, the nuclear physics work is continuing, and studies of the structures of solids and liquids^{1, 2} are vigorously expanding. This rapid growth is illustrated by the new HFBR reactor at Brookhaven National Laboratory where six out of nine neutron beam tubes are allocated to solid-state research³. In line with this trend, it is anticipated that a major number of the thermal-neutron beam tubes provided by ING will also be employed for solid-state investigations.

The various ways in which thermal neutrons are now used to probe atomic behaviour and nuclear structure are briefly described in subsection 1.3. Particular emphasis is placed on the value of the high neutron fluxes now available from modern reactors, and of the further benefits anticipated from the still higher fluxes of ING. The basic ING design discussed in the present proposal provides for a continuous source of thermal neutrons. The possible future development of a storage ring (Chapter XIII. B) would permit the production of pulsed thermal and epithermal neutron beams. The utilization of such beams in physics research is discussed briefly in subsection 1.3 below.

1.2 General Advantages of High Neutron Fluxes

The provision of a high neutron flux permits improvement of experimental conditions in several ways, depending on the type of experiment involved. These may be outlined as follows:

- a) Increased speed with which data may be taken. An example: With in-pile fluxes of $10^{14} \text{ cm}^{-2} \text{ s}^{-1}$, a measurement of part of the spin-wave dispersion relation in a magnetic material may take about

¹ B.N. Brockhouse, et al., Research with Inelastic Neutron Scattering at the NRU Reactor, proc. 3rd U.N. Intl. Conf. Peaceful Uses of Atomic Energy (Geneva, 1964) 7, 419-429 (1965); report AECL-2012 (1964).

² P. A. Egelstaff (editor), Thermal Neutron Scattering, Academic Press, (New York, 1965).

³ G.H. Vineyard, private communication (1966).

one month for each value of sample temperature and externally applied magnetic field. If, within a reasonable period of time, the dispersion relation is to be studied as a function of temperature and of magnetic field, the data-taking time must clearly be reduced. The elucidation of the phenomenon of phase transitions in solids will probably involve many such multi-parameter experiments.

- b) Better experimental resolution. To continue with the previous example: The excited states of a magnetic system (e.g. spin waves) become less well defined as the temperature approaches the transition temperature (above which the long-range magnetic order is destroyed). A detailed study of the energy broadening and energy shift as functions of temperature can be made only if the experimental resolution is much improved. It may also happen that many excited states lie very close together in energy, in which case much better resolution is again the prime requirement. The scattered-neutron intensity, however, falls very steeply as the resolution is improved, and must be compensated by a large increase in source flux if the experiments are not to be prohibitively lengthy.
- c) Small samples. It is now often difficult or impossible to obtain suitably large specimens of certain materials. Single crystals of graphite and of zinc sulfide are two such materials - of great interest to the solid-state physicist - but of which only very small ($\ll 10^{-1} \text{ cm}^3$) specimens are available. With present neutron fluxes samples between 1 and 100 cm^3 are needed for adequate measurements of the phonon dispersion curve. Experiments involving specimens of separated isotopes may also require much higher fluxes to make up for small sample size.
- d) Extension of ranges of experimental parameters. The spectrum of thermal neutrons obtained from a reactor peaks in the vicinity of 10^{-2} to 10^{-1} eV. Scattering experiments with neutrons outside this range are therefore very time-consuming and suffer from severe signal-to-noise problems. Changing the moderator temperature can help (compared to D_2O at 50°C , a BeO moderator at 2000°C would substantially increase the flux of 0.2-eV neutrons), but an increase in total flux is probably also essential. For example, many experiments have been performed to determine the "scattering law" $S(Q, \omega)$ (Q and ω are the momentum and energy changes suffered by the scattered neutrons) for various liquids, and also for polycrystalline solids of interest in reactor physics. But the ranges of Q and ω accessible to the physicist depend on the incident-neutron energy, and extension of the measurements to high Q and/or ω values requires corresponding high incident-neutron energies.
- e) Increased complexity of multiple-parameter analysis. Studies of the nuclear fission process involve coincident detections of fission frag-

ments, prompt neutrons, and radiations emitted during de-excitation of the fragments. The energies and angular distributions of all these products of fission provide valuable insights into its mechanism. Coincident detections of particular fragments at particular angles and at particular energies are clearly rather rare, and the collection of adequate statistics in each "channel" presents a difficult problem. On-line computers are increasingly used to handle this kind of data, and they permit the efficient use of much higher fluxes of thermal neutrons to initiate the fissions.

f) Signal-to-noise ratio. For certain experiments, the background noise must be reduced as far as possible. For typical thermal-neutron detectors, high-energy cosmic rays and the residual radioactivity in the detector materials give a background count-rate that is $< 10^{-3} \text{ s}^{-1}$. Nevertheless, count-rates of 10^{-2} to 10^{-1} s^{-1} are typical for well-shielded detectors when located near a nuclear reactor with some beam holes in use. This rate could be reduced by placing the experimental apparatus further from the reactor, inside rooms heavily shielded to exclude the reactor background. However, fast-neutron contamination of the beam is itself a major source of background. For some experiments, very slow ("cold") neutrons may be transmitted for considerable distances through bent metal pipes. These neutrons are totally reflected by the pipe walls, whereas the fast neutrons escape from the pipe and can be scattered away and absorbed before reaching the experimental area⁴. The double monochromator recently proposed for installation at the NRU reactor⁵ also provides a useful mechanism for reducing background. In this, neutrons of a selected energy are reflected through an angle 2θ (θ is the "Bragg" angle) from a single crystal. A second similar crystal is placed in the reflected beam so that it reflects the monoenergetic neutrons in a direction that is parallel to the original beam direction but displaced laterally from it. The fast-neutron contamination of this new beam is expected to be very low indeed, since two successive scatterings have been interposed. Both the bent pipe for cold neutrons and the double monochromator reduce the signal to some extent and require a higher initial neutron flux to ensure that experiments may be completed in a reasonable length of time.

1.3 Applications in Solid- and Liquid-State Physics

Thermal neutrons are valuable as probes of the solid and liquid states:

- the momentum and energy of thermal neutrons are comparable to the momentum and energy of characteristic excitations

⁴ H. Maier-Leibnitz and T. Springer, *Reactor Sci. and Tech.* 17, 217 (1963).

⁵ B. N. Brockhouse, private communication (1966).

in solid and liquid systems.

- neutrons interact with the nuclei of the constituent atoms, whereas most other probes interact only with the electrons and cannot be used to measure directly changes of both energy and momentum.

For example, X-rays can be used to study momentum changes, but their energies are so much higher than the energies of typical excitations in solids and liquids that energy changes suffered by scattered X-rays cannot be measured directly. Infra-red radiation, on the other hand, permits measurement of the energies, but the momentum involved is much smaller than that of almost all of the excitations.

Neutrons have a number of other properties that are valuable for studying the structure of matter. Generally speaking, neutron-scattering and -absorption cross-sections are relatively small, and neutrons can penetrate several centimeters into a solid (or liquid) specimen. Hence neutron-scattering techniques are not restricted to a particular type of material, and can equally well yield information about metals, insulators, semiconductors and liquids. Furthermore, since the neutron's magnetic moment can interact with atomic magnetic moments, neutron scattering is a most valuable tool for studying the structure and dynamical behaviour of magnetic systems. The great value and importance of thermal-neutron scattering for research in solid- and liquid-state physics stems from this versatility.

One of the most distinctive (and hence important) scattering processes suffered by thermal neutrons incident on a crystalline solid is that of diffraction; the neutrons are elastically scattered from the regular array of atoms in the solid, and interfere with each other to produce a diffraction pattern in the same way as light scattered from a grating. With many solids this diffraction pattern is the most intense and most easily observed part of the total scattering. The diffraction patterns of a simple solid that contains only a few different types of atom are fairly easy to measure in a flux of $10^{12} \text{ n cm}^{-2} \text{ s}^{-1}$, and the crystal structures can then be deduced.

These experiments give essentially the same information as X-ray diffraction measurements. However, neutrons can be used to study problems which are very difficult by X-ray techniques. For example, the study of the position of hydrogen atoms in crystals, and of the ordering of alloys of materials of similar atomic number can be performed better with neutrons than with X-rays. Similarly neutron diffraction from a liquid leads to a knowledge of the pair distribution function $g(r)$, defined as the probability that, given an atom at an origin $r = 0$, there will also be another atom at position r . With the increased fluxes available from modern

reactors, more complex inorganic crystals have been studied successfully in this way. Even higher fluxes will permit the investigation of some of the simpler protein molecules. Neutron diffraction has a most important part to play here, especially in finding the positions of hydrogen atoms. As mentioned above, the neutron's magnetic moment can interact with the magnetic moments in a crystal, whose geometrical arrangement may therefore be deduced from neutron diffraction patterns. There is at present no other way of obtaining such information about magnetic structures.

In addition to the above-mentioned elastic (Bragg) scattering processes, there are inelastic processes which are usually associated with cross-sections many orders of magnitude lower. There is, nevertheless, a vast body of information to be extracted from these low-intensity processes, information concerning the dynamical behaviour of atoms and molecules, and their magnetic moments, if any. A substantial literature has accumulated on this subject during the past ten years² and the pace of this research is still accelerating. Given a flux in the moderator of $10^{14} \text{ cm}^{-2} \text{ s}^{-1}$, it is fairly easy to measure the most prominent features of the inelastic neutron scattering in a crystalline solid; from these the basic forces acting between its constituent atoms (or magnetic moments) can be inferred. To use the customary technical language of this subject, one measures the dispersion relation between the frequency and wave vector of the normal modes of vibration of the solid (or the spin waves in a magnetic system), and deduces interatomic force constants (or magnetic exchange parameters) from this dispersion relation. The availability of neutron fluxes of $10^{14} \text{ cm}^{-2} \text{ s}^{-1}$ enables the determination of phonon (single quantum of a normal mode of vibration) and magnon (single quantum of a spin wave) dispersion relations, at least in fairly simple solids having only a few different types of atom. Such measurements are extremely difficult, to say the least, with a flux of only $10^{12} \text{ cm}^{-2} \text{ s}^{-1}$ at the source.

At present, it is very difficult if not impossible to study the interactions of phonons and magnons with themselves and with other excitations. Fluxes of $10^{16} \text{ cm}^{-2} \text{ s}^{-1}$ are needed if interactions such as those between magnons and phonons, excitons and phonons, and plasmons and phonons are to be studied in detail^{6, 7}. Interactions between excitations give rise to many of the properties of crystals; thus the phonon-phonon interaction is associated with ferroelectricity⁸, while the electron-phonon interaction, which is closely associated with the phenomenon of superconductivity, can be studied through the "Kohn Effect" in phonon dispersion curves⁹. Indeed higher-flux neutron beams provide the only way known at present of determining Fermi surfaces of metals at high temperatures and/or in the

⁶ R.A. Cowley and G. Dolling, Phys. Rev. Letters 14, 549 (1965).

⁷ W. Cochran, et al., Proc. Roy. Soc. (in press).

⁸ R.A. Cowley, Phys. Rev. Letters 9, 159 (1962).

⁹ W. Kohn, Phys. Rev. Letters 2, 393 (1959).

presence of impurities.

Measurements in simple crystalline solids usually determine only the positions of well-defined peaks in the energy distribution of inelastically scattered neutrons. The shapes¹⁰ and intensities¹¹ of these peaks could provide additional distinct information, and this has as yet scarcely been exploited for any solid. Fortunately - within wide limits - the shapes and intensities are not needed for determining dispersion relations, and we have been able to enjoy a large measure of success in applying neutron scattering techniques to the study of crystalline solids - while, at the same time, we have made only moderate progress in applying these techniques to liquids. Generally speaking, to derive information about the behavior of liquids we must measure and interpret the intensities of scattered neutrons - and measuring peak intensities involves very much longer counting times than measuring peak positions. Similar remarks apply to the determination of peak shapes, which are of great importance in the study of interactions between phonons or magnons and other excitations in solids.

We have discussed in broad outline some of the ways in which the techniques of thermal-neutron scattering have been and are being used as tools in solid- and liquid-state physics, and have indicated the limitations that are imposed by the neutron fluxes obtainable. Experiments of the kinds listed below require fluxes of $10^{16} \text{ cm}^{-2} \text{ s}^{-1}$ or higher if they are to be completed in reasonable time.

1.3.1 Solids

- a) Determination of the phonon and/or magnon dispersion relations in materials for which only small single-crystal samples are available (e.g. graphite, zinc sulfide) or for which large absorption cross-sections necessitate the use of small samples (e.g. many rare-earth metals).
- b) Determination of the phonon dispersion relations in materials of complex crystal structure (say 10-20 different atomic species) where the close spacing of the many branches of the dispersion relation requires very high experimental resolution.
- c) Determination of the crystal structure of materials (e.g. simple proteins) too complex to be measured with present-day neutron fluxes. Neutron diffraction would serve to complement X-ray diffraction techniques in this field.

¹⁰ R.A. Cowley, Adv. in Phys. 12, 421 (1963).

¹¹ B.N. Brockhouse, et al., Determination of Polarization Vectors from Neutron Group Intensities, proc. IAEA Symp. on Inelastic Scattering of Neutrons in Solids and Liquids (Chalk River 1962) 2, 23-24, 1963; report AECL-1572 (1962).

- d) Determination of the geometrical arrangement of moments in complex magnetic materials (a field inaccessible to X-ray diffraction).
- e) Determination of the phonon and/or magnon dispersion relations for relatively simple solids, as a function of temperature, pressure, applied electric or magnetic fields, composition (in the case of alloys), or conduction-electron concentration (in the case of semiconductors). Experiments of this type are possible at present, but the time required severely limits the extent to which the experimental parameters can be varied. In spite of this, much valuable information has been obtained in this way concerning
- ferroelectric phase transitions in strontium titanate⁸ and quartz¹²,
 - electronic band structure and Fermi surfaces in molybdenum-niobium¹³ and lead-thallium¹⁴ alloys,
 - phonon-plasmon interaction in degenerate lead telluride⁶, and
 - the antiferromagnetic phase transition in uranium dioxide¹⁵,
- to mention a few recently studied examples.
- f) Investigation of anharmonic effects, phonon-phonon, phonon-magnon interactions, etc. Only the surface of this subject has been sampled so far, and it may well prove to be the most important new field to be exploited with fluxes of $10^{16} \text{ cm}^{-2} \text{ s}^{-1}$. The number and range of new experiments that would become possible are too large for adequate expression here: some tentative steps in this direction are mentioned in section 5) above, but to attempt to predict the future course of this research from the present vantage point would be a profitless exercise.
- g) Study of defects in crystals and disordered crystals. Such studies have already been started (e.g. observation of resonance modes in dilute alloys of Cu(Au)¹⁶ and Cr(W)¹⁷), but once again we stand

¹² M.M. Elcombe, Bull. Amer. Phys. Soc. 10, 435 (1965).

¹³ A.D.B. Woods, Review of Experimental Measurements of Lattice Modes in Transition Metals, proc. BNL Symp. on Inelastic Scattering of Neutrons by Condensed Systems (Brookhaven National Laboratory, Sept. 1965) report BNL 940 (C45), 8-15 (1966).

¹⁴ S.C. Ng and B.N. Brockhouse, Phys. in Canada 22 (2), 23 (1966).

¹⁵ G. Dolling and R.A. Cowley, Phys. Rev. Letters 16, 683 (1966) and to be published.

¹⁶ E.C. Svensson, et al., Solid State Comm. 3, 245 (1965).

¹⁷ H. Bjerrum Møller and A.R. Mackintosh, Phys. Rev. Letters 15, 623 (1965).

on the border of virtually unexplored territory in which the precise measurement of very small effects, and the need to study ranges of composition or defect concentration, make the provision of higher fluxes most desirable. It need hardly be mentioned that most materials in every-day use are not perfect single crystals, and if the discoveries of solid-state physics are to have more direct applications, it will be necessary to make experiments on decidedly imperfect and complicated solids.

- h) Studies of magnetic excitations (magnon spectra) with the aid of polarized neutron beams. Although techniques for polarizing neutrons and for detecting their polarization after scattering are improving, the beams are obtained only at the cost of appreciably decreasing the intensity. Higher starting fluxes would greatly stimulate the development of this almost unexplored field.

1.3.2 Liquids

- a) Determination of the pair distribution function $g(r)$ for complex liquids (organic liquids, mixtures of liquids, etc.), by neutron diffraction.
- b) Determination of the time-dependent pair correlation function for complex liquids and liquids having high neutron absorption (e.g. ^3He) by measurements of the "scattering law", $S(Q, \omega)$.
- c) Extension of the ranges of Q and ω in measurements of $S(Q, \omega)$, both for liquids and for polycrystalline solids of interest as reactor moderators.
- d) Continuation of the search for more-or-less well-defined excitations in liquids (e.g. "phonons" of short wavelength), and the measurement of their dispersion relations¹⁸. Liquid ^3He is again of considerable interest in this connection.

1.4 Applications in Nuclear Physics

Much information about nuclear structure has come from experiments in which target materials were bombarded with neutrons¹⁹, in

¹⁸ S.H. Chen, et al., Phys. Letters 19, 269 (1965).

¹⁹ For a recent review of nuclear physics with neutrons see I. Lovas and Z. Zamori, Atomic Energy Rev. 3, 61 (1965).

particular information on neutron-capture γ -rays^{20, 21} and fission²². Although, as time goes on, more use will probably be made of resonance neutrons (see Section A 2 below), the work with thermal neutrons will be stimulated by any new techniques that give improved sensitivity or resolution. For example, recent advances in solid-state γ -ray detectors²³ have accelerated studies of thermal-neutron capture γ -rays, and recently developed techniques^{24, 25} in photo excitation, which employ thermal-neutron capture γ -radiation as a probe, have opened new ways to explore the excited states of nuclei. This latter field will benefit greatly from the increased γ -ray intensities that ING may provide.

Fundamental information concerning the mean life and β -decay properties of the free neutron has been obtained with neutron beams from reactors^{21, 26, 27}. A high-flux source would give more precise data in this and in other fundamental areas of nuclear physics.

1.4.1 Neutron Capture γ -Rays

Experiments that may become of immediate interest when neutrons from ING are available include:

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- ²⁰ G.A. Bartholomew, *An. Rev. Nuclear Sci.* 11, 259 (1961).
- ²¹ H.T. Motz and G. Bäckström, Beta and Gamma Ray Spectroscopy, K. Siegbahn (ed.) North Holland Publishing Co., Amsterdam (1965).
- ²² J.S. Fraser and J.C.D. Milton, *An. Rev. Nuclear Sci.*, to be published.
- ²³ A.J. Tavendale, *Electronique Nucleaire*, O.E.C.D. Paris, p. 235 (1963).
- ²⁴ J.W. Knowles and N.M. Ahmed, Methods of Applying Compton Scattered Neutron Capture Radiation to Nuclear Excitation, report AECL-2535 (1966).
- ²⁵ J.A. McIntyre and J.B. Randall, *Phys. Letters* 17, 137 (1965).
- ²⁶ J.M. Robson, *Phys. Rev.* 83, 349 (1951).
- ²⁷ M.A. Clark and J.M. Robson, *Can. J. Phys.* 39, 1 (1961).

- a) Measurements of energies, intensities, coincidences and γ - γ angular correlations of thermal neutron capture γ -rays from targets with very small capture probabilities as measured by their barn-mol product. Possible targets are the scarce, separated isotopes with small capture cross-sections and, in certain cases, radioactive materials. The external neutron beam facility²⁸ used for this type of measurement at the NRX reactor was not designed for work with small samples. The "pure" thermal-neutron beam at this facility has a flux of about $5 \times 10^5 \text{ cm}^{-2} \text{ s}^{-1}$ and experiments are possible for targets with capture probabilities greater than ~ 0.5 barn mol. ING could provide beams about 10^6 times more intense and, allowing a factor of $\sim 10^2$ for losses during 'clean-up', targets with capture probabilities as low as 5×10^{-5} barn mol could be studied.
- b) Internal-conversion spectroscopy. Measurements of the spectra of internal-conversion electrons and internal pair electrons following neutron capture are valuable for determining multipolarities of capture γ -rays and for obtaining spin and parity information. Such measurements have, as yet, been little exploited. Targets must be thin so that the emerging electrons suffer negligible scattering and energy loss - and yet the counting rates must be adequate. A higher neutron flux would extend the range of possible target elements to those with small neutron-capture cross-sections.

Applications a) and b) both involve external neutron beams and may be beset with background problems caused by neutron capture in materials surrounding the target, by epithermal neutron capture, and by stray radiations emanating from neighbouring experiments. All of these effects can be reduced if a very pure thermal-neutron beam can be brought to a location remote from other sources. One promising method of doing this, as mentioned earlier, is to conduct cold neutrons through internally reflecting bent pipes.⁴ Whether the advantages of this technique outweigh the concomitant loss of overall intensity is a matter for detailed study in the planning of a particular experimental arrangement and it will not be pursued here.

- c) High-resolution spectroscopy of neutron-capture γ -rays with the target placed in the high-flux region of the beam tube and the γ -ray detector externally mounted. With the high resolution and sensitivity provided by modern Ge(Li) detectors, adequate counting rates can now be achieved even with neutron-capture γ -ray sources of

²⁸ G.A. Bartholomew and M.R. Gunye, Can. J. Phys. 43, 1128 (1965).

very low intensity²⁹. However, situations can be anticipated that will require still higher resolutions and better signal-to-background ratios than those given by Ge(Li) detectors. This improvement can come with crystal diffraction spectrometers³⁰, in particular the double flat crystal diffraction spectrometer. Such devices have relatively low efficiency and require intense sources - which could in principle be obtained by installing the targets in the high-flux region of ING. Provision of 'L-tubes' in the ING thermal facility (Chapter VII) will facilitate the cooling of targets in this position.

1.4.2 Photo-Excitation Experiments

The neutron flux provided by ING greatly facilitates photo-excitation experiments, as illustrated by the following examples:

- a) Photo-excitation measurements, which include the resonance and self-absorption of radiation in a wide range of target nuclei, are made at present²⁴ in a system at the NRU reactor that gives a source of γ -rays of variable energy. To achieve this, a few kilograms of nickel are placed in a thermal-neutron flux of $2 \times 10^{13} \text{ cm}^{-2} \text{ s}^{-1}$. Some of the resulting 9.0 MeV (n, γ) radiation from ^{59}Ni undergoes Compton scattering on an aluminum reflector. The system permits measurements of radiation widths of excited states over a wide range of energies up to 9.0 MeV. Radiation widths, for E1, M1, E2 and M2 γ -rays of energies between 0 and 10 MeV in ^{27}Al and ^{238}U , obtained from semi-empirical estimates³¹ are plotted as broken lines in Fig. V.1. The ranges accessible to measurement with neutron fluxes $\phi = 10^{12}$, 10^{14} and $10^{16} \text{ cm}^{-2} \text{ s}^{-1}$ lie above the appropriately labelled full lines in the same figure. Each line gives the radiation width Γ_γ as a function of excitation energy E which can be measured after two hours counting time to a statistical precision of 3% when the (n, γ) source is irradiated by a thermal-neutron flux ϕ . For example, if $\phi = 10^{14} \text{ cm}^{-2} \text{ s}^{-1}$ the range of measurement is limited to radiation widths $\geq 10^{-3} \text{ eV}$ at 1 MeV and $\geq 10^{-1} \text{ eV}$ at 8.5 MeV. This includes primarily E1 and M1 transitions. For a neutron flux $\phi = 10^{16} \text{ cm}^{-2} \text{ s}^{-1}$, the range of measurement is considerably extended to include E2, M2 as well as E1 and M1 transitions over a wide range of energies.

²⁹ O.A. Wasson, et al., Phys. Rev. 136, B1640 (1964).

³⁰ J.W. Knowles, Alpha-, Beta- and Gamma-Ray Spectroscopy, K. Siegbahn (ed.) North Holland Publishing Company, (Amsterdam 1965).

³¹ D.H. Wilkinson, Analysis of Gamma Decay Data, Nuclear Spectroscopy Part B, F. Ajzenberg-Selov (editor). Academic Press, New York. 852-889 (1960).

FIG. V. 1 Range of Operation of Variable Energy γ -ray Beam.

- b) A flux of $10^{16} \text{ cm}^{-2} \text{ s}^{-1}$ could be used to produce a variable-energy γ -ray beam with 0.1% resolution, some ten times the resolution of the present facility. This improved resolution would permit detailed studies of excited states lying between 1 and 8 MeV and separated by only 0.1% in energy.
- c) A resonance excitation spectrometer²⁵, with a resolution of $1:10^7$, suitable for the excitation of closely spaced nuclear levels becomes practical if the strength of a variable-energy γ -ray beam, such as that described above, can be increased by a factor of from 10 to 10^2 . The basis of such a spectrometer is the change of energy brought about by nuclear recoil during resonance scattering. Because recoil energy is transmitted to the scattering nucleus, the energy of the scattered radiation is less than that of the incident radiation by an amount which is a function of the scattering angle. For example, if a beam of γ -radiation incident on a lead target excites a level 7 MeV above the ground state, the energy of the scattered radiation varies between 7 MeV at a scattering angle of 0° and 7 MeV less 500 eV at 180° . Thus the scattered radiation forms a variable-energy γ -ray probe with resolution of $1:10^7$ which can be used to excite resonances in the range from 7 MeV less 500 eV to 7 MeV in any target material.
- d) Many different photo-excitation experiments could be done if the intensity of the incident beam could be substantially increased:
- Lithium-drifted germanium detectors could be used for high-resolution spectroscopy following photo-excitation.
 - Inelastic resonance scattering could be studied by detecting coincidences between cascade γ -rays, and the spins of excited levels could be measured by $(\gamma\text{-}\gamma)$ angular correlation of the resonantly scattered γ -rays.
- e) All photo-excitation experiments described above require an internal source and face the source cooling problem mentioned in Section 1.4.1. Resonance-scattering experiments with the energy balance supplied by a preceding cascade γ -ray can be carried out with an external neutron beam and external uncooled source of capture γ -rays. Such experiments, only just possible in selected cases with existing fluxes, may find a wider range of applicability with the neutron beams of ING.
- f) Photofission is an extremely useful tool for investigating the transition state spectrum²², that is the states available to the fissioning nucleus at the saddle point³². For example in an even-even nucleus. Photo-absorption proceeds by dipole and to a lesser extent quadrupole excitation. Thus fission occurs only through

³² A. Bohr, On the Theory of Nuclear Fission, proc. UN Intl. Conf. Peaceful Uses Atomic Energy (Geneva) 2, 151 (1955).

1- and 2+ states, each of which leads to a characteristic angular distribution of fragments²². The energy separation between the lowest 1- and 2+ states gives information on the K-band structure of the transition states and this in turn can help to answer the question of whether or not a stable octupole deformation exists at the saddle³³. The interesting region is near threshold at γ -ray energies of about 5 MeV. Here the cross-sections are a few millibarns, but an energy resolution of only about 2% is needed.

1.4.3 Fission Experiments

ING's principal advantage for fission research - as for other nuclear structure work - will probably lie in the resonance-neutron region; this research is discussed in the next section (V.A 2). In the thermal-neutron region, the advantage comes from an ability to produce purer beams - this reduces background and permits experiments to finish in shorter times. At NRU a typical four-parameter experiment (V_{f1} , V_{f2} , V_n , θ_n) must run for about a year to gather adequate statistics. There is a clear advantage in being able to do such an experiment in a week.

- a) Purer beams and the reduced background would make possible experiments on fission γ -rays, X-rays and conversion electrons. The γ -rays are interesting in studies of the decay of neutron-rich nuclei, well removed from the valley of β stability and inaccessible by other means, as well as for studies of the angular momenta of the fragments. The X-rays are useful for studying the charge distribution. The availability of high-resolution Ge(Li) detectors has renewed interest in these subjects^{34, 35} but so far the work has been limited to the spontaneous fission of ²⁵²Cf.
- b) Increased intensity would aid more detailed studies of rare modes of fission. For example, in the region of symmetric fission - just where the intensity is low and the background high - many interesting things appear to happen to the neutron emission³⁶, the

³³ S.A.E. Johansson, Nuclear Phys. 22, 529 (1961).

³⁴ H.R. Bowman, et al., The Prompt Gamma-Ray, Prompt Electron and Prompt X-Ray Spectra Associated with Fission Fragments of Specific Mass, proc. IAEA Symp. on Physics and Chemistry of Fission (Salzburg) 2, 125 (1965).

³⁵ T.D. Thomas, et al., X-Rays Emitted in Coincidence with the Fission of ²⁵²Cf, Ibid, 1, 385 (1965).

³⁶ J.C.D. Milton and J.S. Fraser, The Energies, Angular Distribution and Yields of the Prompt Neutrons from Individual Fragments in the Thermal-Neutron Fission of ²³³U and ²³⁵U, Ibid, 2, 39 (1965).

charge division³⁷ and the γ -ray emission³⁸. A knowledge of true ternary fission (that is division into three roughly equal-sized fragments) is essential for a proper understanding of the liquid-drop theory. Muga's³⁹ counter experiments gave a probability of about 1 ternary to 10^6 binary fissions, but a radiochemical search⁴⁰ for nuclides that he found in high abundance gave yields 3 to 7 orders of magnitude lower than his. The evidence for alpha particles⁴¹ and other light particles⁴² accompanying fission is more reliable, but it is still difficult to correlate mass, energy and neutron emission for the comparatively rare case (1 in 300) in which fission is accompanied by an alpha particle.

- c) A broad field could be opened up at ING by installing a fission-fragment mass separator. A double-focussing mass separator with both electric and magnetic fields has been used on fission fragments at Munich⁴³, but the counting rates are low and detectors must be photographic emulsions. Furthermore, masses can be resolved only in the heavy peak where the variation of average energy with mass is favorable and wide energy acceptance can be used. An RF mass separator⁴⁴ could also be developed for fission

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- ³⁷ E. Konecny, et al., Primary Distributions of Nuclear Charge for Fission-Fragment Masses 132, 134, 136 and 137 from Thermal Fission of ^{235}U , Ibid 1, 401 (1965).
- ³⁸ H. Maier-Liebntz, et al., Prompt and Delayed Gamma-Rays From Fission, Ibid, 2, 113 (1965).
- ³⁹ M.L. Muga, Ternary Fission, Ibid, 2, 409 (1965).
- ⁴⁰ R.W. Stoenner and M. Hillman, Phys. Rev. 142, 716 (1966).
- ⁴¹ N. Feather, The Emission of Long-Range Alpha Particles in Fission, proc. IAEA Symp. on Physics and Chemistry of Fission (Salzburg) 2, 387 (1965).
- ⁴² S.L. Whetstone, Jr. and T.D. Thomas, Phys. Rev. Letters 15, 298 (1965).
- ⁴³ H. Ewald, et al., Zeit. f. Natur. 19, 194 (1964).
- ⁴⁴ W. Paul, et al., Zeit. f. Phys. 152, 143 (1958).

fragments. Examples of the uses of such a device are:

- determination of the charge distribution in fission by direct β counting,
- β and γ spectroscopy of nuclei well removed from the valley of stability.

1.4.4 Zero-Energy n-n Scattering

The n-n scattering cross-section has been obtained indirectly from the interaction of neutrons with deuterium nuclei. In that method it was assumed that the proton and neutron in the deuterium nucleus are free, but it is not clear that the assumption is valid near zero energy. It has been suggested^{45, 46} that a high flux of thermal neutrons $>10^{15} \text{ cm}^{-2} \text{ s}^{-1}$ provides a practical gas target for studying the direct interaction of elementary particles with neutrons.

The n-n scattering experiment, originally described by Muehlhause⁴⁶ required an evacuated space in the thermal column of a high-flux reactor. The same experiment could be performed using a comparable space in the D_2O moderator surrounding the ING target. The physical boundaries of the vacuum chamber seen by the detector must be outside the region of appreciable neutron flux. A typical geometry is shown in Fig. V.2. Neutrons scattered from neutrons in a target volume V have a probability Ω of being scattered into detector D . The neutron counting rate, I_{nn} , at the detector, assuming 100% detector efficiency is

$$I_{nn} = \sigma_{nn} (\bar{N})^2 V \Omega / v$$

where $\bar{N}$ is the average flux of thermal neutrons in the target volume, circumscribed by the broken line in Fig. V.2, σ_{nn} is the n-n scattering cross-section, and $v \simeq 2 \times 10^5 \text{ cm s}^{-1}$ is the velocity of thermal neutrons at normal temperature. For the dimensions shown in Fig. V.2 (which correspond to the 8-inch-diameter through-tube of Fig. VII.1), $V\Omega = 5.10^{-3} \text{ cm}^3$. The counting rates at the detector have been estimated for a range of neutron fluxes on the assumption that $\sigma_{nn} = 60 \text{ barns}$ ⁴⁷ and they

⁴⁵ A.I. Yavin, Experiments with Neutron-Gas Targets, proc. Summer Study on Storage Rings, Accelerators and Experimentation at Super-High Energies, BNL-7534, 406 (1963).

⁴⁶ C.O. Muehlhause, Proposed Experiment to Observe n-n Scattering, proc. Intl. Conf. on Nuclear Physics with Reactor Neutrons, ANL-6797, 21 (1963); NBS-7583, NBSR-8 (1963).

⁴⁷ K. Ilakovac, et al., Phys. Rev. 124, 1923 (1961).

D_2O MODERATOR

S SHIELDING

D THERMAL NEUTRON DETECTOR

B THERMAL NEUTRON BAFFLE

V VACUUM CHAMBER, 8" DIAMETER

$\bar{N}$ REGION OF THERMAL NEUTRONS

T SOURCE OF FAST NEUTRONS

FIG. V.2 n-n Scattering Geometry.

are listed in the second column of Table V.A.1. It is assumed that a gas pressure of 10^{-7} mm Hg, which corresponds to a gas density $\zeta = 4 \times 10^9$ atoms cm^{-3} , can be maintained in the volume V . The background counting rates from residual air scattering are estimated using the equation

$$I_B = \sigma_B \cdot \bar{N} \zeta V \Omega.$$

where the mean cross-section for the scattering of thermal neutrons in air is $\sigma_B = 10$ barns. A comparison of columns 2 and 3 shows that, although n-n scattering experiments suffer from serious background effects at a flux of $10^{14} \text{ cm}^{-2} \text{ s}^{-1}$, they become much more feasible at $10^{16} \text{ cm}^{-2} \text{ s}^{-1}$.

TABLE V.A.1
COUNTING RATES IN N-N SCATTERING EXPERIMENTS

$\bar{N}$ $\text{cm}^{-2} \text{ s}^{-1}$	I_{nn} s^{-1}	I_B s^{-1}
10^{14}	0.03	0.2
10^{15}	3.0	2.0
10^{16}	300	20

1.4.5 Beta-Decay of the Free Neutron

The beta decay of the free neutron was extensively investigated during the period 1950 to 1960 in Canadian, American, and Russian laboratories, using thermal-neutron beams from reactors. The basic constants of the decay were established with a precision which at the time was considered as great as could readily be obtained and which was adequate for the general verification of the theory of the weak interaction. The fundamental constant, the half-life of the neutron, was measured with a claimed precision of 3%, and the other constants with slightly less precision.

The limitation on the accuracy of the measurements was to a large extent due to the nature of the beams of neutrons which in general were too

weak and too heavily contaminated with fast neutrons and gamma rays. Ideally a high-intensity source of thermal neutrons with a low ratio of fast-to-thermal components provides the best beam for such experiments. One might therefore use the ratio $(\text{thermal flux})^2 \div (\text{fast flux})$ as a criterion by which to measure the usefulness of various sources for future neutron-decay experiments. The values of this ratio for NRU, typical of the type of source used for the experiments carried out during the 1950's, HFBR, a modern reactor, and ING close in (12 cm) and far out (76 cm) from the neutron-producing source, are as follows:

	$\phi_{\text{th}}^2 / \phi_{\text{f}}$
NRU	$\sim 10^{14}$
HFBR	$\sim 10^{17}$
ING (12 cm)	$\sim 10^{17}$
ING (76 cm)	$\sim 5 \times 10^{18}$

Thus ING could be a better source for neutron-decay experiments than those now available.

1.4.6 Very Cold Neutrons

Very cold neutrons with velocities of a few metres per second could be employed in interesting experiments on gravity. For example⁴⁸ a search for a gravity-nucleon spin interaction could be attempted by measuring the deflection of a beam of unpolarized neutrons in a region free of magnetic field. Fascinating experiments on the wave nature of neutrons and on their total reflection could be done if neutrons of very long wavelength were available and they might lead to useful results. Such experiments improve in quality with the number of neutrons of long wavelength available and would clearly benefit from the fluxes available at ING.

⁴⁸ See also, D. Paya, et al., Acceleration of Free Neutrons Under Gravity, proc. Intl. Conf. on Nuclear Physics with Reactor Neutrons, ANL-6797, 30 (1963).

2. Resonance Neutrons

Information obtained by studying neutron resonances is of value, both for a better understanding of nuclear structure and as an aid in the design of fission reactors. Quantities of interest in nuclear physics are

- fundamental parameters for individual resonances, such as energy, spin, parity, and the probabilities of various modes of decay,
- 'statistical' parameters for many resonances such as level spacing and the neutron strength function,
- decay properties such as γ -ray decay schemes, α -decay schemes, and fission modes.

Among quantities of interest in reactor physics are absolute cross-sections for scattering, capture and fission, neutron excitation functions and fission-product yields. In this section we attempt to show the potential usefulness of the resonance-neutron time-of-flight facility by indicating its ability to supply information in a few of these many areas.

2.1 Fundamental and Statistical Resonance Parameters

Recent experiments¹ with the Nevis Cyclotron time-of-flight facility have, for many nuclides, resolved individual resonances well into the keV region. These measurements yield the level spacings of the strength function and also partial level width distributions. Spins, radiation widths, neutron widths and various correlations between resonance parameters in the keV range have been reported for many elements by the Saclay group². As discussed in Section VII.B, ING should permit transmission measurements to about 1 MeV with resolutions about equal to the Doppler width of a nucleus near $A = 100$. Therefore, ING could extend both the detection of individual resonances and the measurement of various resonance parameters into the regions of tens or hundreds of keV or higher depending on the target nucleus.

¹ J. Rainwater, et al., Proc. Intl. Conf. Study of Nuclear Structure with Neutrons (Antwerp, 1965) North Holland, to be published.

² J. Julien, et al., Phys. Letters 10, 86 (1964) and various papers in Proc. Intl. Conf. Study of Nuclear Structure with Neutrons, (Antwerp, 1965) North Holland, to be published.

2.2 Neutron-Capture γ -Rays

Several groups have used NaI detectors to study neutron-capture γ -rays from individual resonances in many elements³. Such measurements have not extended much beyond a few hundred electron-volts, in neutron energy⁴, and even here the quality could be much improved by using Ge(Li) detectors. Whether as single detectors or in coincidence arrangements, these devices are only now beginning to be applied to the γ -ray spectroscopy of resonance neutron capture.

Measuring the γ -rays produced by resonance capture is a natural extension of measuring those produced by the capture of thermal neutrons (see subsection V.A.1). Resonance capture has the great advantage that it involves a single excited state of the compound nucleus, whereas - in many nuclides - thermal-neutron capture involves a complicated state to which more than one resonance is contributing. Thus, resonance capture provides a convenient method of studying aspects of the radiative process from highly excited states under relatively uncomplicated conditions (no Coulomb barrier and no competition from competing γ -ray-producing reactions and small spin changes).

To obtain a rough measure of the potential of the ING time-of-flight facility for resonance-capture γ -ray studies we compute, for different experimental conditions, the flux at the end of the flight path, in the energy interval spanning a resonance, that would be required to give a minimum acceptable γ -ray counting rate and deduce the range of neutron energies over which this flux or greater would be available. We assume a nucleus with mass number $A = 100$ and, for simplicity, that neutrons are captured in an energy interval at the resonance equal to twice the Doppler width. This interval, 2Δ , will be too large for some narrow resonances and too small for others, but is probably reasonable for comparisons; at 1 keV it is about 2 eV. We assume the target has an area of $A \text{ cm}^2$ and is of such thickness that absorption is black over the interval 2Δ . The flux F (see Chapter VII, Section B) to give a γ -ray count rate C in a detector of efficiency ϵ and solid angle Ω for a transition of absolute intensity p is then:

$$F = C[2A\Omega\epsilon p]^{-1}$$

³ G.A. Bartholomew, Ann. Rev. Nuclear Sci. 11, 259 (1961).

⁴ For a recent example covering many resonances see V.O. Huynh, et al., Proc. Intl. Conf. Study of Nuclear Structure with Neutrons (Antwerp, 1965) North Holland, to be published.

In Table V.A.2 we calculate F for a number of detector arrangements with the assumption that the minimum acceptable count rate, C is $4 \times 10^{-3} \text{ s}^{-1}$ (or about 10^4 counts per month). In the last column we reproduce from Fig. VII.50, Chapter VII.B the upper limit of neutron energy, E_{max} , at which fluxes greater than F would be available. Thus, for γ -ray transitions with intensity of 5% it should be possible to make NaI measurements to ~ 10 keV and Ge(Li) measurements to ~ 2 keV. For coincidence measurements between NaI and a Ge(Li) array, it should be possible to measure a cascade of 5% intensity to about 300 eV.

TABLE V.A.2

ENERGY LIMITS FOR
REPRESENTATIVE RESONANCE (n, γ) EXPERIMENTS

Detector	A cm ²	Ω	ϵ %	p %	F cm ⁻² s ⁻¹	E_{max} keV
Single NaI	100	0.2	20	5	10^{-2}	10
Ge(Li) array	100	0.2	2	5	10^{-1}	2
NaI, Ge(Li) array, in coincidence	100	0.04*	0.4*	5	2.5	0.3

* product for two detectors

2.3 Spin Measurements with Polarized Neutrons

As suggested in Section VII.B, beams of polarized neutrons can be produced with good intensities over a wide range of energies in the resonance region. These neutrons could be used to extend the range of resonance spin determinations after the method pioneered by Sailor and co-workers⁵ and by Stolovy⁶.

⁵ H. Marshak, et al., Phys. Rev. 128, 1287 (1962).

⁶ A. Stolovy, Phys. Rev. 118, 211 (1960); 134, B68 (1964).

2.4 Fission Experiments

Understanding fission widths (that is the relative probability of fission) is difficult at present because we do not know the spins of the capturing levels. To date these have been determined unambiguously only for a few levels in the compound nucleus ^{240}Pu . Measuring level spins by the method mentioned in the previous section would greatly aid the interpretation of fission data and increase our understanding of the process. Systematic searches could be made for the variation with spin of properties such as widths, symmetric yields, neutron emission, α emission and γ emission.

Measuring the angular distribution of the fragments from aligned nuclei can determine the K-band structure of the transition nucleus⁷. It can also determine the spin, but the angular distribution is not very sensitive to this, and a separate determination is desirable. Thus resonance capture can be used to pick out transition states with specific spins, $I_0 \pm \frac{1}{2}$ and to give information similar to that discussed in subsection 1.4.2 f. Although the gap in even-even transition-state nuclei is about 2.5 MeV, the ability to scan the band structure over a 1-MeV interval with good precision would be very useful.

If we know the sub-threshold fission cross-section we can determine the relative contributions of p-wave and s-wave fission (see for example de Vroey, et al.⁸). On even-even targets this determines the parity of the lowest transition state and in general may give the separation of the odd and even parity transition states.

Attempts have been made⁹ to measure partial fission cross-sections, that is the cross-section for specified fragment mass on total kinetic energy. The intensities are so low that admittedly crude techniques must be used. With higher intensities less ambiguous interpretations can be made.

⁷ J.W.T. Dabbs, et al., Effects of Orbital Angular Momentum and Target Spin on Fission Anisotropy, paper SM-60/7 presented at IAEA Symp. Physics and Chemistry of Fission (Salzburg) 1, 39 (1965).

⁸ M. DeVroey, et al., The Fission Cross-Section of ^{240}Pu for 0.03-2.0 MeV Neutrons, Ibid, 1, 281 (1965).

⁹ M.S. Moore and L.G. Miller, Channel Effects in the Kinetic Energy of Fragments of Fission Induced by Low-Energy Resonance Neutrons, Ibid, 1, 87 (1965).

2.5 Nuclear Data for Reactor Development

A pulsed neutron source for time-of-flight measurements of cross-sections could provide better data for nuclear reactor design. It is very difficult to forecast which of the many data involved will still be insufficiently well known at the date ING becomes operational. The field of interest includes absorption (or total) and radiative capture cross-sections for atoms of fuel, structural and other materials present in reactors, as well as the average yield of neutrons from each fission event. These quantities vary with neutron energy and, in the resonance region especially, high-resolution measurements are required. A time-of-flight facility with an intense, short-pulse, neutron source would be very useful for such measurements.

Recent trends in the needs of such measurements are illustrated by a series of EANDC compilations¹⁰ of the data requested in North America and Western Europe. While the data of primary importance for designing reactors such as CANDU are now known reasonably well, higher accuracy being desired only for a few of these data, it appears that the sophistication of methods used for designing advanced reactor types (such as high-temperature or fast reactors) is still increasing, so that additional data are likely to be called for, much of it in the resonance region. The measurement program will probably remain unable, for some considerable time, to provide all the data requested. The high intensity of ING renders it capable of measuring these quantities up to quite high energies (100 keV, 1 MeV, or even higher), so its capabilities nearly complement those of Van de Graaff accelerators.

3. Future Extensions (Storage Ring)

The purpose of the storage ring (Chapter XIII) is to convert the essentially continuous beam of protons from the main accelerator into a pulsed beam. The protons are bunched together into pulses of pre-selected width and repetition rate, and then allowed to strike the liquid-metal target (Chapter VII). In this way, pulses of (a) thermal and epithermal neutrons and (b) resonance neutrons may be produced, in which the instantaneous neutron fluxes may far exceed those obtained by operating the machine continuously. The requirements for (a) and (b) are rather different, and are discussed separately below. Preliminary consideration of possible modes of operating the storage ring (Chapter XIII) indicates that the pulse repetition rate could not easily be varied and would be difficult to reduce

¹⁰ Compilation of EANDC Requests, EANDC-43 (1965); EANDC-55 (1966) and earlier reports of this series.

much below 500 Hz. It is found that this repetition rate and a dump time of $0.15 \mu\text{s}$ form acceptable compromises between the needs of the experiments and the design requirements of the ring.

- a) Since neutron thermalization times are of the order of a few microseconds (much longer than the dump time), experiments that use thermal or epithermal neutrons would be performed with the help of a mechanical chopper system that would be phased with respect to the storage ring pulses and would define the neutron burst width from the moderator to be, say, $5 \mu\text{s}$. At first sight, it appears that the effective instantaneous flux, can be 400 times that of a continuously operated system, but in practice the benefits would be rather less - particularly if the requirement is for low-energy thermal neutrons ($< 0.05 \text{ eV}$). This arises because the initial fast-neutron pulse is spread out during thermalization, and the bunching tends to be dissipated. But the pulse is still relatively sharp at epithermal energies ($> 0.1 \text{ eV}$), and experiments at these energies could benefit greatly from the storage ring.

To illustrate, let us consider some idealized examples assuming

- that the same time-average neutron source strength can be achieved both in continuous and in storage-ring-pulsed (SRP) operation,
- that the requirement is for $5\text{-}\mu\text{s}$ pulses at 500 Hz, of either thermal ($< 0.127 \text{ eV}$) or epithermal ($0.127 < E < 1.46 \text{ eV}$) neutrons,
- that in both modes of operation the neutron pulses are defined by a mechanical chopper.

In the SRP mode, the chopper is phased with respect to the storage ring to optimize the transmission of neutrons of the desired energy; more detailed consideration of this may be found in AECL 2059, p. 53-56, and the references cited therein. We define an enhancement factor (E.F.) as the ratio of the effective neutron flux during the $5\text{-}\mu\text{s}$ chopper pulse from any given moderator configuration to the neutron flux for optimum continuous operation. (The latter condition is obtained with a large ($> 120 \text{ cm}$) blanket of D_2O .) The calculations described in the above references show that, with appropriate moderator design, E.F. may be as high as 10^2 for epithermal neutrons, and 10 for thermal neutrons. These improvements could be utilized either to speed up the experiments or (more likely) to improve the experimental resolution.

Several experiments that would benefit from such a device have been previously mentioned in this section. Especial benefits would accrue to measurements of the dispersion

relations for high-energy excitations in solids (e.g. spin waves in iron-group metals), to the study of interactions between these excitations, and to the extension to larger momentum and energy transfers of partial differential cross-section measurements in both liquids and solids.

- b) As shown in Section VII.B the storage ring would provide about 10^3 times the flux of the resonance-neutron facility at a resolution equal to the Doppler width at $A = 100$ up to about 8 keV. At high neutron energies, limitations of the flight path length would make operation at very high resolutions impractical, but the storage ring would still give extremely high intensities at reduced resolution. This facility would be very useful for carrying out experiments in the keV region with relatively low counting efficiency - such as the γ - γ angular correlations, n - γ angular distributions, and various multiple-coincidence fission experiments.

4. Energetic Nucleons

The region of nuclear physics and particle physics made accessible by bombarding energies from 100 to 1000 MeV is now called intermediate-energy physics¹. This includes, roughly, the region between the threshold for pion (π -meson) production, and the threshold for K-meson and other strange-particle production. It is largely in this range of energies that the interests and techniques of nuclear and high-energy physicists overlap.

Much of our present knowledge of intermediate-energy physics was summarized at a recent conference². This knowledge is the product of work that has been in the nature of a general survey of the subject - highly successful, but passing over many details of the mechanisms by which the particles are created and interact³. For greater understanding more experimental precision is required. This calls for improved detection techniques, and also for increased intensity.

The fundamental interaction of interest in nuclear-structure physics - that which arises from the exchange of pions between nucleons - is one of the phenomena that could be profitably studied. The pions created in nucleon-nucleon collisions and the mu mesons into which they decay are themselves useful tools in the study of nuclear structure. These applications will be covered in Section V A 5.

¹ H. Bethe (Chairman) Report of an Ad Hoc Panel on Meson Factories to the Office of Science and Technology (March, 1964).

² The Williamsburg Conference on Intermediate Energy Physics, The College of William and Mary, Williamsburg, Virginia, February, 1966. (To be published).

³ E. Lomon, Phys. in Canada, 21 (6) 8 (1965).

Nucleons of intermediate energies are of value in nuclear-structure and nuclear-reaction physics, because the energy of the bombarding particle is large compared with the kinetic energies of the particles in the nucleus; this allows us to make simplifying assumptions about the mechanism of the interaction, and thus reduces the uncertainty in interpreting results. The phenomena to be observed, which include removing many particles from the nucleus and creating mesons, are qualitatively different from those at low energies. Furthermore, the short deBroglie wavelength of proton or neutron projectiles in this energy range allows the local structure of nuclei to be studied, providing in effect a 'snapshot' of the nucleus¹. Studies with intermediate-energy nucleons may give answers to questions such as: What clusters of nucleons exist in the nucleus? What is the probability of very high momentum? Is the interaction between two nucleons in the nucleus the same as between two free nucleons? Do nucleons interact in pairs or in threes and fours?

In the remainder of this section we discuss the types of experiments that would likely be done if ING existed today. For convenience they have been broken into two groups: subsection V.A 4.1 contains experiments relating to the nucleon-nucleon force, and V.A 4.2, experiments relating to nuclear structure. In subsection V.A 4.3 we discuss the relation between the experiments envisaged and the special properties of the ING beams.

4.1 The Nucleon-Nucleon Force

4.1.1 Nucleon-Nucleon Scattering

There is a need for more and better information on the cross-sections, polarization and triple-scattering coefficients for n-p, p-p, and n-n scattering. There are fairly complete data up to about 300 MeV for p-p and n-p scattering, and at 660 MeV for p-p scattering. Cross-section and angular-distribution data for both p-p and n-p scattering exist up to and beyond 1 GeV. (Highly accurate ($\pm 0.2\%$) total cross-sections exist up to 7 GeV⁴). But at the time of the monographs of Wilson⁵ and Moravcsik⁶, information on polarization and triple scattering at other energies - and on n-p and n-n scattering - was non-existent. These gaps are probably due mainly to experimental difficulties; the low-intensity beams hitherto available, especially of neutrons, and the difficulty of controlling and detecting neutron beams. It is likely that

⁴ R.F. George et al. Phys. Rev. Letters 15, 214 (1965).

⁵ R. Wilson, The Nucleon-Nucleon Interaction, Interscience Tracts on Physics and Astronomy. (John Wiley and Sons, 1962).

⁶ J. Moravcsik, The Two-Nucleon Interaction, Oxford Library of the Physical Sciences (Clarendon Press 1963.)

within the next few years further nucleon-nucleon programs will begin, for example at Los Alamos (LAMPF) up to 800 MeV, at CERN and the SREL centre near Williamsburg, Va., at 660 MeV, and at Zurich (ETH) and B.C. (TRIUMPH) at 500 MeV.

Below 300 MeV - the energy at which pion production starts to represent an appreciable fraction of the nucleon-nucleon cross section - extensive data are now available and these are consistent with the assumption that forces between neutrons are the same as those between protons (charge symmetry). The data have been intensively analysed by Breit⁷ and others. At single energies the data fit precisely, but attempts to fit over a large energy range with a smoothly varying set of phase shifts have not been wholly satisfactory⁸.

Above about 300 MeV, the complications caused by pion production demand that either the number of measurements, or their accuracy, be roughly doubled to give an equivalent theoretical understanding. Intense well-collimated beams of protons and neutrons are required, and polarized particles can be usefully exploited.

4.1.2 Single-Pion Production in Nucleon-Nucleon Collisions

The study of pion production is interesting in itself because it may improve our understanding of the interactions between pions and nucleons. Also, accurate information about these interactions is needed to help establish theoretical models of the nucleon-nucleon (N-N) scattering experiments mentioned in the previous section. Experiments with pion production are difficult because there are usually more than two outgoing particles. Since any particle detector has low overall efficiency, the detection of coincidences between two or more particles is infrequent - and the intense well-defined beams that would be available from ING become a valuable asset.

Near 400 MeV, pion production is governed by resonances whose character is well known, and the process is dominated by only a few reactions. Consequently the interpretation of the results is fairly satisfactory. Near 1000 MeV, many more meson-nucleon resonances, whose character is not so well established, contribute and consequently, the interpretation is less complete.

⁷ G. Breit, Nucleon-Nucleon Interaction and Nucleon Structure, proc. Intl. Conf. Nucleon Structure (Stanford University) 188 (1963).

⁸ G. Breit, Nucleon-Nucleon Scattering, proc. Williamsburg Conf. Intermediate Energy Physics, op.cit. ref. 2.

Possible one-pion-producing reactions from N-N interactions are as follows:

and

An experimental facility with beams of sufficient intensity to detect pairs of emerging nucleons, either proton or neutron, and both π^+ and π^- would give precision to studies of the symmetry relations between pairs of these reactions.

The production of mesons by n-n reactions - although it can be predicted by symmetry arguments from the results of the above experiments - may be worth studying to enhance confidence in the theory. These reactions can be approached by noting differences between the reactions below. By suitable choice of the momentum of the reaction particles, it is possible to select events in which one of the nucleon in the deuterium interacts with the incident nucleon while the other is only a "spectator".

and

These reactions appear sensitive to the states of the product nuclei as witness the predominant yield of $\pi^+ d$ in the $p + p$ reaction (Eqn. V.1) and so may also be useful in the study of the structure of the light nuclei, T and He^3 .

4.1.3 Reactions Producing Two Pions

The threshold for two-pion production is 587 MeV, and the 1000-MeV beam from ING will be energetic enough to initiate copious two-pion reactions. A partial list of these reactions follows:

A similar list could be made with the deuteron as a target for proton and neutron bombardment.

As the experimental data and theoretical interpretation of nucleon-nucleon scattering become more precise it may be anticipated that the one-pion-exchange model will no longer be adequate. Reliable information on higher modes of pion production will be needed. These higher modes will be governed by pion-nucleon resonances and pion-pion resonances, which also have intrinsic interest for the understanding of the properties of pions. The lowest-energy pion-pion resonance occurs at 765 MeV⁹, and so will be within the range of the 1000-MeV beam from ING.

Reactions in which two pions are emitted usually involve four emitted bodies. The need for high beam intensity and sophisticated detection facilities will be even greater than that for single-pion experiments discussed in the previous subsection.

4.1.4 Bremsstrahlung from p-p and n-p Scattering

Measurements of bremsstrahlung production by nucleons would help in deciding among a number of models for the nucleon-nucleon force, each of which fits the scattering data (subsection A 4.1.1) equally well. A theoretical treatment has existed for some time.^{10, 11} Because

⁹ A.H. Rosenfeld et al., Rev. Mod. Phys. 37, 633 (1965).

¹⁰ M.I. Sobel and A.H. Cromer, Phys. Rev. 132, 2698 (1963).

¹¹ J. Ashkin and R.E. Marshak, Phys. Rev. 76, 989 (1949); and Phys. Rev. 76, 58 (1949).

of the extremely small cross-sections, bremsstrahlung has only recently been observed in p-p scattering^{12, 13}, and has not yet been seen in n-p scattering. The p-p experiments were surprising in that the observed cross-sections at 45 MeV¹⁰ and 350 MeV¹¹ were smaller than predicted, by factors of 10 and 4, respectively. Up to the present no theoretical model has been found to explain the results¹⁴. It would be desirable to continue this work at the higher energies provided by ING. Experiments with n-p bremsstrahlung will be much more difficult.

4.2 Nuclear-Structure Experiments

At bombarding energies large compared with the energies of the nucleons within the nucleus, direct reactions become more important than the compound-nucleus reactions observed at lower energies. In direct reactions, strong angular correlations are usually observed and a comparatively simple theoretical description, often called the impulse approximation, can be employed. Several forms of direct interaction have been observed at energies up to about 200 MeV^{15, 16, 17}. Possible experiments of this type at ING beam energies of 400 and 1000 MeV are described in this section. Descriptions of several nuclear-structure experiments that do not come under this category of direct reaction, e.g. fission and fragmentation, are also included.

4.2.1 Optical Model

The optical model of the nucleus has had considerable success in describing the large amount of nuclear scattering data available below about 100 MeV¹⁸. In addition to its intrinsic interest, this

¹² R.E. Warner, Phys. Letters 18, 289 (1965).

¹³ B. Gottschalk et al, Phys. Letters 16, 294 (1965).

¹⁴ P. Signell, Some p-p Bremsstrahlung Calculations, proc. Williamsburg Conf. op. cit. ref. 2.

¹⁵ L.R.B. Elton, Direct Interactions in the 100-200 MeV Region, proc. IUPAP conf. on Direct Interactions and Nuclear Reaction Mechanisms (Padua, 1962), 1093 (1963).

¹⁶ D.H. Wilkinson, Some Structure Problems Chiefly in the Light Nuclei, proc. Intl. Conf. on Nuclear Structure (Kingston, Canada) 20 (1960).

¹⁷ A.B. Clegg, Reactions of High Energy Nucleons, Deuterons and Alpha Particles with Nuclei, proc. Intl. Conf. on High Energy Physics and Nuclear Structure (CERN, 1963); report CERN 63-28 (1963).

¹⁸ P.B. Jones, The Optical Model in Nuclear and Particle Physics, Interscience Tracts on Physics and Astronomy, J. Wiley and Sons, (1963).

model is of importance in describing the effects of the nucleus as a whole on incoming and emerging nucleons in many nuclear reactions - regardless of the reaction mechanism. The theoretical basis of the model has been less satisfactory, for example the potentials used have not been quantitatively related to nuclear matter calculations, and the surface effects are not adequately understood. Although much work has already been done near 50 MeV, the regions around the ING energies of 400 MeV and 1000 MeV have been only surveyed. Indeed, it is not clear whether the same phenomenological description is adequate for the entire energy range.

4.2.2 Direct-Interaction Inelastic Scattering

Inelastic-scattering reactions that can be studied with ING are $(p, p' \gamma)$ and $(n, n' \gamma)^{14}$. Direct-interaction inelastic scattering is characterized by a strong forward maximum in the angular distribution of the outgoing nucleon and usually by an energy loss small compared with the bombarding energy. It is of interest because it can be described in terms of the optical model for the incident and emerging nucleons, and usually simple properties of the target nucleus¹⁹. The reaction has been extensively studied at low energies^{15, 16, 17} and recently has been seen at 1000 MeV²⁰. Although no new nuclear properties are involved at high energies, as far as is known at present, the measurements are of value because it is near 1000 MeV that the mean free path for nucleons in nuclear matter reaches a maximum, so that the probability of multiple scattering within the nucleus is small. At this high energy, the impulse approximation should be valid. If the product γ -rays are observed the nuclear states involved can be unambiguously identified. The recently developed Ge(Li) gamma spectrometers²¹ will have a large role to play in these experiments. A versatile beam-handling system will be required with good spatial and energy definition ($\Delta E \lesssim 1$ MeV).

4.2.3 Quasi-elastic Scattering

When a high-energy incident nucleon ($E \geq 100$ MeV) is scattered with a large energy transfer to a single nucleon, the nuclear binding energy of the struck nucleon is assumed to be unimportant, except for its contribution to the initial momentum of the two-nucleon

¹⁹ W. Tobocman, Theory of Direct Nuclear Reactions, Oxford University Press, (1961).

²⁰ H. Palevsky et al, Amer. Phys. Soc. Bull. series 11, 11, 300 (1966), also
J. L. Friedes et al, Nuclear Structure Measurements with the Brookhaven Cosmotron, proc. Williamsburg Conf., op.cit. ref. 2.

²¹ G. T. Ewan and A. J. Tavendale, Can. J. Phys. 42, 2286 (1964).

system. The study of quasi-elastic scattering is one of the few ways of determining the momentum distribution of tightly bound nucleons^{22, 22a}.

The quasi-elastic reactions that could be studied with ING are (p, 2p), (p, pn), (n, 2n) and (n, np) at 400 and 1000 MeV. Much of the previous work has been done near 400 MeV, and work at 1000 MeV is in progress¹⁸. A beam-energy resolution of the order of 10 MeV is required.

4.2.4 Charge-Transfer Reactions

The spectra of emitted neutrons in the $Z^A(p, n)(Z+1)^A$ reactions at low energies have shown strong peaks^{15, 23, 24}, attributed to the isobaric analog states in the residual nucleus. Presumably the (n, p) reaction will show corresponding phenomena, and the two reactions should be studied together. The information gained can be used to estimate the size of the isotopic spin component of the optical potential^{15, 24a}, and through the vibrational levels in light nuclei, to augment our knowledge of the nucleon-nucleon force^{24b}. An energy resolution of 1 to 10 MeV will probably be sufficient.

4.2.5 Pick-up Reactions

As the name implies, in reactions of this type the incident particle is assumed to pick up a nucleon from the target nucleus, and the two emerge as a single entity²⁵. It is necessary for the momentum of the picked-up particle to be approximately equal, inside the

²² H. Tyrén, et al, Quasi-free Proton-proton Scattering in Light Nuclei at 450 MeV, loc.cit. ref. 15, 1109 (1963).

G. Tibell, et al, Quasi-free Proton-proton Scattering at 185 MeV, ibid, 1134 (1963).

J.C. Jacmart, et al, Inelastic Scattering of 156 MeV Protons on Light Nuclei, ibid, 1145 (1963).

^{22a} G. Jacob and Th. A.J. Maris, Rev. Mod. Phys. **38**, 121 (1966).

²³ A. Langsford, et al, Collective Excitations in (p, n) Interaction at 138 MeV, op.cit. ref. 15, 1150 (1963).

²⁴ C.J. Batty, et al., Phys. Letters **6**, 292 (1963).

^{24a} A.M. Lane, Nuclear Phys. **35**, 676 (1962).

^{24b} G.E. Brown, Vibrations and Single Particle Excitations in Nuclei, proc. Eastern Theoretical Physics Conf. (U. of Virginia, 1962) p.1 (1963).

²⁵ D. Bachelier, et al., Pick-up Reactions $^{12}\text{C}(p, d)^{11}\text{C}$ and $^9\text{Be}(p, d)^8\text{Be}$ at 155 MeV and the Structure of ^{12}C and ^9Be Nuclei, op.cit. ref. 15, 1141 (1963).

nucleus, to that of the bombarding particle. According to present theoretical models, the distribution of momentum inside the nucleus is such that only a few nucleons with momenta in the high-energy tail could participate in these reactions, and therefore the cross-section at an energy of, say 400 MeV will be small. The experiments may nevertheless be of value, because measuring this small component of the momentum distribution may provide a sensitive test of nuclear models. The beam geometry and energy definition required for such experiments should be about the same as for the experiments described in subsection V A 4.2.4.

4.2.6 Cluster Ejection

There is evidence that clusters of nucleons²⁶, forming for example, alpha particles He^3 or T^3 , have a transient existence within larger nuclei. The potential well that is experienced by such particles is not well known, but is probably such that the occurrence of high-momentum conditions is even more infrequent than for the single nucleons discussed above. Consequently, reactions in which an energetic particle knocks out a cluster are expected to have a small cross-section. Here again the measurement of such weak effects may be a sensitive test of nuclear models. It is expected that the change of cross-section with energy will be small, so that measurements at 400 and 1000 MeV will make significant contributions.

4.2.7 Multiple-Nucleon Emission

When a nucleus is struck by an energetic nucleon, the most probable consequence is the successive emission of several protons, neutrons, and to a lesser extent tritons, alphas and heavier particles, in an evaporation process²⁷. At energies of 400 to 1000 MeV, the average ratio of the change in charge, ΔZ , to the change in mass, ΔA , is about 1/4. Thus the spallation products tend to be slightly neutron-deficient. However, very large spreads in the ratio $\Delta Z/\Delta A$ occur (the reaction $^{209}\text{Bi}(p, 18n)^{192}\text{Po}$ has been reported^{27a}), and as a result, a few very neutron-deficient nuclei are produced.

²⁶ K. Wildermuth, et al, Cluster Structure and Direct Reaction Processes, loc.cit. ref. 15, 62 (1963) and
G.C. Phillips, Cluster Dissociation Studies, loc.cit. ref.15, 869 (1963).

²⁷ H.W. Bertini, Phys. Rev. 131, 1801 (1963); 138B., AB2 (1965);
I. Dostrovsky, et al, Phys. Rev. 111, 1659 (1958).

^{27a} P.A. Tove, Arkiv Fysik 13, 549 (1958).

The decay schemes of the nuclei formed by spallation can be studied (see subsection V.C. 1.1 below) and the cross-sections of their formation will be useful for developing theoretical models of level densities and similar statistical nuclear properties at high excitations.

4.2.8 Pion Emission from Nucleon Bombardment of Nuclei

The cross-section for pion production by two nucleons depends on their relative momentum. Since the production of pions by nucleon bombardment of a nucleus reflects the sum of the reactions between the incident nucleon and the individual nucleons of the nucleus - plus effects due to scattering of the particles within the nucleus - the observed cross-section and angular distribution can give information on the distribution of nucleons and their momenta within the nucleus²⁸. A model such as the π -nucleus optical model will be required for the interpretation of such experiments.

4.2.9 Fragmentation and Fission

At energies above about 500 MeV, a little-understood phenomenon known as fragmentation occurs. Fragments such as ${}^8\text{Li}$, ${}^{24}\text{Na}$ and ${}^{32}\text{P}$ are formed with cross-sections - nearly independent of energy above 1 GeV - of a few millibarns²⁹. The emission energy of these fragments is also nearly independent of target and bombarding energy being about 50 to 100 MeV in all cases²⁹. The phenomenon is thought to be fast and violent yet cannot be classified as a form of direct interaction. Fragmentation differs from fission in the speed of the reaction and in the mass, energy and angular distribution of the products. The study of the cascades and fragment emission leads to knowledge of the sub-structures, or clusters, found within the nucleus, and their average lifetimes. Up to the present, radio-chemical and other non-counter techniques have been used for this work thus limiting the studies to radioactive species. With the advent of a much larger beam intensity, multiple counter systems with greater energy and angular resolution can be used with consequent increase in precision.

²⁸ E. Lillethun, Phys. Rev. 125, 665 (1962).

²⁹ N.A. Perfilov, Fragmentation Induced by High Energy Particles, proc. Intl. Conf. on High Energy Physics, and Nuclear Structure (CERN 1963); report CERN 63-28 (1963);
R. Wolfgang, Phys. Rev. 103, 394 (1956),
R. Korteling and E.K. Hyde, Phys. Rev. 136, B425 (1964).

High-energy fission is a similar and related phenomenon. The results do not seem to show qualitatively new effects at high bombarding energy^{30, 31}. Although some features, such as the cross-section and the mass distribution have been determined, detailed measurements have not been made. Such measurements could assist in elucidating the mechanism of low-energy fission. Because of neutron multiplication, fission may also be of great interest in systems designed to use spallation reactions for the economic production of energy (see Sec. V.B).

Fission experiments usually involve more than one counter, and therefore will benefit from the high proton and neutron fluxes from ING. Energies of several hundred MeV, as well as large currents, will be needed for studies of the less-fissile nuclei, such as gold, where the cross-section for fission with 156-MeV protons is only 24 mb - compared with uranium's 1.37 barns at the same energy³².

4.2.10 Experiments with Neutrons in the <14 MeV Range

In subsection VII.D.2.1 it is shown that, near the peak (about 3-4 MeV) of the neutron evaporation spectrum that results from 1-GeV proton bombardment of a lead target, ING is likely to provide the most intense beams available from any accelerator, and that these will be one to two orders of magnitude higher than those currently available. The current studies of direct reactions and fission and those based on the cluster and optical models could be profitably extended. Some of the reactions that would be of interest are $(n, x \gamma)$, (n, p) , (n, α) , (n, d) , (n, T) and (n, He^3) . Many interesting fission experiments could be done in the range 0.1 to 5 MeV. These experiments are plagued with intensity problems at the present time, but measurements of the variation of the total kinetic energy, and of the angular distributions with neutron energy would make interesting comparisons with similar experiments now done using the (d, pf) reaction³³.

³⁰ E.K. Hyde, The Nuclear Properties of the Heavy Elements, Fission Phenomena, 3, Prentice-Hall, (1964).

³¹ G. Friedlander, Fission of Heavy Elements by High-Energy Protons, proc. IAEA Symp. on Physics and Chemistry of Fission (Salzburg), 2, 265 (1965).

³² L. Kowalski, Ann. Phys. (Paris) Series 13, 9, 211 (1964).

³³ H.J. Specht, et al, Phys. in Canada, 22, 61 (1966).

4.3 Properties of ING Beams of Importance to Intermediate Energy

4.3.1 Intensity

With present technology, most proton experiments cannot use the 1-mA beam, except in the case of very thin, refractory targets, or targets that can be moved at a high speed, as proposed for the meson targets exposed to beam No. 1 (section VII.C). However, the 1-mA beam can be used to compensate for the loss in intensity that results from the use of degraders for altering the beam energy (see Section 4.3.3) and of analysers for selecting beams of well-defined energy.

The intensity of high-resolution neutron beams is likely to be limited by heat dissipation in the liquid deuterium target. It would appear that, at present, $100\mu\text{A}$ is the maximum practical current³⁴ with a target that is 15-MeV thick. As target technology improves it may ultimately become possible to use even more than 1-mA for fast-neutron production in beam No. 2.

For experiments using the continuous neutron spectrum from proton bombardment of heavy nuclei, ING beam No. 2 is equal to the LAMPF facility. For part of this spectrum, 14 to 20 MeV, low-energy high-current accelerators using the T-D reaction for neutron production, would be superior to either ING or LAMPF³⁵. At lower neutron energies, ING again offers an advantage over the low-energy accelerator.

If solid or liquid (Pb) targets can be used with more than 1 mA, ING can make a unique contribution in experiments that employ a continuous neutron source spectrum in the range from 100 to 1000 MeV (cascade neutrons). The experiments depend on our being able to determine the energy of individual incident neutrons by time of flight from the neutron-producing target to the experimental target. This technique relies on having some time marker such as a prompt gamma ray or charged particle emitted by the experimental target for every neutron-induced event.

4.3.2 Homogeneity

Much of the current available for proton experiments may be used to improve energy resolution. Thus if the 1-mA ING beam has an energy spread of 8 MeV, about $12\mu\text{A}$ can be taken from it with 0.1-MeV energy spread. Although the experiments described above call for energy resolutions of from 1 to 10 MeV, it is quite conceivable that an order-of-magnitude improvement might at some time be required.

³⁴ A Proposal for a High-Flux Meson Facility at Los Alamos, Los Alamos Scientific Laboratories (1964).

³⁵ W.G. Cross, private communication, (May, 1966).

The energy resolution in neutron production is limited to ~ 17 MeV in the most favourable case, the $D(p, n)^2p$ reaction with thin targets and monoenergetic protons. Thick targets, which cause a further broadening of the neutron spectrum, will not be necessary to get adequate neutron yields if a large proton current is available.

4.3.3 Energy Variation

The principal SOC staging energies are 50, 400 and 1000 MeV. By degrading, it will be possible to reach 300 and 900 MeV, or with much reduced intensity, 200 and 800 MeV. These ranges are not wide enough to make ING a powerful tool for experiments in which reactions are studied as the proton energy is varied. Although energy variability would be desirable for N-N scattering experiments, for certain types of fast-nucleon experiments, (e.g. subsections 4.2.4, 4.2.6 and 4.2.10) this requirement is not necessary.

4.3.4 Polarization

Beams of polarized protons and neutrons are in principle available from ING, but with a much smaller intensity than the unpolarized beams. These beams are essential for measuring the spin dependence of nucleon-nucleon scattering outlined in part 1, above. For many experiments with a polarized beam there is a corresponding experiment, giving the same information, that uses an unpolarized beam and a polarized target. Although polarized targets suitable for use with low-intensity proton beams are now in use, polarization deteriorates rapidly under bombardment - so, with these targets, the stronger beams available from ING offer little or not advantage. As yet, polarized targets large enough for neutron bombardment are not in general use.

Similarly, polarized beams are essential for completeness in the study of elastic scattering from nuclei and of direct interactions.

Polarized beams might also be of value in studies of bremsstrahlung, pion production, pick-up, and charge-transfer reactions. The use of polarized beams in the other experiments suggested above does not at present seem to offer any advantage. It appears that a program of development of polarized beams should follow soon after the unpolarized beams become available.

For polarized beams, the energy range and resolution requirements are the same as for unpolarized beams. Probably, with ING, polarized beams can best be produced by scattering. The use of a polarized ion source for selected pulses (to be later deflected into beam No. 2) may be possible in principle, but it appears impracticable at

present. Polarized sources now give 10^{11} protons/second, and may in the near future have 100% polarization. Assuming that beam No. 2 takes 1% of the pulses, and that the buncher efficiency is 60%, some 0.6% of the initial beam, i.e. 6×10^8 protons/second will be available. This is close to the present performance of the proton linear accelerator at the Rutherford High Energy Laboratory. Recent developments in polarized ion sources show promise of increase of an order of magnitude in current. On the other hand, according to the LAMPF report³⁴, by scattering a 1-mA beam at 700 MeV one can achieve 1.5×10^{10} protons/second, 41% polarized in a solid angle of 5×10^{-5} steradians (0.23° half angle).

The availability of polarized neutrons is again limited by the heat dissipation in a liquid-deuterium target. The polarized neutrons are produced by the (p,n) reaction at a small angle ($\sim 20^\circ$). Other processes for polarized-neutron production do not look promising.

5. Pions and Muons

At present, the ING facility most likely to attract a participation by scientists outside AECL is the production of mesons (Chapter VII.C). Although several facilities of comparable capability, commonly referred to as 'meson factories' have been proposed^{1, 2, 3} active study continues only on LAMPF³ and on TRIUMF⁴, a 20 μ A, 500-MeV negative-ion cyclotron based on the UCLA design¹. Although the muon was discovered in 1936, the pion in 1947, and their properties such as mass, lifetime, and decay modes are known rather accurately, their potential use as probes has been little more than surveyed^{5, 6}. Yet pions and muons could be very useful tools not only in elementary-particle physics (the investigation of the basic interactions between particles), but also in nuclear physics (the investigation of the structure of complex nuclei or the interactions of nucleons in nuclei).

Pions and muons have many useful properties for nuclear-structure research. First they are complementary in that the pion interacts strongly with nucleons, the muon only weakly through the electromagnetic interaction. A pion of 200 MeV has about the same de Broglie wavelength ($\lambda \approx 0.4$ F) as a 300-MeV electron and can therefore be used, as high-energy electrons are used, to determine nuclear form factors, but with the difference that the pion "feels" the presence of the neutrons as well as the protons in the nucleus. In addition pions, unlike electrons, can be used to introduce a large and accurately known amount of energy (140 MeV plus kinetic energy) over a wide range of momenta (from 0 to about 800 MeV/c). Finally, the similarity between the negative muon and the electron means that mesic atoms can be formed, but the large mass of the muon results in a Bohr radius of only 2.5 F. The muon thus spends considerable time inside the nucleus and provides an excellent probe of the charge distribution in nuclei.

¹ Pion Facility, A High Energy Cyclotron for Negative Ions, (UCLA) TID 20822 (1964).

² A Final Report on the Design of a Very High-Intensity Proton Linear Accelerator as a Meson Factory at an Energy of 750 MeV (Yale) TID 21282 (1964)

³ A Proposal for a High Flux Meson Facility at Los Alamos, (Los Alamos Scientific Laboratory), (1964).

⁴ The TRIUMF Project (University of British Columbia, Simon Fraser University and University of Victoria) (January, 1966).

⁵ H. Bethe, et al., Report of an AD HOC Panel on Meson Factories to the Office of Science and Technology (March, 1964).

⁶ E. Lomon, Phys. in Canada 21, (6), 8 (1965).

For many years both nuclear structure and elementary-particle physics have been studied at synchrocyclotrons in the energy range from 100 to 700 MeV. The increased intensity available from ING makes it possible to:

- do more precise experiments,
- improve resolution,
- shorten experiment durations,
- investigate rare decay modes or rare targets.

In the following we list examples of experiments that could be done with ING, divided into categories according to the type of information they provide. The categories are:

- 1) properties of the elementary particles,
- 2) properties of the strong interaction,
- 3) properties of the electromagnetic interaction,
- 4) properties of the weak interaction,
- 5) properties of nuclei,
- 6) miscellaneous.

These experiments have been extracted mainly from previous proposals^{1, 2, 3}. It is expected that, as experience grows, category 5 will undergo the most vigorous development while interest in some of the other areas may decline as the questions they pose are answered.

5.1 Experiments with Pions

5.1.1 Properties of Elementary Particles

- 1) π^- mass by pionic X-rays.
- 2) π^0 mass by $\pi^0 - \pi^-$ mass difference using $\pi^- + p \rightarrow \pi^0 + n$.
- 3) $\pi^+ - \mu^+$ mass difference using $\pi^+ \rightarrow \mu^+ + \nu$.
- 4) ν_μ mass by radiative π decay ($\pi^+ \rightarrow \mu^+ + \nu_\mu + \gamma$).
- 5) Charge structure of the pion from radiative π decay.

5.1.2 Properties of the Strong Interaction

- 1) π - π interaction from π production in π -N inelastic scattering.
e.g. $\pi + N \rightarrow 2\pi + N$.

- 2) π -N interaction from π -N elastic scattering including charge exchange and including polarization measurements. Determination of phase shifts.
- 3) N-N interaction from stopped π^- capture in D.
 $(\pi^- + d \rightarrow 2n + \gamma)$
- 4) 3-body N-N forces from
 $\pi^+ + H^3 \rightarrow 3p + \pi^-$
 $\pi^- + He^3 \rightarrow 3n + \pi^+$

5.1.3 Properties of the Electromagnetic Interaction and Tests of Quantum Electrodynamics

- 1) Radiative π decay
 $\pi^+ \rightarrow \mu^+ + \nu_\mu + \gamma$
 $\pi^+ \rightarrow e^+ + \nu_e + \gamma$
- 2) Pionic X-rays

5.1.4 Properties of the Weak Interaction

- 1) Branching ratio $(\pi^+ \rightarrow e^+ + \nu_e) / (\pi^+ \rightarrow \mu^+ + \nu_\mu)$
 Test of universality of V-A theory for μ and e processes
- 2) Beta decay of pion $(\pi^+ \rightarrow \pi^0 + e^+ + \nu_e)$
 Tests of conserved Vector Current hypothesis.

5.1.5 Properties of Nuclei

- 1) π - nucleus elastic scattering. Determination of effective potentials.
- 2) π - nucleus quasi-elastic scattering. Study of shell-model states.
- 3) π - nucleus inelastic scattering. Production of nuclear states with large energy and small angular momentum. Production of new nuclides.
- 4) π - nucleus charge exchange scattering. Isotopic spin multiplets.
- 5) π^- capture by nuclei.
 140-MeV excitation - no momentum transfer. Study of N-N correlation and momentum distributions in the nucleus. Energies and widths of two-hole states.

- 6) π^- X-rays. Radial distribution of nucleons especially near the surface.
- 7) Pion production.

$$p + X(A, Z) \rightarrow p + \pi^\pm + X(A, Z \pm 1)$$

$$\pi + X(A, Z) \rightarrow \pi + \pi + X(A, Z \pm 1, \text{ or } Z \pm 2, \text{ or } Z \pm 3)$$

Gives information on π -N and N-N interactions off the energy shell. See also subsections V.A.4.1.2 and 4.1.3.

5.2 Experiments with Muons

5.2.1 Properties of Elementary Particles

- 1) μ^- mass by muonic X-rays.
- 2) μ^+ magnetic moment.
- 3) Direct measurement of anomalous magnetic moment.
- 4) Electric charge and electric dipole moment of μ .
- 5) Properties of μ (other than mass), that might distinguish it from an electron.

5.2.2 Properties of the Strong Interaction

- 1) μ^- capture by deuterium ($\mu^- + d \rightarrow 2n + \nu_\mu$) gives neutron-neutron scattering length.

5.2.3 Properties of the Electromagnetic Interaction and Tests of Quantum Electrodynamics

- 1) Direct measurement of the anomalous magnetic moment.
- 2) Radiative decay, $\mu^- + p \rightarrow n + \nu_\mu + \gamma$.
- 3) Energy levels of muonium.
- 4) Muonic X-rays. Vacuum polarization.
- 5) μ scattering by protons.

5.2.4 Properties of the Weak Interaction

- 1) μ^- capture in hydrogen ($\mu^- + p \rightarrow n + \nu_\mu$), universal Fermi interaction.
- 2) Muonium-antimuonium coupling. Test of whether the mu quantum number is additive or multiplicative.

3) Tests for neutral currents

$$\mu \rightarrow e + \gamma, \mu \rightarrow 3e, \mu + e \rightarrow 2\gamma,$$

$$\mu^+ + e^- \rightarrow \mu^- + e^+, \mu + Z \rightarrow e + Z$$

4) Tests for non-locality and intermediate boson; μ lifetime, momentum dependence of Michel parameter, momentum dependence of electron helicity in μ decay.5.2.5 Properties of Nuclei1) μ^- nucleus scattering. Electromagnetic form factors of nuclei.2) μ^- nucleus inelastic scattering. Coulomb excitation with μ^+ and μ^- .3) μ^- capture. Production of new nuclides.

4) Muonic X-rays.

Charge and magnetic-moment distribution Quadrupole moments.

5.2.6 Miscellaneous1) μ^- induced fusion, "molecules".

2) Atomic processes involving muonium.

3) μ probe in solid-state physics. Knight shift, μ depolarization.4) Atomic analysis using μ^+ 's.5) μ^- -induced fission.

6. Neutrinos

In this section we concern ourselves with neutrinos only as projectiles. Other experiments relating to such quantities as the neutrino mass have been listed in Section 5.1.1 and 5.1.4. ING produces neutrinos in two rather distinct energy regions:

- 1) very-low-energy (~ 1 MeV) electron neutrinos from the β^+ decay and K capture of spallation products in the main lead-bismuth target,
- 2) intermediate-energy neutrinos (~ 200 MeV) from the decay of π and μ mesons.

It seems likely that the second category will be of greatest interest and the remainder of this section will be devoted to a discussion of experiments involving them.

All four types of neutrinos are made through the reactions:

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Because the abundance of π^+ and μ^+ mesons is about five times that of π^- and μ^- , the π^+ and μ^+ beams will be the preferred source of neutrinos. The neutrino flux calculated for LAMPF¹ could also be obtained with ING (see Section VII.C), since comparable pion fluxes are available. The spectrum is about 100 MeV wide, peaks at 200 MeV, and gives a neutrino flux of $\sim 2 \times 10^5 \text{ cm}^{-2} \text{ MeV}^{-1} \text{ s}^{-1}$ at 50 ft from the pion decay point when a magnetic horn is used². These fluxes are two to three orders of magnitude greater than those available from the CERN-PS and the BNL-AGS¹. On the other hand, the cross-section of the $\nu_e + n \rightarrow p + e^-$ reaction is $1 \times 10^{-39} \text{ cm}^2$ at 200 MeV, increases to a maximum of about $8 \times 10^{-39} \text{ cm}^2$ at 1 GeV and then becomes asymptotic to $7.5 \times 10^{-39} \text{ cm}^2$ at higher energies. Thus ING would have a counting-rate advantage of one to two orders of magnitude over present high-energy accelerators.

¹ A Proposal for a High Flux Meson Facility at Los Alamos, (Los Alamos Scientific Laboratory) (1964).

² S. van der Meer and K.M. Vahlbruch, Neutrino Flux Calculations, The 1963 NPA Seminars: The Neutrino Experiment, CERN 63-37, 97 (1963).

Neutrinos interact with matter only through the weak interaction and thus they are useful principally for studying that interaction, although experiments in nuclear structure have been proposed¹. Their role in the weak interaction is however a critical one and the necessary experiments, though extremely difficult, are of great interest. The LAMPF proposal¹ lists 30 reactions that would be amenable to study; here we mention only three.

1) Difference between μ and e neutrinos. The experiment of Danby, et al.⁴ showed that under the assumption of a universal Fermi interaction, ν_μ could not be identical to ν_e . Recent experiments at CERN have shown that any mixing between the two particles is less than 1%⁵. It should be possible to lower this limit by an order of magnitude.

2) Is the muon quantum number additive or multiplicative? (see Section A.5.2.4). If it is multiplicative⁶ then the reaction

$$\mu^+ \rightarrow e^+ + \bar{\nu}_e + \nu_\mu$$

should occur in addition to the μ^+ decay listed at the beginning of this chapter. If the reaction occurs, it should be possible to detect the $\bar{\nu}_e$ in the reaction

$$\bar{\nu}_e + p \rightarrow e^+ + n,$$

for which the cross-section is given above.

3) Neutrino-electron scattering. This is perhaps the most important experiment in the theory of weak interactions. The vector-current theory of Feynmann and Gell-Mann⁷ predicts that the elastic scattering reaction

$$\nu_e + e^- \rightarrow \nu_e + e^-$$

should have a cross-section of $3 \times 10^{-42} \text{ cm}^2$ at 200 MeV⁸. On the other hand, the reaction

$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$

³ T. D. Lee and C. N. Yang, Phys. Rev. Letters 4, 307 (1960); N. Cabibbo and R. Gatto, Il Nuovo Cimento 15, 304 (1960).

⁴ G. Danby, et al., Phys. Rev. Letters 9, 36 (1962).

⁵ G. Bernardini, CERN Courier 5, (1), 9 (1965).

⁶ A Final Report on the Design of a Very High-Intensity Proton Linear Accelerator as a Meson Factory at an Energy of 750 MeV (Yale) TID-21282 (1964).

⁷ R. P. Feynmann and M. Gell-Mann, Phys. Rev. 109, 193 (1958).

⁸ T. D. Lee and A. Sirlin, Rev. Mod. Phys. 36, 666 (1964).

should occur only if the neutrino has an electromagnetic form factor and its cross-section should be reduced over that of the previous section by α , the fine-structure constant.

B. NUCLEAR POWER TECHNOLOGY

1. The Reactor Physics of Electrical Breeding

The Intense Neutron Generator has an important role to play in nuclear power generation; however the nature of this role will depend on the efficiencies achieved in the proton beam production and in the specific neutron production. It will also depend on - or, alternatively, will influence - the course of evolution of the expanding nuclear power complex. This potential application of high-energy high-current particle accelerators was early recognized by Lewis^{1, 2} and in the MTA project³.

The importance of ING in the nuclear power field arises from two of its properties. First, it produces a large number of free neutrons that are not "committed" to use in keeping a reactor critical and therefore may be used to convert fertile atoms to fissile. Second, the high-energy protons may be used directly to produce fission in fertile materials with a net gain of energy. Either of these properties, or possibly a combination of the two, may be exploitable for the production of cheaper nuclear power, and for the expansion of our nuclear energy reserves.

Consider first the production of fissile material from fertile. Known Canadian resources of uranium and thorium are roughly equal, though little intensive prospecting has been done for thorium. Of this only about 1/140 of the uranium (^{235}U) and none of the thorium may be fissioned immediately in a thermal-neutron reactor to produce power. However, adding one neutron each to the remaining uranium (^{238}U) atoms or to the thorium atoms will produce the new fissile isotopes ^{239}Pu and ^{233}U respectively, which may then be "burnt" in a thermal-neutron reactor. Thus if the necessary free neutrons were available, the energy that could be extracted from our nuclear fuel resources would be increased about 300-fold. Within a thermal-neutron reactor of the CANDU type, some excess neutrons are available, and these are used to produce ^{239}Pu , some of which is then burnt in situ and increases the energy yield but only by a factor of < 2 above what could be obtained by burning the natural ^{235}U completely. By recovering and re-using the Pu in discharged fuel, the energy extracted may be multiplied a few times further, but if the reactor operates so that fewer new fissile atoms are

¹ W.B. Lewis, Atomic Energy Objectives for Applied Nuclear Physics Research, report DR-23 (1952)

² W.B. Lewis, The Significance of the Yield of Neutrons from Heavy Nuclei Excited to High Energies, report AECL-968 (1960)

³ Status of the MTA Process, report LRL-102 (1954).

produced than destroyed, the limit of fuel exploitation by this scheme is soon reached. For example, in CANDU reactors with an average conversion factor of 0.8, the theoretical maximum energy that can be obtained by recycling is only five times that from the ^{235}U contained in natural uranium.

If enough extra neutrons are available in a power-reactor system, the conversion factor may be increased still further and under some circumstances actual "breeding" will occur - that is, more fissile material will be produced than destroyed. In principle this condition enables the total utilization of the reserves of fertile material to produce power; however, some limitations must be placed on this simple picture.

Breeding ratios high enough to cope with processing losses and with the requirements of an expanding power complex are possible only with fast breeder reactors operating on a Pu-U cycle, since only in the fast fission of Pu are sufficient excess neutrons produced to achieve the necessary breeding ratio (1.2 - 1.3). Fast reactors are being developed in a number of countries to exploit the possibility of complete burning of uranium reserves; however the economics of such reactors are still uncertain.

In contrast, ^{233}U , the fissile isotope produced by the neutron irradiation of natural thorium, cannot be efficiently burned in fast reactors - since the neutron yield per fission does not increase appreciably at the neutron energy that is characteristic of fast reactors. On the other hand at thermal and intermediate energies the neutron yield per neutron captured in ^{233}U is greater than for the other two commonly available fissile isotopes (^{235}U and ^{239}Pu). The ^{233}U -Th cycle is potentially the best for thermal-neutron reactors since, with careful attention to neutron economy in the reactor, the conversion ratio may be increased to the point that marginal breeding occurs. The rate of such breeding, if achievable, will most likely not be sufficient to offset reprocessing losses and increasing power demands; moreover the frequent reprocessing required to effect the necessary neutron economy may raise the power costs prohibitively. Thus it is probably preferable to operate such a reactor on a "near-breeding" or "advanced-converter" fuel cycle. This cycle requires "make-up" fissile material from an external source and it is here that ING could play a part as a ^{233}U producer.

The second nuclear power aspect of ING derives from the fact that the absorption of a high-energy proton in a fertile material such as thorium or ^{238}U will in most cases result in fission reactions with their attendant release of energy as well as with double the number of neutrons that would have been produced in a lead-bismuth target. Thus one has the possibility of producing useful quantities of nuclear power directly from the fission of fertile atoms at the same time as one is converting

large numbers of other fertile atoms into fissile reactor fuel.

Thus, having chosen to develop the natural-uranium heavy-water-moderated line of power reactors in Canada, and, in addition, being so fortunate as to have (in the Elliot Lake district) the major known North American resources of both thorium and uranium, the development of the nuclear power potentialities of ING forms a natural next extension of our power reactor studies.

The economics of such a system may be understood by reference to Fig. V.3 below.

FIG. V. 3 Components of a Power System Using ING.

$$E_{rf} \sim 0.8$$

$$E_b \sim 0.9$$

$$E_{ne} \sim 0.5$$

$$Y(\text{Pb, Bi}) 4$$

$$Y(\text{U, Th}) 11$$

$$Y_t(\text{non-mult.}) 1$$

$$Y_t(\text{mult.}) \geq 10$$

$$W 180$$

$$Y_r \sim 0.9$$

$$E_{th} 0.35$$

The left-hand enclosure in the figure indicates a device such as ING which is optimized to produce not a high flux of neutrons, but rather a high total number of neutrons. These are moderated and caught in fertile ^{232}Th in a "blanket" and produce fissile ^{233}U , which may then be extracted and fed into the "advanced-converter" power reactor shown in the right-hand enclosure. As shown, some fraction of this power will be required to drive the accelerator of the production facility, but with the parameters that one might expect to attain, it appears that such a system is energetically feasible. The pertinent efficiencies and yields are as follows:

- E_{rf} - efficiency of converting AC power to RF (Estimate for ING = ~ 0.8)
 E_b - efficiency of converting RF power to proton-beam power
 (Estimate for ING = ~ 0.9)
 E_{ne} - fraction of beam energy expended in nuclear interaction in target
 (Experimentally shown to be about 0.5 for 1 GeV protons).
 Y - yield of neutrons per 100 MeV of nuclear interaction in target.
 (Experimentally shown to be about 4 for Bi and 8 for a 4-in-diameter uranium target - which may be extrapolated to about 11 for a very large target).^{4, 5}
 Y_t - yield of fissile atoms per neutron into blanket.
 (Nearly 1 for a non-multiplying blanket, but may be increased one or more orders of magnitude with a near-critical blanket).
 W - fission power produced in reactor per fissile atom destroyed.
 (Approx. 180 MeV for ^{233}U).
 Y_r - new fissile atoms produced in reactor per fissile atom destroyed.
 (Approx. 0.9 for ^{233}U -Th CANDU-type reactor).
 E_{th} - net thermal-to-electrical conversion efficiency of station.
 (Current technology value ~ 0.35).

Now to produce one atom to feed to the reactor requires

$$\frac{100}{E_{rf} E_b E_{ne} Y Y_t} \text{ MeV}$$

and the electrical energy derived from the net loss of one fissile atom in the reactor is

$$\frac{W E_{th}}{1 - Y_r} \text{ MeV}$$

Therefore, the condition for a net gain from the cycle is

$$\frac{100}{E_{rf} E_b E_{ne} Y Y_t} < \frac{W E_{th}}{1 - Y_r}$$

Substituting the appropriate values for a depleted-uranium target and a non-multiplying blanket, the inequality becomes

$$\begin{aligned}
 \text{L.H.S.} &= \frac{100}{0.8 \times 0.9 \times 0.5 \times 11 \times 1}; & \text{R.H.S.} &= \frac{180 \times 0.35}{1 - 0.9} \\
 &= 25 \text{ MeV} & &= 630 \text{ MeV}
 \end{aligned}$$

⁴ J. Thibaudeau & E. Critoph - Private communication (1966)

⁵ J.S. Fraser & J.C.D. Milton - Private communication (1966)

Thus the cycle is energetically feasible, only 4% of the power being fed back to keep it in operation. Even this loss can be made up if the target heat can be efficiently used to produce power, since in a large uranium target about 90 MeV of heat ($\sim 70\%$ fission energy, 30% ionization energy) is released per neutron produced⁵. At a net conversion efficiency of 0.35 this would produce about 32 MeV, that is, enough to provide the 25 MeV required to operate the accelerator.

If the simple blanket is replaced by a sub-critical assembly, the yield of fissile atoms per neutron, Y_t , can be raised and the inequality further increased. If f_f is the fraction of neutrons captured in fissile material in the assembly with η neutrons produced per neutron thus absorbed, the sub-critical assembly will have a multiplication constant $k = \eta f_f$. Now it is easily shown that the net gain in fissile material per neutron into the assembly is

$$Y_t = \left(\frac{f_c - f_f}{1 - k} \right)$$

where f_c is the fraction of neutrons captured in fertile material.

For ^{233}U , $\eta = 2.3$ and it can easily be arranged that k is just below critical, say 0.99, so that $f_f = 0.43$. From reactor experience we know that we can make $(f_c + f_f) \approx 0.95$

Therefore $f_c = 0.52$ and

$$Y_t = \frac{0.52 - 0.43}{0.01} = 9$$

Thus the inequality becomes

L.H.S. = 2.8 MeV; R.H.S. = 630 MeV,
and if we consider the power in the target, we see that per fissile atom produced it has become $\frac{9.0}{9} = 10$ MeV thermal or $0.35 \times 10 = 3.5$ MeV electrical, again sufficient to operate our accelerator. We note, though, that an accelerator of the same size now produces nine times as much fissile material.

To produce these nine fissile atoms in the blanket there were $\frac{f_f}{1-k} = \frac{0.43}{1-0.99} = 43$ fissile atoms burned up, i. e. $\frac{43}{9} = 4.8$

per fissile atom produced. These released in the blanket $4.8 \times 200 = 960$ MeV thermal energy (which could be converted to $0.35 \times 960 = 336$ MeV electrical energy).

Thus the inequality becomes

$$\text{L.H.S.} = 2.8 \text{ MeV}$$

(electrical energy expended
per fissile atom produced)

$$\text{R.H.S.} = 3.5 + 630 + 336 = 970 \text{ MeV}$$

(electrical energy produced per
fissile atom extracted from blanket)

Only a negligible fraction of the output energy must be fed back to operate the accelerator and this may be supplied from the target power. However, we note that in this case about one-third of the total energy is produced in the blanket, and this must be attached to the accelerator. Further, to derive any appreciable gain from a blanket it must be operated close to critical, and thus must be about as complex and costly as a power reactor.

Whether a multiplying blanket is of value will depend largely on the overall economics of the whole nuclear power complex - cost of uranium and thorium, reprocessing costs, system expansion rate, etc. It should be noted that small changes in k and Y_r will produce large changes in the denominator terms $(1-k)$ and $(1-Y_r)$; thus the numbers presented should be considered more qualitative than quantitative.

It is interesting to speculate crudely about the economics of an accelerator-based breeding plant. It is plausible that a second-generation plant with a multiplying blanket and a 100-MW beam could be built for $\sim \$10^8$. However, about two-thirds of this cost is assignable to the conventional nuclear power portion of the station, and thus only $\sim \$3 \times 10^7$ is properly chargeable to the ^{233}U production facility. Assuming 20%/annum for depreciation, interest and operating charges, this gives $\$6 \times 10^6$ /year or $\sim \$2 \times 10^4$ /day. (As shown previously, the plant would be electrically self-sustaining, and fuelling charges are negligible - about 1 kg ^{238}U /day.)

The target would produce 3.4×10^{19} neutrons/second which, if captured without multiplication, would yield ~ 1.1 kg fissile material/day, i.e. at a cost of $\$20$ /g. The multiplying blanket would lower this cost by up to an order of magnitude, and it would then successfully compete with the current ^{235}U price of $\$12$ /g. Even without significant blanket multiplication, uranium ore costs need rise only by a factor of ~ 3 before the accelerator-based production of ^{233}U would become competitive. Such a price rise is foreseen (see reference ⁶ for example) when initial sources of high-grade ore are used up. Thus the economic feasibility of electro-nuclear breeding at some stage seems clear.

To generalize, the role of machines like ING in the field of nuclear power must be based on the following considerations.

⁶ W.B. Lewis, Long Term Conclusions from the Nuclear Fuel Inventory Problem, report DM-73 (1964)

- The accelerator is basically a device to produce fissile material from fertile, and thus may be considered only as a useful adjunct to a non-breeding power reactor complex. Some fission power is derivable from the fertile material in the target, but there is no appreciable net gain from this source.
- The accelerator requires some feed-back of power for its operation but this may be reduced to a negligible fraction of the output power potential by the use of a power-producing sub-critical assembly in place of a simple non-multiplying blanket.
- Non-breeder reactors - or the expansion of a complex of thermal breeders with marginal breeding ratios - will ultimately require some system to provide make-up fissile material if the nuclear power potential of the fertile material supply is to be efficiently exploited. In this situation the accelerator, which converts fertile material to fissile, might seem to be in competition with the diffusion plant which extracts the fissile component from natural uranium. However, under these circumstances, there is really 'no contest', because the diffusion plant makes no use of the fertile component, whereas - in principle - the accelerator permits it all to be usefully burned.

2. Areas of Research

Before the nuclear power aspects of electrical breeding can be realized, considerable fundamental and applied research must be done to determine accurately the values of the parameters discussed in the previous section. Some of this work will of necessity be carried out in the design of ING, but improvements will undoubtedly be possible and necessary if such a machine is to be optimized for the competitive field of power production.

Ways of improving E_{rf} , E_b , E_{th} and the shielding of very fast neutrons are already under study, but the reactor-physics-type parameters upon which the power cycle is much more sensitively dependent will most certainly have to be determined experimentally by using ING itself or a special facility attached to ING. Areas of research already apparent are listed below.

- Variation of neutron yield from heavy elements bombarded with high-energy charged particles as a function of
 - 1) target element
 - 2) target geometry
 - 3) target cooling mechanism
 - 4) particle energy
 - 5) special neutron multiplying techniques (e. g. $Be(n, 2n)$ reaction)

- Neutron moderation effects as a function of
 - 1) moderator material
 - 2) direction
 - 3) neutron energy
 - 4) target, structural and coolant material
- Blanket efficiency as a function of
 - 1) fertile material in blanket
 - 2) moderator
 - 3) lattice spacing
 - 4) direction from target
 - 5) average neutron energy in blanket
 - 6) initial fissile material in blanket (blanket multiplication)
 - 7) integrated irradiation of blanket
 - 8) blanket coolant mechanism
 - 9) non-fertile irradiation requirements.

Much of this work may be carried out in the nuclear power technology facility described in section VII. F of this report; in other cases the main target and proton beam will be of value. Ultimately the information gained in this research could be used to demonstrate the overall feasibility of the system by building and operating the power-breeder target outlined in section XIII. C.

3. Accelerator Development

The accelerator required for ING is almost identical with that of interest for nuclear power applications - a high-current high-efficiency particle accelerator of "intermediate" energy (about 1 GeV). In several respects, the objectives of the ING accelerator technology differ from those of high-energy particle physics where usually the highest energy is sought with little regard to efficiency. However, no incompatibility exists between these viewpoints and it is conceivable that new accelerating mechanisms sought by the high-energy physicists may offer the high intrinsic efficiency required for neutron-production applications. For example developments in super-conducting linear-accelerator cavities⁷ promise low-loss structures that will efficiently transfer RF energy to the beam. Similarly, the high-current techniques required for neutron production may be of interest to high-energy physicists.

Many of the accelerating devices recently proposed in the literature have involved high rates of acceleration - to achieve high energies in short distances and hence presumably more cheaply. Several of these involve intimately coupling electron streams (which supply the

⁷ H. A. Schwettman, et al., Measurements at High Field Strengths on Superconducting Accelerator Cavities, proc. 5th Intl. conf. High Energy Accelerators (Frascati, Italy, 1965).

power) with a proton beam in a common structure. Examples include Blewett's suggestion for exciting periodic waveguide structures⁸ by a bunched electron beam that interacts with a backward travelling wave, Lewis's "Staticelerator" which is similar but uses the forward wave and closer synchronism of the electron and proton bunches⁹, and Russell's Super-SOC in which the electron and proton beams are separated but interact with the same RF cavities¹⁰. These schemes in principle bypass or at least minimize RF-power requirements, an important economic consideration since the RF power supply is the dominant item in the cost of ING.

Veksler¹¹ pointed out some coherent interaction processes that could in principle accelerate protons. Coherent interactions in plasmas have been discussed by Fainberg¹² and more recently by Mills¹³, while some experimental work has been reported by Berezin et al¹⁴ and others.

Some schemes may be tested with small-scale laboratory experiments - for example, with electron analogue devices - but many cannot, and all will ultimately require proof tests with particles accelerated to an appreciable fraction of the velocity of light. Thus, while the exercise of designing and building the ING accelerator will be a major step in the technology, the facility itself will provide an important means of proof-testing new accelerating structures, since proton beams of various energies and intensities can be extracted from it. However no specific advanced-accelerator development has yet been proposed so no definite provisions have been made in the ING facility. Obviously, early prospects for test are superconducting structures, though for this purpose the alternative linear accelerator discussed in Chapter XIV would probably be more convenient.

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- ⁸ J. P. Blewett, A New Design for a Proton Linear Accelerator, report, BNL AADD-23 (Nov. 1963)
 - ⁹ W. B. Lewis, Travelling Wave Accelerators and the Staticelerator, report, FSD/ING-17, (1965) (also see section XV. B of this report).
 - ¹⁰ F. M. Russell The Super-SOC, A Valveless Accelerator, Electronic Components, 133 (Feb. 1966)
 - ¹¹ V. I. Veksler, Coherent Principle of Acceleration of Charged Particles, proc. CERN Symp. on High Energy Accelerators and Pion Physics, (Geneva) 1 80 (1956).
 - ¹² Y. B. Fainberg, The Use of Plasma Waveguides as Accelerating Structures in Linear Accelerators, proc. CERN Symp. on High Energy Accelerators and Pion Physics (Geneva) 1, 84 (1956)
 - ¹³ F. E. Mills, Coherent Acceleration of Protons, 5th Intl. Conf. High Energy Accelerators (Frascati, Italy, 1965)
 - ¹⁴ A. K. Berezin et al., Particle Acceleration in Plasma and Plasma Wave Guides by Means of Longitudinal Waves, Intl. Conf. High Energy Accelerators, (Dubna), 2, 1412 (1963)

C. CHEMISTRY AND MATERIALS RESEARCH

1. Chemistry Research

1.1 Nuclear Chemistry

ING's high-intensity neutron flux will permit us to develop new areas of research in nuclear chemistry and to revive old ones abandoned because of inadequate neutron source strength. The high-intensity high-energy proton beams will open areas of research previously unavailable to Canadian nuclear chemists. Typical of these researches are:

1.1.1 Decay-Scheme Studies

It will be possible to produce radioactive nuclides high on both sides of the valley of nuclear stability: neutron-deficient nuclides by proton-induced spallation and neutron-rich nuclides by multiple neutron capture. Rapid chemical and mass separations will be required to identify the nuclides produced. The results will include nuclear Q-values that will define the slope of the stability valley in areas yet unexplored. It will thus be possible to verify extrapolations of current mass formulae by direct experiment and the results will provide firm basis for further development of semi-empirical mass formulae. The data obtained will be pertinent to the understanding of nuclear structure, nucleo-genesis, nuclear reactions in stars and related topics where considerable success has already been achieved by this approach¹.

It is to be expected that solid-state detectors and advanced pulse-analysis techniques will give much precise information about the details of the radiations emitted during the decay of these nuclides far from stability. Since some of these will be in regions of the "Chart of the Nuclides" where proton or neutron shells are complete, our knowledge of closed-shell nuclei, and consequently nuclear structure, will be extended. Other nuclides may be in new "magic" or "doubly-magic" regions predicted² but as yet unobserved. Similarly, new nuclides in regions of strong nuclear distortion may be produced both in familiar mass regions and in regions where distorted nuclei are predicted to exist².

A method that has already been exploited with considerable success (³, for example) and that promises to give further useful information about nuclear structure is the observation of the α -particle fine structure resulting from the decay of nuclides in the neutron-deficient region near neutron number 82 in the rare earths.

¹ A.G.W. Cameron and R.M. Elkin, Can. J. Phys., 43, 1288 (1965).

² E. Marshalek, et al., Rev. Mod. Phys., 35, 108 (1963)

³ R.D. Macfarlane, Phys. Rev. 136, B941, (1964)

Studying the decay schemes of the heaviest nuclei will confirm and extend the shape of the nuclear stability valley in a region where "nuclear systematics" are important for predicting the nuclear properties needed in planning the production of new elements and in interpreting the results of experiments. New information about the half-lives for spontaneous fission is particularly useful because this mode of decay may determine the lifetimes of the heaviest nuclides. Recent evidence⁴ suggests that these may be longer than was thought possible four or five years ago. The prospects of producing further heavy elements are therefore brighter now, but further work is required to establish the trend.

The high neutron flux in ING will be extremely valuable for producing heavy elements and the chemical interest in this subject will be elaborate in section V.D.

Studying the decay schemes of nuclides in the fission-product region - but far removed from the stability line - will give information that is currently lacking and that will permit more accurate fission-yield measurements by radiometric methods. These results will be useful for extending our detailed interpretations of reactor behaviour. It is expected that these studies will more easily be done by permitting successive neutron captures in selected targets than by isolating from fission products, because the mixture of products will be less complex, in both their chemical and radioactive properties.

Spallation reactions induced by high-energy protons should produce nuclides that decay by proton emission. Nuclear decay of this type was observed a few years ago⁵ and has attracted widespread attention. This mode of nuclear decay has been discussed in some detail and a survey of possible proton emitters as well as nuclides decaying by two-particle emission has been presented⁶.

1.1.2 Fission and Spallation Reactions

Many topics of interest in the field of thermal-neutron fission remain in an unsatisfactory state of development owing to the difficulties of working with the low fluxes available. Irradiations of larger quantities or for longer times can sometimes compensate for low flux. However, the advantages of larger quantities are often offset by the extra time required for chemical processing and by self-shielding effects.

⁴ E.K. Hulet, et al., Phys. Rev. Letters 13, 343 (1964)

⁵ R. Barton, et al., Can. J. Phys. 41, 2007 (1963)

⁶ A.I. Baz', et al., Usp. Fiz. Nauk. 72, 211 (1960)

Similarly, the advantages of longer irradiations can, for short-lived products, be nullified by the saturation that is reached when the yield is balanced by the decay.

- Measurements in the valley of the mass-yield curve have indicated a symmetrical component in low-energy fission⁷; but the results are not clear-cut.
- Similarly the shape of the wings of the mass-yield curve is to some extent uncertain and, for example, it is not entirely clear whether the ^{66}Ni observed in ^{235}U fission⁸ is the result of a very asymmetric division of mass or whether it arises from the division of the nucleus into three large charged particles.
- There is evidence for tri-partition from experiments with counters⁹ and these have suggested that light radioactive species (mass number about 40) might be produced, but a radiochemical search has not been made.
- Measurements of the independent yields of fission products and the ratios of isomers produced in low-energy fission have given much information about nuclear charge and spin distribution in the fission reactions (⁷ and ¹⁰ and references cited therein), but the results are controversial at present.

The yield of significant fission products for investigations of these questions is usually very small and the high neutron flux that would be available in ING can be expected to give results unattainable at present.

Measurements of fission-product yields are important, both to help us understand the fission process and to help us calculate how the reactivity of nuclear fuel changes during irradiation. Since fissile samples exposed to a higher neutron flux develop higher concentrations of fission products, ING will permit us to extend the range of mass-spectrometric measurements and so cover fission products of low yield - i. e. ones that can now be determined only by less accurate radiometric methods.

⁷ A. C. Wahl, Mass and Charge Distribution in Low-Energy Fission, proc. IAEA Symp. Physics and Chemistry of Fission (Salzburg) 1, 317 (1965)

⁸ J. C. Roy, Can. J. Phys. 39, 315 (1961)

⁹ M. L. Muga, Ternary Fission, proc. IAEA Symp. Physics and Chemistry of Fission (Salzburg) 2, 409 (1965)

¹⁰ D. G. Sarantites, et al., Phys. Rev. 138, B353, (1965)

By spallation and neutron capture in ING it should be possible to produce sufficient quantities of fissile trans-plutonium isotopes to permit counter measurements of the mass-yield curves - both those from spontaneous fission and those from fission induced by thermal neutrons. This will bridge the gap that currently exists between mass 240 ($^{239}\text{Pu} + n$) and 252 (^{252}Cf , spontaneous fission).

Studies of fission induced by resonance and higher-energy neutrons will also benefit from the large flux of epithermal neutrons that will be available from the machine. In the past, at Phillips Petroleum Co., Idaho Falls¹¹, and at a number of other laboratories, the measurements of the valley yields from resonance-neutron fission have been handicapped by low activity and poor counting statistics. At Harwell interesting studies of the fission of ^{235}U were made by people using p-wave neutrons (about 125 keV)¹²; however, the flux of neutrons produced indirectly by a Van de Graaff accelerator was low and consequently the counting rate in the valley of the mass-yield curve scarcely exceeded the background rate, and only rudimentary results could be obtained. Nevertheless these results were significant and were contrary to theoretical expectations. Clearly this is an interesting topic that bears further study with the higher fluxes that will be available from ING.

Although studies with low-energy neutrons are most likely to lead to a thorough understanding of nuclear fission, investigations of fission induced by charged particles with energies of many hundreds of MeV have revealed many interesting features. At these energies other reactions, such as spallation and fragmentation, compete with fission and much remains to be learned. For example, in a recent review of high-energy fission¹³ Friedlander states "Further mapping of charge dispersion curves for the products of various high-energy fission processes is clearly desirable, particularly in mass regions not yet covered ($A > 140$) and other proton energies". Hyde¹⁴ also calls for more careful measurements in the mass region between "typical fission products" and heavier products in order to elucidate the true nature of fission competition. This involves rather rare products, but ING's intense beams of high-energy protons will improve the accuracy of both mass-spectrometric and radiometric measurements.

¹¹ R.B. Regier, et al., Phys. Rev. 119, 2017 (1960)

¹² J.G. Cuninghame, et al., Nuclear Phys. 27, 154 (1961)

¹³ G. Friedlander, Fission of Heavy Elements by High-Energy Protons, proc. IAEA symp. Physics and Chemistry of Fission (Salzburg) 2, 265 (1965)

¹⁴ E.K. Hyde, Fission Phenomena The Nuclear Properties of the Heavy Elements, (Prentice Hall Inc) 3, 470, (1964)

In connection with the dispersion of charge in high-energy fission, Friedlander points out (¹³, p. 272) that the high-energy interactions in uranium differ from those in lead. It would seem that a further understanding of the differences would be desirable if trans-lead targets are to be used in power-generating machines working on the ING principle, as well as for purely scientific reasons.

1.1.3 Spallation and Fragmentation

As pointed out in the preceding section these reactions compete with fission at high excitation energies. In bismuth the fragmentation process begins to play a significant role at about 500 MeV, and at about 1500 MeV fission and fragmentation make approximately equal contributions to the yields in the "fission-product region". Much remains to be learned about the fundamental nature of these reactions; the question of charge dispersion was mentioned in the previous section and the kinetic energy of the fragments is another subject that requires attention. A good deal of the current information has come from measurements of the radioactive species formed. Recently, however, mass-spectrometric techniques have been shown to be equally or even more powerful¹⁵ but these have been limited to high-yield elements. With higher proton currents it should be possible to extend the mass-spectrometric methods to elements formed in lower yield, and so to add significantly to our knowledge.

Quite apart from their fundamental value, these fission-product data are required in assessments of radiological health hazards and for the design of shielding at installations based on high-energy reactions. Current information is probably adequate for present needs but more will be required for further advances. Of particular importance are the yields in thick targets where reactions induced by secondaries often overshadow the effects of the incident nucleons. Some information on this subject is available (¹⁶, for example) but our present position rests mainly on approximate calculations.

Thick-target yields are also useful for interpreting observations of nuclear abundances in meteorites, tektites, and other extra-terrestrial matter. Already considerable information about the cosmic-ray exposure-ages of such materials, as well as about the spatial and time variation of cosmic rays has accrued. However, much more will be deduced as our knowledge of high-energy reactions improves.

¹⁵ G. Friedlander, Phys. Rev. 129, 1809 (1963)

¹⁶ C.B. Fulmer, et al., Nuclear Instr. and Methods 31, 45 (1964)

1.1.4 Thermal- and Resonance-Neutron Cross-Sections

The intense neutron flux in ING will facilitate measurements of the neutron-capture cross-sections of radioactive nuclides. Some of these are important in planning the commercial production of isotopes and others for the interpretation of reactor behaviour. For example, radio-activation measurements at Phillips Petroleum Co., Idaho Falls¹⁷ indicated that the thermal-neutron-capture cross-sections and resonance integrals for both isomeric states of ¹⁴⁸Pm are large and that ¹⁴⁸Pm should be considered in reactivity studies of long-irradiated fuel. In these experiments fission-product ¹⁴⁷Pm was irradiated in the highest flux available at the time (about 5×10^{14} n cm⁻²s⁻¹ in the MTR core) to produce ¹⁴⁸Pm and ¹⁴⁹Pm. However, the yield of ¹⁴⁹Pm was very small and did not permit accurate measurements of the cross-sections of the ¹⁴⁸Pm isomers; an increase in flux would likely improve this situation. Other workers (¹⁸ and ¹⁹) have attempted to get better accuracy at low fluxes by using mass-spectrometric techniques, but there are other difficulties that limit accuracy and the results are discordant at the moment.

Dr. W.H. Walker has pointed out²⁰ that there may be other high-cross-section fission-products that would be important for our understanding the reactivity changes that take place in reactors, and he has initiated experiments in the high-flux Savannah River reactor. The even higher flux that will be available in ING can be expected to open up further possibilities for cross-section measurements of this type.

1.2. Chemical Studies of the Heavy Elements

Although large quantities of trans-plutonium elements could be produced in ING for technological applications such as "point" neutron or heat sources - and these would raise important chemical problems in processing, purification and analysis - only the scientific prospects will be emphasized here. From the scientific point of view the chief interest is in the chemical properties of elements heavier than lawrencium (Z = 103). According to contemporary views lawrencium should mark the completion of the 5f electron shell and terminate the actinide series of rare-earth-like elements. Accordingly, element 104 should have

¹⁷ R.P. Schuman and J.R. Berreth, Nuclear Sci. and Eng. 12, 519 (1962)

¹⁸ R.H. Tomlinson, (Department of Chemistry, McMaster University, Hamilton, Ontario.) private communication (1965)

¹⁹ N.C. Fenner, (Atomic Weapons Research Establishment, Aldermaston, England.) private communication (1965)

²⁰ W.H. Walker, private communications, (1965)

chemical properties similar to the Group IV B elements, Ti, Zr and Hf. There have been preliminary reports about the preparation of element 104²¹ but no chemical properties have been reported.*

Of necessity, the first chemical experiments with element 104 will be on a tracer scale and would be designed to show that element was a chemical analog of Hf. Of course, the chemical properties of elements even heavier than 104 will be of interest and will be studied in similar ways.

Fermium ($Z = 100$) is probably the heaviest element that can be produced in observable quantities by neutron irradiation in present-day reactors. The trans-fermium elements have been produced by charged-particle irradiations. With the superior flux that would be available in ING it may be possible to produce trans-fermium elements by neutron irradiation. However, at the moment, a more probable route involves the use of long-lived nuclides such as 480-d ²⁵⁴Es and 80-d ²⁵⁷Fm, produced in ING, as targets for charged-particle irradiation in a suitable accelerator. As mentioned earlier, observations of chemical properties on a tracer scale are of most interest, and the target would be designed to permit observations of fast chemical reactions in flowing systems or to involve high-temperature diffusion. Mass and charge identification would rest on the nuclear systematics of the region, already mentioned in sub-section V. C. 1. 1, and the properties of radioactive progeny.

Because the heavy elements are members of one of two chemically similar families in which inner electron shells become successively more complete as the atomic number increases, a quantitative comparison of their physico-chemical properties using macro-amounts gives much valuable information not obtainable from tracer studies. Comparisons among the elements heavier than plutonium have been hampered by the small amounts available for research, and have been impossible beyond californium. With higher fluxes the quantities available will increase, and the very highest fluxes, such as those in ING, will be reserved for the preparation of milligram amounts of the heaviest elements. Typical research topics likely to give rewarding chemical information are oxidation-reduction potentials, optical absorption spectra and magnetic properties of compounds in solution as well as crystal structures of simple dry compounds.

²¹ G.N. Flerov, et al., *Atomnaya Energiya* 17, 310 (1964) Sov. J. Atomic Energy (a translation in English) 17, 1046 (1964)

* Preliminary chemical experiments are reported in JINR-D-2710 by I. Zvára, et al., Chemical Properties of Element 104 (This report was received after this section was written and seems to bear out the expected similarity to Hf.)

1.3 Activation Analysis

In activation analysis current practice is, wherever possible, to measure a short-lived activation product; thus the limit of detection for a particular element depends directly on the neutron flux, and one can expect increased sensitivity for many elements when ING is available. The importance of trace impurities is now widely appreciated in subjects as diverse as nutrition and the properties of semi-conductors. Studies of the accumulation of extra-terrestrial dust on the polar ice cap²² and in deep-sea sediments, as well as trace-element fractionation in meteorites²³ are typical of the applications of activation analysis. The determination of impurities in the order of one part in 10^9 , equivalent to one grain of salt in a freight train load of sugar, is not uncommon with neutron fluxes currently available. While one cannot state the particular applications to which the high flux of ING will be put, it is reasonable to expect that the increased sensitivity will give valuable information in all fields of science and engineering.

1.4 Radiation Chemistry

The high-intensity sources of protons, neutrons and fission fragments provided by ING will extend our studies of linear energy transfer, dose and dose rate. However, the meson facilities of the machine promise to be even more rewarding for radiation-chemistry research. Negative pions penetrate matter with very little interaction unless captured by nuclei. After capture, the pion may interact with the nucleus or decay to a μ^- meson and then decay with the emission of about 15 charged particles. Thus, this results in momentary "irradiation sources" capable of producing relatively high-energy densities centered about the capturing site. This combination of low intensity of ionization along the entrance path combined with strong ionization in the "star" at the end makes negative-pion beams especially useful for radiation-chemistry and biology research. Already pion irradiation has been used to investigate the "spherical hot spot" theory for the initiation of explosives²⁴, and more experiments will be done when intense meson beams are more readily available.

²² J. Brocas and E. Picciotto, Estimation of the Accumulation Rate of Extraterrestrial Matter by the Nickel Content in Antarctic Ice, proc. 20th Intl. Congress of Pure and Applied Chemistry (Moscow) Abstract c-10 (1965).

²³ H. Akaiwa and E. Anders, Trace Element Fractionations in Meteorites, proc. 20th Intl. Congress of Pure and Applied Chemistry (Moscow) Abstract c-25 (1965)

²⁴ J. Cerny and J. V. R. Kaufman, J. Chem. Phys. 40, 1736 (1964)

2. Materials Research

The interests in ING for materials research can be divided into three categories as follows:

- 1) Basic science
- 2) Irradiations of interest to current power reactors
- 3) Studies related to ING materials themselves

In each category some experiments may be envisaged using fast neutrons and others using thermal neutrons at flux levels of about 10^{16} n cm⁻² s⁻¹.

2.1 Basic Science

2.1.1 Radiation Damage

The collisions between fast neutrons and atoms in solids result in the ejection of some atoms from their normal lattice positions and their subsequent passage through the crystal. These primary knock-on atoms can in turn eject secondaries, tertiaries etc., producing vacant lattice sites and interstitial atoms. As the energies of these atoms decrease the mean free path between collisions decreases to the point at which it approaches the interatomic spacing. This latter condition results in the production of energy spikes, the size, nature, and number of which can markedly influence the properties of the materials. All of these defects are non-equilibrium ones and tend to be annihilated either by recombination of vacancies and interstitials, by migration to sinks, such as surfaces, grain boundaries or dislocations, or by clustering. A saturation concentration of damage will be established when the rates of production and annihilation are equal. The production of damage is a function of the fast-neutron flux and the scattering cross-section of the material, while its annihilation is a function of temperature and the specific properties of the material. The high fluxes available in ING will permit the establishment of saturation effects in a few days rather than the years now required. The investigation of the nature and distribution of the damage should also prove to be a rewarding study.

2.1.2 Damage by High-Energy Particles

The radiation damage produced in a solid crystalline lattice by a high-energy particle such as a fission fragment is very intense since an energy of nearly 10^8 eV is liberated along a track some 10 μ m in length. This energy is enough to raise to 4000°C a cylinder that is 10^4 atoms long and 100 atoms diameter. The resulting zones of damage contain 10^4 to 10^5 displaced atoms and have been observed in thin films examined in the electron microscope. As the number of zones increases unusual structural changes and growth effects occur, and these effects cannot be produced by bombardment with fission neutrons.

Since ING will generate appreciable fluxes of protons and neutrons with energies of several hundred MeV, it could be used to produce primary knock-on atoms in non-fissile materials that are comparable in effect to fission fragments especially near the end of their range. Thus the exciting possibility arises of producing exceedingly intense radiation damage without introducing foreign atoms such as uranium and fission products to the lattice.

2.1.3 Thermal-Neutron Scattering

The damaged regions and defect clusters in irradiated materials can markedly influence the mechanical properties. The size of such regions can be deduced from low-angle scattering of intense beams of thermal neutrons, and this technique would supplement electron microscopy.

2.1.4 Radiation-Enhanced Diffusion

Solid-state diffusion is the continual migration of constituent atoms which jump from one lattice site to another through the crystal. The rate of atom jumps is directly proportional to the concentration and mobility of point defects. Fast-neutron irradiation increases both the concentration of vacancies and the production of interstitials, and it therefore enhances the average diffusion rate of all the atoms. For the fluxes available in reactors, however, the enhancement is sometimes extremely small and difficult to detect. The very high fluxes proposed for ING should increase the defect concentration to the point at which the enhancement becomes more readily observable. The major interest lies in determining the magnitude of the effect on the stability of alloys or ceramics in high radiation fields.

2.1.5 Gases in Metals

The build-up of hydrogen and helium in metals probably always has a deleterious effect on mechanical properties. With reactor fluxes of $\sim 10^{13} \text{ n cm}^{-2} \text{ s}^{-1}$, significant quantities of helium are produced only in beryllium, lithium and boron. However, at fast-neutron fluxes of $10^{15} - 10^{16} \text{ n cm}^{-2} \text{ s}^{-1}$, the (n, p) and (n, α) reactions can produce appreciable quantities of hydrogen and helium in many other metals. ING's neutron flux would permit studies of gas build-up not possible in the current experimental facilities at CRNL.

In the study of nucleation, growth and migration of gas bubbles in solids, one technique is to introduce quantities of boron or lithium and then irradiate the material with thermal neutrons. By using the highest neutron flux available - consistent with maintaining the sample at some desired low temperature - the interaction between the sample and its environment is minimized, and there is the added convenience

of a short irradiation period. Also, it is normally advantageous to have a high ratio of thermal to fast flux in such experiments. For these experiments, therefore, ING would provide an excellent facility.

2.2 Power-Reactor Materials

2.2.1 Irradiation of Crystal-Bar Zirconium for Later Thin-Film Electron Microscopy of Defect Aggregates

The form of the radiation damage produced by a high dose of fast neutrons depends on the interactions between the defects formed during the irradiation. The proposed experiment would use an extremely high neutron flux to determine if the interactions result in a final steady-state defect configuration and to investigate the effect of irradiation temperature on this final configuration. This information, obtained by direct observation in the electron microscope, could then be used to interpret and predict the changes in the mechanical properties of zirconium that are produced by very high doses of fast neutrons.

2.2.2 Anisotropic Growth of Zirconium Single Crystals

The anisotropic growth of zirconium during fast-neutron irradiation could be contributing to the enhanced creep rate that is measured during such irradiations. Testing this hypothesis depends on an accurate measurement of the zirconium growth parameters and these could be obtained more accurately with the high integrated fluxes attainable in ING.

2.2.3 Saturation of Radiation Damage in Zirconium Alloys

Power reactors are now being designed to employ zirconium alloys for critical components and operation is at temperatures at which these alloys are strengthened by neutron irradiation. Strength, however, is of secondary importance to ductility (or toughness) when the possibility of catastrophic failure is considered, and there is now considerable evidence that the deleterious effects of irradiation may effectively be saturated at integrated fluxes in the range $10^{20} - 10^{21} \text{ n cm}^{-2}$. The possibility exists, however, that the apparent saturation is only a plateau in the property/flux curve. Thus, experimental evidence at integrated fluxes of $\geq 10^{22} \text{ n cm}^{-2}$ is urgently required by reactor designers.

In reactor operation, hydrogen pick-up can reduce ductility more than irradiation does. It is desirable, therefore, to hold hydrogen uptake to a minimum by keeping the irradiation period as short as possible. ING promises to permit irradiation to high integrated fluxes with a minimum hydrogen pickup and thus should lead to improved accuracy in the estimation of in-reactor component life.

2.2.4 Structural Changes in Heat-Treated Zirconium-Niobium Alloys

Either irradiation may decrease the number of fine precipitates in heat-treated Zr - $2\frac{1}{2}$ Nb by dissolving them in "energy spikes", or it may increase the number by adding nucleation sites and enhancing the diffusion rate. In some cases, such as enhanced diffusion, the change depends on the defect concentration introduced during irradiation, and hence on the instantaneous fast-neutron flux if the defects are mobile at the irradiation temperature. The high fluxes attainable in ING would increase the sensitivity of this type of measurement and allow predictions for practical longer-term cases at lower fluxes.

2.2.5 Effect of Dose Rate on Mechanical Properties of Zirconium Alloys

The effects of neutron irradiation on the tensile properties of zirconium alloys are now fairly well established for integrated fluxes up to 10^{21} n cm⁻² and for instantaneous fluxes up to $\sim 10^{14}$ n cm⁻² s⁻¹. In the next few years various zirconium alloys will be evaluated at these fluxes from the fracture mechanics point of view. Irradiation effects are normally expressed in terms of integrated flux, and thus far there is no evidence that instantaneous flux is a significant variable. But then no tests have been conducted at fluxes $> 10^{15}$ n cm⁻² s⁻¹, and ING would allow these to begin.

2.2.6 Effect of High Dose Rates on the Deformation of Zirconium Alloys

Most mechanisms of enhanced creep during irradiation indicate that creep rates are proportional to the instantaneous fast-neutron flux. A facility with higher flux than that now available would give greater sensitivity and reduce the long time required for preliminary tests.

2.2.7 Effect of Flux on the Corrosion Behaviour of Zirconium Alloys

It is hoped that the effect of fast-neutron flux on the oxidation of Zr alloys in water will be resolved by experiments in reactors now available since current evidence suggests that the effect saturates in the region of 10^{14} n cm⁻² s⁻¹ (> 1 MeV). If this problem is not resolved, however, then the higher fluxes available in ING could assist considerably.

2.3 ING Materials Studies

2.3.1 Life of Beryllium Flux Multiplier

At a fast flux of 10^{16} n cm⁻² s⁻¹ the rate of conversion of Be to He is initially $\sim 4\%$ /year. This amount of helium is equivalent to a gas content of 360 cm³ at NTP per cm³ metal. Apart from inducing

severe embrittlement, gas contents of this magnitude can be expected to cause high internal stress and possibly lead to severe swelling. There is no experimental information on the effects from gas quantities $> 30 \text{ cm}^3 \text{ cm}^{-3}$, and control experiments in ING would be required to help predict the performance and lifetime of the beryllium flux multiplier around the target.

2.3.2 Transmutation Reactions

The transmutation rates of possible ING structural materials will be appreciable. For example, in a thermal flux of $10^{16} \text{ n cm}^{-2} \text{ s}^{-1}$ aluminum is converted to silicon at about 7%/year. The consequent effect on the mechanical properties of Al-Si alloys would make an interesting study - since the transmuted atoms are deposited and may remain in a non-equilibrium configuration; i. e. solid solubility limits may be exceeded by a wide margin and metastable clusters of Si might form to produce changes in strength and ductility. Another reaction of practical interest is the conversion of zirconium to molybdenum, 0.4%/year.

2.3.3 Corrosion-Resistant Materials for ING

No test facility is available in which we can gain a lead time over ING in studying the combined effects of Pb/Bi and high neutron flux on candidate structural materials. To a major extent ING would therefore have to operate as its own test-bed, and post-mortem examinations of structural materials would represent a very important feature of the work.

D. ISOTOPE PRODUCTION

Only the production of isotopes for research purposes is considered here; commercial production is treated in Chapter XII. Also, isotope production in connection with heavy-element research has been discussed in Section V.C.1.

The use of radioactive sources and tracers in all fields of science and engineering is now so commonplace that it needs no comment here. ING will facilitate the further application of isotopes by making available

- isotopes of higher specific activity
- a greater variety of isotopes.

The following example of the benefits of higher specific activity is taken from research work at CRNL.

In studying the penetration of ions into single crystals, Dr. J.A. Davies¹ employed radioactive tracers. However the unwanted isotopes of the tracer - which were much more abundant - caused radiation damage to the crystal, or saturated it, before he could inject enough tracer to give good counting statistics. With increased specific activity the unwanted isotopes of the tracer element and the deleterious effects that accompany them would be reduced; higher counting rates and a better statistical accuracy could therefore be achieved.

Some isotopes needed for specific purposes, e.g. Mossbauer sources, as well as tracers for a number of elements cannot be formed by neutron irradiation. For many of these, proton irradiation gives a suitable product, and thus ING will give a variety of isotopes not available from fission reactors. For example, a few years ago a fluorine tracer was required in studies of the effect of fluoride ion on the corrosion of zirconium. The isotope formed by neutron capture, 11-s ^{20}F , was too short-lived for the purpose and a secondary reaction $^{16}\text{O}(\text{t}, \text{n})^{18}\text{F}$ had to be used to produce tracer amounts of 1.9-h ^{18}F . The tritons were obtained from the neutron irradiation of lithium. Proton-induced spallation of a number of light elements using ING could produce larger quantities of ^{18}F more directly. Other isotopes that could be produced by proton irradiation are 2.6-yr ^{22}Na , 4.5-d ^{47}Ca , 314-d ^{54}Mn , 267-d ^{57}Co (a typical Mossbauer source), 85-d ^{88}Zr and 20.8-d ^{230}U , to name a few.

¹ J.A. Davies, private communication (1964)

E. BIOLOGICAL AND MEDICAL APPLICATIONS

1. Bio-Medical Research

For biological and medical applications the usefulness of ING appears to arise almost entirely from the availability of mono-energetic beams of high-energy protons and negative pions. Such beams are valuable because they can deliver higher doses to sharply localized regions than to the surrounding tissue. The high localization is possible because of the (Bragg) peak in energy loss that occurs near the end of the particle range, because these particles are scattered less than are gamma rays, electrons or low-energy neutrons and finally, in the case of negative pions, because, following capture at the end of their range, the dose is delivered mainly by nuclear star products of short range, giving high linear energy transfer (LET) and high relative biological efficacy (RBE).

Probably of greatest interest in biomedical research is the highly selective irradiation of single organs or parts of organs with such sharply defined beams. This possibility opens up a wide field of functional studies in biochemistry, physiology and neurology, in experimental animals of any size. By combining a rotation or multiple-field technique with utilization of the high concentration of RBE dose at the end of the track, it should be possible to destroy specific regions in the brain or endocrine glands (for example) with relatively light damage to the surrounding regions. For volumes not more than a centimetre or so in depth, this appears to be feasible with high-energy protons, although a more concentrated dose distribution in the irradiated area would be possible with negative pions.

In a completely different field, the diffraction of slow neutrons has been suggested for studying the molecular structure of proteins. Because of the complexity of this structure, the neutron flux required is larger than any available at present. Preliminary estimates made at Oak Ridge suggest that a flux of the order of $5 \times 10^{16} \text{ cm}^{-2} \text{ s}^{-1}$ would be required. The flux from ING might be adequate for such studies.

2. Medical Therapy

The therapeutic use of beams of high-energy protons and alpha particles is expanding rapidly. Even when no advantage is taken of the Bragg peak, the relatively low scattering (compared with gamma rays or electrons), combined with rotation of the patient, permits concentration of dose within the volume of interest that is sufficient for certain purposes. An outstanding example is the suppression of hypophyseal function in cases of cancer, diabetic retinopathy and acromegaly².

² J.H. Lawrence, et al., J. Amer. Med. Ass. 186, 236 (1963).

The ablation of other small regions in the brain may offer advantages over the surgical methods now employed.

Radiation therapy of large and deep-seated tumors is both much more difficult and has more widespread importance. The essential problem is that of delivering sufficient dose to destroy virtually all malignant cells without seriously damaging the surrounding healthy tissue. The difficulty is increased by the deficiency of oxygen in tumors and the fact that cells in an anoxic environment are less sensitive to radiation than oxygenated cells. This relative sensitivity, expressed by the "oxygen enhancement ratio" (OER), can be partly overcome and the resultant dose to the surrounding tissue reduced by about 1.7 times^{3, 4, 5}, if radiation of high LET is used. Some success in reducing the OER has also been achieved with high-pressure oxygen.

Of all types of radiation available for treating deep-seated tumors, negative pions have the unique advantage of combining high LET with a favorable spatial distribution of dose. The striking potentialities of pions have been demonstrated by Fowler³. An example of the calculated distribution of dose with depth is shown in Fig. V. 4 for parallel beams of various types of radiation. All the results except those for neutrons are due to Fowler. For the charged particles, the energy distribution of each incident beam was chosen to give nearly uniform damage over the interval 10 to 15 cm. The numbers in brackets give very approximate values of the OER for the dose in this interval. These calculations indicate that, even apart from the reduced OER, the use of pions would permit doses to tumors many times higher than are used at present, without increasing the dose to surrounding tissue. If an improvement at all comparable to this could be achieved under practical conditions the potential rewards of pion therapy would be very great.

3. Radiation Dosimetry

Many dosimetric problems will arise in connection with biomedical research and therapy that use beams of protons or negative pions. The most obvious are concerned with the dose, RBE and LET distributions and oxygen effect in the region close to the end of such a beam. Unusually high spatial resolution of the dosimetry systems may be required. The results of such experiments should indicate whether or not the great advantages predicted for negative pions are likely to be achieved and whether the greater complications of using these particles are justified.

³ P. H. Fowler, Proc. Phys. Soc. 85, 1051 (1965).

⁴ D. K. Bewley, Radiology 86, 251 (1966).

⁵ J. F. Fowler, Neutrons in Radiotherapy: Slow Neutrons, Fast Neutrons and Other Heavy Particles, paper SM-44/55 presented at Symp. Biological Effects of Neutron and Proton Irradiations (Brookhaven National Laboratory, 1963) 2, 185 (1964).

FIG. V. 4 Relative Values of RBE Dose as a Function of Depth in Tissue for Parallel Beams of Various Incident Radiations (The energy distribution of the charged particle beams has been chosen to give a nearly uniform dose at depths of 10 to 15 cm. The numbers in brackets give the approximate OER for the dose in this interval.

From the point of view of protecting personnel, and in addition to programs that use its special facilities, the very existence of ING will require a research program in dosimetry and applied biophysics. The possibilities of stray fluxes of high-energy neutrons, protons and pions, many orders of magnitude greater than any now in existence, will greatly increase the importance of accurate dosimetry for these particles. There is considerable practical and theoretical work to be done. New instruments and systems of personal dosimetry will be needed. For some of these problems satisfactory solutions will be required before the machine operates, but the search for better and more accurate methods of dosimetry will continue for many years.

4. Beam Requirements

If a proton beam is used directly for either research or therapy, the beam current required is very much smaller than that available from ING. A beam of 10^{-3} μ A of 150-MeV protons, spread over 5 cm², could deliver a typical therapeutic dose (5-10 krem) near the end of its path in less than a minute. If the beam is to be stopped in tissue there is no obvious advantage in using protons of energy much above 200 MeV. However, if only a higher-energy beam (400 MeV) were available, it could be degraded to the required energy, analyzed magnetically and refocused, with a loss of intensity of perhaps a factor of 100. An incident beam of 1 μ A would therefore be more than adequate.

The proton beam current required for producing useful doses of negative pions is many orders of magnitude larger than that required to give the same dose directly. To realize the potentially high ratio of dose near the end of a pion's track to that near the rest of the track, the energy spread of the pion beam must be restricted by an amount that depends on the thickness of the region to be irradiated. For a region a few mm thick, as might be required in biological research, an energy resolution of ± 1 MeV would be desirable. For the therapy of deep-seated tumors, a total energy spread of between 6 and 10 MeV should be adequate. To obtain a uniform dose, it might be preferable to sweep a more nearly monoenergetic beam through a controlled energy range rather than to use a beam that was initially poorly analyzed.

With 70 -MeV negative pions, a dose rate of 100 rem/min over a target volume of 100 cm³ could be produced³ by a beam containing 10^8 particles/second and with an energy spread of 10 MeV. This dose rate would be adequate for therapy and for many types of biological research. A beam of such an intensity could be produced by 1 mA of 800-MeV protons on a 6-g/cm² target⁶; it could be available from

⁶ H. Bethe et al., Report of Ad Hoc Panel on Meson Factories (1964).

ING, but is well beyond the capabilities of present synchro-cyclotrons. However, some of the preliminary practical problems associated with the therapeutic use of pion beams can be investigated with existing accelerators.^{7, 8}

5. Special Facilities

It is expected that most of the facilities for producing, collimating and analyzing a proton or negative-pion beam could be used for both physics research and biomedical purposes. Biological and medical applications would require lower energies and perhaps more flexible energy variation than the majority of physics experiments, and it would be necessary to be able to adjust the analyzing system quickly and easily for these different requirements. One or two shielded rooms situated in the meson experimental area would be needed for the irradiation of patients and experimental animals. Since the beam entering these rooms will be only about 10^{-3} μ A of protons or 10^{-5} μ A of pions, the shielding would be required primarily to keep out radiation produced within the rooms. An adjacent small, shielded area would be needed for the protection of personnel supervising medical irradiations.

⁷ C. Richman, et al., Amer. J. Roent. Rad. Ther. Nuc. Med. 96, 777 (1966).

⁸ M.R. Raju, et al., Pion Studies with Silicon Detectors, report UCRL-16071, 1965.

CHAPTER VI

ACCELERATOR AND BEAM TRANSPORT

A.	REFERENCE DESIGN (P.R. Tunncliffe)	VI.1
B.	GENERAL DESCRIPTION (P.R. Tunncliffe, S.B. Hodge)	12
1.	The accelerator System	12
2.	General Layout	14
3.	Ion Source, Pre-Accelerator Linac Injector and Stage-1 SOC	14
4.	The Separated-Orbit Cyclotrons	19
5.	Beam Transport System	29
6.	Services	29
C.	ION SOURCE AND PREACCELERATOR (J.H. Ormrod)	31
D.	INJECTOR LINAC (B.G. Chidley)	35
E.	SOC STAGES	38
1.	Selection of Parameters (B.G. Chidley, G.E. Lee-Whiting)	38
2.	Accelerating Cavities (W. Watson, S.B. Hodge)	45
3.	Magnetic System (A. Harvey, H.J. Underhill, K. Marshall)	60
4.	Injection and Extraction (B.G. Chidley)	81
5.	Vacuum (S.B. Hodge)	85
F.	RADIO-FREQUENCY SYSTEM (F.J. Heath, R. Poirier, F. Konopasek)	92
1.	Possible RF Generators	94
2.	RF Amplifier Chain	96
3.	RF Power Distribution System	106
4.	RF Control System	110
5.	AC and DC Power for Amplifier Chains	114
6.	Amplifier Cooling Requirements	115
7.	Departures from Reference Design	116
G.	CONTROL SYSTEM	119
1.	Overall System (H.R. Schneider)	119
2.	Cavity Control System (G. Porcelli)	122

H.	BEAM TRANSPORT	127
1.	Primary Beam Transport (B.G. Chidley)	127
2.	Beam Splitters (J.S. Fraser)	128
3.	Meson Beams (J.S. Fraser)	134
I.	SHIELDING AND ACTIVATION (I.M. Thorson)	137
1.	Introduction and Beam Spill	137
2.	Direct Radiation Shielding	138
3.	Operating Radiation Levels	140
4.	Activation Radiation	141
APPENDIX VI.1	Selection of Current and Energy (J.C.D. Milton)	142
VI.2	Selection of SOC Parameters (G.E. Lee-Whiting)	148
VI.3	SOC Ion Optics (B.G. Chidley)	160
1.	Orbit Dynamics	160
2.	Machine Errors	175
3.	Limitations	179
VI.4	Beam-Cavity Interaction	180
1.	Theoretical Studies (G.E. Lee-Whiting, K.B. Winterbon)	180
2.	Electron Analogue Experiment (H.R. Schneider)	188
VI.5	Effects of Space and Image Charges (T.D. Newton)	192
VI.6	SOC Side Yoke Magnets (H.J. Underhill)	194
1.	Magnet Design	194
2.	SOC Assembly	198
3.	Cost Comparison	198
VI.7	Theory of Cavity Loops and Tuning Devices (W. Watson)	200

VI. ACCELERATOR AND BEAM TRANSPORT

A. REFERENCE DESIGN

This chapter describes the "reference design" accelerator and beam-transport system that has been used for engineering studies and cost estimating. The description is of necessity incomplete, particularly in detailed concepts, because considerably more study of both the physics and conceptual engineering is required. Sufficient work has been done to indicate the system is feasible in principle, although several important questions remain.

The reference design is staged at 300 MeV, an energy that was chosen for minimum cost before other requirements became evident. However, experimenters in meson physics prefer 400 MeV as an available intermediate energy. A change in staging energy from 300 MeV to 400 MeV would probably have only an insignificant effect on cost, but the detailed ion optics of machines staged at 400 MeV have not been studied nor have the necessary engineering designs yet been prepared. Consequently the design staged at 300 MeV is described in this report.

Following a summary of reasons for selecting the Separated-Orbit Cyclotron and the principles of its operation, a description is given of the system. The remainder of the chapter is devoted to discussion of components and sub-systems of the machine. The appendices describe some of the more detailed theoretical studies and their results, particularly the ion optics of the main accelerator.

Selection of the proton energy and current at 1 GeV and 65 mA is discussed in Appendix VI. 1. In principle one seeks the cheapest combination of energy and current that will give the specified flux in the thermal-neutron target. Effects of space-charge in the accelerator and of power density in the target suggest it is prudent to use a lower current and higher energy than the apparent cost-minimum. The increase in capital and short-term (5-year) operating costs at 1 GeV is about 4%. (One cannot permit too large a penalty in initial costs (capital) for efficient operation; for this study we have minimized the sum of capital costs and the present value of the 5-year operating cost.)

It is essential that few of the protons be spilled during acceleration - for these will induce radioactivity in the machine structure. The spill must be sufficiently low for the machine to be repairable without resort to extensive and costly remote handling techniques. The estimated permissible spill when the proton beam approaches the final energy is 1 μ A. (See Section VI. I).

If the project is to be completed in 1974, a start must soon be made on the detailed development and engineering design of the machine. It should be based if possible on existing proven designs or, at the very least, on well understood and established principles and on materials and components within the reach of existing technology.

A number of advanced concepts have been examined and these are discussed in Chapter XV. There it is concluded that a high-current DC accelerator of modest energy (~ 20 -40 MeV) could be developed as an injector for the main accelerator, but the latter will use RF fields to accelerate the proton beam to 1 GeV.

Cyclic particle-accelerators capable of achieving this energy are isochronous cyclotrons, synchrocyclotrons, synchrotrons, and linear accelerators. Isochronous cyclotrons and synchrocyclotrons of conventional design have a serious extraction problem. Towards the final energy, the spacing between successive orbits becomes small, and it is difficult to deflect protons from the final orbit without scattering those in the preceding orbit. The Oak Ridge National Laboratory proposed an isochronous machine, a spiral ridge cyclotron, for 800 MeV¹. By raising the energy gain per revolution to 1 MeV and inducing a radial betatron oscillation, they expected to achieve an extraction efficiency of 90%; the remaining 10% would be scattered into the pole faces. It may not be possible to achieve a circulating beam of 65 mA in this machine, but even if it is the induced radiation fields would make manual repairs and adjustments impossible. Synchrotrons also have extraction problems, but even if these can be solved, such machines can probably not produce much more than 10^{15} protons per second (~ 0.1 mA)² before instabilities destroy the beam.

There remain two machines that appear capable of achieving the requirements of energy, current and small beam spill. When this study began the linear accelerator was rejected as a low-efficiency device: losses in the structure and the poor efficiencies of apparently suitable UHF generators indicated an AC power consumption in excess of 200 MW³. The Separated-Orbit Cyclotron (SOC) proposed

¹ A Proposal for the Mc² Isochronous Cyclotron, ORNL-3540, (1963).

² A Proposal for Increasing the Intensity of the Alternating-Gradient Synchrotron at the Brookhaven National Laboratory, BNL 7956, 182-187, (1964).

³ P.R. Tunnicliffe, The 65-mA 1 GeV Proton Accelerator, proc AECL Symp. The Generation of Intense Neutron Fluxes (Chalk River, 1965); AECL 2177, paper 2 (1965).

by F.M. Russell⁴ promised much lower RF power losses and, because of the lower frequencies possible for a satisfactory design, better RF generator efficiency. Consequently this machine was selected for more detailed study and is the basis of the reference design presented in this report.

Recent developments have revived interest in the linear accelerator. In particular, studies at the Los Alamos Scientific Laboratory for a High-Flux Meson Facility have yielded waveguide structures of greatly improved shunt impedances^{5, 6, 7, 8}. A crossed-field microwave device, the Amplitron, shows good prospects as a highly efficient RF generator for such a machine^{9, 10}. Consequently a detailed study of a linear machine for ING has been started. It has not, at the time of writing, reached a point where a decision can be made to adopt it in preference to the SOC.

A plausible concept of a suitable linac has been used to estimate costs. Within the accuracy of these estimates, costs show no clear advantage for either the linac or the SOC. The decision will therefore depend on an assessment of the technical and engineering

⁴ F.M. Russell, A Strong-Focussing Cyclotron with Separated Orbits, ORNL 3431, (1963).

⁵ A Proposal for a High-Flux Meson Facility, LASL document (unnumbered) (September 1964).

⁶ B. C. Knapp, et al., Resonantly Coupled Accelerating Structures for High Current Proton Linacs. IEEE trans. Nuclear Sci. NS-12 (3), 159 (1965).

⁷ E. A. Knapp, Design Construction and Testing of RF Structures for a Proton Linear Accelerator. IEEE trans. Nuclear Sci. NS-12 (3), 118 (1965).

⁸ H. A. Hoyt, Numerical Studies of the Shapes of Drift Tubes and Linac Cavities. IEEE trans. Nuclear Sci. NS-12(3), 153 (1965).

⁹ T. E. Ruden, The Amplitron as a High Power Efficient RF Power Source for Long Pulse High Resolution Linear Accelerators. IEEE trans. Nuclear Sci. NS-12 (3), 169 (1965).

¹⁰ The Amplitron and its Use in an RF System for a CW Proton Linear Accelerator, Raytheon Technical Report No. MPO-023 AECL document FSD/ING-50 (March, 1966).

problems, some known, others perhaps not - and of possible improvements. Further study is required. The linear machine is discussed in detail in Chapter XIV.

Either machine would be operated on a 100% duty cycle*. Pulsed operation, with higher instantaneous currents would in principle improve the RF-to-beam efficiency. But pulsing is undesirable both for the physics experiments and for machine design. Space-charge problems would become severe in the low-energy sections of the machine, and the cost of the RF system, a major item, would be significantly increased.

The classical cyclotron is an isochronous machine, that is, the particle orbital time is constant, and it can be operated continuously. Such a machine cannot be designed to function above ~ 20 MeV. To compensate for the relativistic increase in mass (a factor two at 1 GeV) it is necessary to increase the magnetic field with radius to maintain isochronism. The field then becomes "defocussing", the particles are quickly driven into the magnet poles, and the machine will not accelerate any significant number of particles. AVF cyclotrons¹¹ overcome this by adding an azimuthal modulation to the field to give a net focussing force. The difficulty of extracting the beam from such a machine because of the small orbit separation has been mentioned. Russell overcame this in his proposed Separated-Orbit Cyclotron⁴ by using a large energy gain per revolution, ~ 30 MeV. The orbit separation then becomes large enough to separate isochronism and focussing problems and 100% extraction is relatively easy. The alternating-gradient strong-focussing principle¹² can be applied and the circulating beam can be made stable and well confined assuring, in principle, little beam spill throughout the machine. The large energy gain per turn is achieved by using a large number of radial RF resonators instead of the more familiar dee structure, an extension of the technique of the Mc^2 cyclotron proposal¹.

The machine bears little resemblance to the more familiar cyclotron, indeed it behaves more like a rolled-up linear accelerator although the RF power loss (~ 10 MW) is less; smaller cavity-resonator area and lower electric fields contribute about equally to the saving.

* It should be noted the beam will contain a micro-structure characteristic of the RF acceleration process.

¹¹ J. J. Livingood, Principles of Cyclic Particle Acceleration, Van Nostrand, Chapter 13, p. 219 (1961).

¹² *ibid.*, chapter 12.

Russell originally proposed to displace successive orbits axially to separate the orbits sufficiently; this is unnecessary below 1 GeV, a flat machine can be designed which is easier to assemble and align. He also proposed to operate at 200 MHz; cheaper machines can be built at lower frequencies.

An illustration of the basic configuration of the machine appears in Fig. VI. 1. The accelerating cavities are rectangular boxes excited by RF energy in their lowest resonant mode - the electric field is parallel to the narrow dimension and tangential to the particle trajectories. The cavities are excited in constant phase relations between each other, and the total phase change around the machine is an integral multiple of 2π . Magnets to guide and focus the beam are placed at each orbit between cavities. The position, length and strength of these are chosen to satisfy the requirements for isochronism i. e. the particle transit time between cavities must match the phase shift between them.

The machine is in fact designed to be isochronous when the ideal particle arrives before the RF voltage has reached its maximum ($\sim 30^\circ$ in phase) to maintain automatic synchronism between the beam and the RF voltage. Because a strong-focussing machine has high momentum compaction (the particle trajectories are nearly independent of small energy errors), a particle moving too fast arrives early and receives less energy gain: similarly a slow particle receives an extra energy gain. Thus particles tend to focus about the correct energy and maintain synchronism. This "phase stability" is identical to that used in linear accelerators and synchrotrons¹³. The machine will accept injected particles only in a limited range of energy and phase; it is necessary to "bunch" the injected beam if a reasonable fraction is to be captured and successfully accelerated.

Each magnet is divided into a number of alternating-gradient cells to focus the beam. The magnetic field, Fig. VI. 2, has the ideal value only at the central or "equilibrium" orbit. The poles are contoured to give a strong radial gradient in the magnetic field strength. Effectively, the particles see a rapid series of positive and negative lenses for both horizontal and vertical displacements - each lens is positive in one direction and negative in the other. The net result is an effective relatively-strong focussing force in both directions and the particles oscillate about the equilibrium orbit provided certain stability criteria are satisfied.

Isochronism can be satisfied by a wide range of electrical and dimensional parameters for the machine. It was evident early in the study that some criterion was needed to limit the scope to those

¹³ *ibid.*, chapter 6.

FIG. VI. 1 Sketch of a simple SOC.

VI.A

FIG. VI. 2 Principle of Alternating Gradient Focussing.

designs worthy of detailed investigation. A procedure has been developed for seeking the cheapest combination (see Appendix VI. 2). A computer program has been written to calculate the combination of parameters needed to give an isochronous machine and the part of the cost that depends on the design parameters being considered. The program automatically adjusts the combination to seek a minimum cost. The machine so derived is then examined in detail for its ability to accept and successfully accelerate protons (see Appendix VI. 3). These calculations also indicate the tolerances that could be permitted in construction and operation.

An apparent minimum-cost design may not in fact have satisfactory orbit dynamics. It must be able to accept the inevitable spread in positions and energies of injected particles. Its tolerances must also be within feasible limits.

The procedures for selecting the best design still need refinement. The cost-minimizing procedure does not adjust all possible parameters, a judicious choice of some must be made as input and a series of cases run if these are to be varied over a range. The choice of input values depends on engineering judgments, constraints imposed by possible methods of constructing and assembling the machine, experience from the results of previous orbit-dynamics calculations, magnet design problems and other factors. The choice is inevitably affected by our detailed studies of plausible designs derived from first guesses and then by the development and test program derived from these designs. The unit cost data, which is part of the input, is similarly affected. Furthermore detailed understanding of the physics of the machine continues to grow, and calculations of the particle trajectories improved. Other variants of the basic design remain to be considered.

Thus arriving at the best design is an iterative process which is not yet complete. The design presented in this report is plausible and probably close to the best derivable from present knowledge and understanding.

Often the effects of varying one of the input parameters or basic design assumptions cannot be isolated - each interacts with other parameters to retain isochronism and adequate orbital stability. Some comments on variants are:

- a. The resonators are rectangular cavities but economies may come from tapering horizontally and radially.
- b. All magnets in one sector (between cavities) have a common yoke and exciting coil that extend radially from the inner to outer orbits. Yokes returning the magnetic

flux in the space between cavities and magnets would save a considerable amount of steel. Alignment would probably be more difficult and the effect of the yoke field on the proton beam is not yet known.

- c. The design frequency is 50 MHz. The main RF generators are conventional thermionic gridded tubes whose efficiency could improve at lower frequencies. In principle the machine would be cheaper because fewer cavities could be used, but orbital stability and adequate focussing place a lower limit on the number of sectors. The region below 50 MHz has not been adequately explored, but a much lower frequency is unlikely to give a cheaper overall design. A more desirable frequency is 40.68 MHz because it is in an "Industrial Scientific and Medical" band where no limit is imposed on radiated RF energy. Two other ISM bands are at 13.56 and 27.12 MHz. If 13.56 MHz could be used, RF shielding requirements would be minimal because the two higher-frequency bands are at its 2nd and 3rd harmonics. Other RF generators of better efficiency and lower cost are possible. A satisfactory Amplitron may be developed at 200 MHz; a more radical innovation in which the machine is driven directly by bunched high-energy electron beams has been proposed by Russell¹⁴ (the frequency is immaterial over a wide range).
- d. The cost begins to rise sharply if one attempts to design an SOC that will more than double the proton velocity; it is cheaper to stage the machine at intermediate energies. An injection energy of 10 MeV is achieved with a linear accelerator and two intermediate staging energies are adjusted for minimum cost. A detailed study of the economic injection energy has not yet been done but it is believed the total cost would be reduced if it were increased.
- e. The available beam aperture is chosen so the tightest magnet position tolerance is not less than 10^{-3} in. The aperture directly affects the required total magnetic flux and hence the amount of yoke steel. Because of the so-called "momentum damping" the aperture is reduced in successive stages (see Table VI. 1). The aperture also depends on the predicted properties of the primary ion-source; experimental verification is needed. In principle the aperture could be reduced (or tolerances relaxed) if beam oscillations caused by errors were reduced with correcting magnets introduced at intervals in the orbit. Ample space

¹⁴ F. M. Russell, Electronic Components, p. 133 (February 1966).

exists for the necessary sensing devices and steering magnets once per revolution because one cavity is left out to permit injection. This is only feasible if the focussing system is sufficiently linear for the beam to oscillate as an entity. It is not yet known if the required effective linearity of the magnetic field gradients can be achieved.

- f. The minimum turn separation specified is related to estimates of difficulty in achieving adequate uniformity of magnetic field gradient in a given magnet in the proximity of its neighbours. The machine overall size and cost is relatively sensitive to this limit. Permissible errors in the gradient and interaction effects are not yet well enough understood to adopt a less conservative value.

A number of major questions remain to be answered before the feasibility of SOC accelerators is established. These are:

- a. The amount of beam spill. Fully detailed calculations of the particle orbit in the machine have yet to be done. These require large amounts of computer time. So far only sample calculations have been done; insufficient to predict the small spill required. To obtain the dimensions and tolerances given in later sections, simplifying assumptions have had to be made to survey the many problems in conceptual design which have had to be considered.
- b. Ability to establish or maintain the necessary cavity voltages. Considerable difficulty has been experienced at ETH (Zurich) in achieving 300 kV across a similar cavity¹⁵. A full-scale experiment is being prepared.
- c. The magnet assemblies have difficult technical problems. It is believed the necessary alignment precision can be achieved, but it is not yet known if this can be easily and reliably maintained. Magnet end-effects on the orbit dynamics are still to be determined.
- d. About 90% of the RF power fed to the cavities is absorbed by the beam. The beam-cavity interaction is believed to be manageable provided lower-order modes can be avoided. An electron-analogue experiment is being prepared to verify theoretical predictions.

¹⁵ P. Lang, et al., Results of First Measurements on the 1:1 Model of a H101 Cavity for the ETH Cyclotron, proc. Intl. Conf. on Isochronous Cyclotrons, (Gatlinburg, 1966) (May 1966).

- e. An RF power supply of ~ 2 MW capacity and adequate reliability is not assured. While two possible tubes of the necessary capacity exist, neither has been operated CW at the required power and frequency. A test program is essential, and
- f. It is not yet known if a reliable DC ion source of satisfactory emittance characteristics can be built.

Since the reference design was prepared for this report, some revisions have been made in unit cost estimates. In particular it has been suggested the cost of RF power should be decreased significantly¹⁶. The cost estimates given in Chapter XI use best values currently obtained in engineering appraisals of the reference design.

¹⁶ F. J. Heath, Memorandum on RF Power Costs, FSD/ING-49 (May 1966).

B. GENERAL DESCRIPTION

1. The Accelerator System

Schematically this is:

The protons originate in the ion source from a magnetically confined plasma generated by an electrical discharge. They are extracted from the plasma by an electric field and rapidly accelerated in a short multi-electrode column by 750 kV D. C. The resultant beam is shaped by a series of magnetic lenses and slits. A resonant cavity excited by radio frequency energy, the buncher, imposes a small velocity modulation so that after a drift space the beam is separated longitudinally into bunches which can be captured by the radio frequency acceleration system. About 80% of the beam is captured by the linear accelerator and accelerated in a single resonant tank to 10 MeV. The tank is excited by RF energy in a mode with an electric field parallel to the beam; electrodes ("drift tubes") in the tank shield the beam bunches during the times when the electric field is reversed. Magnetic lenses within the drift tubes keep the beam transversely confined.* More lenses, magnetic quadrupoles, continue to confine the emergent beam until it is steered into the initial orbit of the first stage SOC by a pair of bending magnets. Similar systems are used to transfer the beam between the three SOC stages at 50 and 300 MeV. Further lenses are required to confine the emergent beam all along its trajectory. Bending magnets steer it into the top of the thermal-neutron target. A pulsed electric field deflecting system is used to pick off two small fractions of the main beam. More magnets are used to transfer these to the meson targets and the resonance-neutron target.

The principal parameters of the accelerator system are listed in Table VI.B.1.

* See Chapter XIV for a more detailed discussion of "Alvarez" linear accelerators.

TABLE VI. B.1

PRINCIPLE ACCELERATOR SYSTEM PARAMETERS

<u>Ion source</u>	D. C. Duoplasmatron current 130 mA	<u>Separated Orbit Cyclotrons</u>
<u>Preinjector</u>	750 kV D. C.	Frequency 50 MHz Mean magnetic field 7.5 kg Stable Phase angle 30° Minimum Cavity - Magnet Clearance 20 cm Beam current 65 mA
<u>Linac Injector</u>	Frequency - 50 MHz Diameter - 4 m Length - 5.8 m Mean gradient 2.3 MV/metre RF Power loss 0.83 MW RF Total Power 1.45 MW Beam Current 65 mA	

SEPARATED-ORBIT CYCLOTRONS

	<u>Stage 1</u>	<u>Stage 2</u>	<u>Stage 3</u>
Energy range - MeV	10 - 50	50 - 300	300 - 1000
No. sectors	13	13	33
Harmonic number (RF cycles/rev)	20	18	25
No. turns	17	31	28
Peak RF field MV/metre	1.2	1.2	0.91
RF losses MW	1.26	2.50	4.32
Magnetic field indices	10	11	80
Magnet steel tons	405	2835	4767
Coil Copper tons	14	20	40
Magnet power MW	0.33	0.62	1.27
Min orbit separation cm.	10	9	8
Beam aperture inches	2	1.75	1.5
Accelerator diameter ft.	42	85	150

Total RF losses	~ 8.1 MW
Total Magnet Power	~ 2.2 MW
Total Steel	~ 8000 tons
Total Copper	74 tons

2. General Layout

Fig. VI. 3 shows the general layout of the system in plan. The spacing between the various stages of radio frequency acceleration is necessarily limited. The bunching must be retained if the beam is to be wholly captured in succeeding stages; inevitable energy inhomogeneities will destroy it during too long a drift space. Preservation of bunching is particularly difficult between the linac injector and the first stage SOC. The two machines are therefore located in the same building.

The Separated-Orbit Cyclotrons are arranged for convenient access from the single maintenance and assembly building; there is little restriction on the output and input directions of each stage.

Each machine building is covered with sufficient shielding to ensure negligible radiation outside. The radio frequency generators, one per cavity, are housed in shielded galleries as close as possible to their connecting cavities. Sand shielding is used in preference to a dense material (e.g. heavy concrete) where there are no space limitations.

After leaving the final SOC stage, the proton beam passes through a series of heavily shielded tunnels to the various targets. The beam first passes through a thin target, for meson production, then through a splitter which diverts left 1:100 of the micropulses (its inherent RF structure) to form Beam-2 and 1:10³ right to form Beam-3. The residual main beam (Beam-1) then passes through a second meson target and at the end of the main-activity tunnel is bent 20° left towards the thermal-neutron facility. (The bend is intended to help shield the succeeding tunnel from the main tunnel.) At the thermal neutron facility building the beam is bent 20° upward and then 110° down into the main target where it is completely stopped.

The split beams-2 and 3, are picked off by magnets after they have diverged sufficiently from the main beam. No. 2 (~ 1mA) is then bent left 90° into a channel which may house meson or neutron producing targets and is finally bent down into a beam dump in the ground. No. 3 (~1 μA) is bent right 30° and terminates in the pulsed-neutron facility. A second splitter diverts part of it into the nuclear power technology facility.

All beams are confined by systems of quadrupole lenses. A vacuum of ~ 10⁻⁶ torr will be maintained throughout the beam path by a series of sputter-ion pumps.

3. Ion Source, Pre-Accelerator, Linac Injector & Stage 1 SOC

The Ion Source, Pre-accelerator, Linac Injector and Stage 1 SOC are accommodated in one building as illustrated in Figs. VI. 4

FIG. VI. 3 General Layout of Accelerator and Beam Target System.

FIG. VI. 4 Ion Source, Preaccelerator, Linac Injector and Stage 1 SOC (Plan).

FIG. VI. 5 Ion Source, Preaccelerator, Linac Injector and Stage 1 SOC (elevation)

and 5. The Linac Injector, Stage 1 SOC and the RF Generators are contained in sand shielded sections of the building and the ion source, pre-accelerator, mechanical services area, electronics shop, control room and office space in the remainder. A curved tunnel connects the accelerator vault to the maintenance and assembly building.

The ion source is expected to have a life of only a few hundred hours and to require frequent servicing. Two ion sources and pre-accelerators are therefore provided, with a beam-switching magnet placed between them for rapid changeover. The two ion sources and pre-accelerators are placed symmetrically about the centre line of the linac injector and surrounded by 18" of light concrete. There are two 9" concrete walls between the units so that one may be used while the other is either being serviced or used for testing new ion sources. A local control room is provided for the pre-accelerator and injector system. The Linac Injector and Stage 1 SOC room is serviced by a 25 ton overhead travelling crane.

The system before the injector starts with a duoplasmatron ion-source. This is mounted on an insulating stack and 750 kV D.C. is supplied to it from a cascade generator to accelerate the positive ions emerging from the source. The high voltage system is air insulated to allow easy access to the source. The pre-accelerator, which follows, is a multi-electrode column designed to minimize the space-charge blowup of the beam. The beam is then steered by a switching magnet into a system of focussing lenses and diagnostic equipment into the buncher and then into the injector linac.

The injector is an Alvarez linac constructed from copper clad steel, about 4 m in diameter by 5.8 m long.* No detailed study has been made of the linac injector since it is anticipated the design will be conventional and present no serious problems.

The stage 1 SOC is in most respects similar to the other two stages, described in the next section, except that the vacuum pumps for the RF cavities and the beam tubes are located in the same room close to the cavities, since the radiation levels in this stage will be less.

4. The Separated-Orbit Cyclotrons

Fig. VI.6 shows the arrangement of the three SOC's in plan. Elevation sections of stages 2 and 3 are shown in figures VI.7 and VI.8 respectively. These stages are housed in annular vaults covered by sufficient sand shielding to ensure negligible radiation outside (see section VI.1). Elevators provide access to the central areas containing some of the service equipment for the machines. The RF generators, one per cavity, are housed in circular tunnels around the stages with sufficient shielding to allow limited access for servicing

* The length has been decreased from 13 m since Figs. VI.4 and VI.5 were prepared.

FIG. VI. 6 Plan of Separated Orbit Cyclotrons.

FIG. VI. 7 Section through second Stage SOC.

FIG. VI. 8 Section through 3rd Stage SOC.

during operation. The RF generator galleries are shown diagrammatically since the dimensions were unknown when the drawings were produced.

Machine components will be assembled and tested in the assembly and maintenance building and then transferred through a service tunnel on a trolley. An overhead crane then takes over. The greatest load to be handled by the cranes is the top or bottom yoke assembly of each magnet.

The SOC foundations must be extremely stable because each magnet sector must be located and held within relatively close tolerances. Misalignments could be caused by settlement, shrinkage, creep or vibrations due to earthquakes. To counteract this an isolation system is illustrated with the magnets and cavities mounted on a rigid concrete ring supported by a large number of springs appropriately spaced. The springs rest on a similar rigid concrete ring supported on large diameter caissons on bedrock. To support the ring beam uniformly, a load sensing and a levelling sub-assembly will be incorporated in each ring. The ring will then be uniformly supported automatically, even if the pile cap ring should sink slightly due to changes in the length of the caissons. The outside diameters of these concrete rings are approximately equal to the outside diameter of the SOC machines.

It will not be necessary to transfer the weight of any building to bedrock since the reference site is covered with an overburden of glacial till with a bearing capacity of about 10,000 psf. The building foundations will be conventional strip or spread footings. Gaps must be left between the building foundation and the machine foundation to allow differential movement during earth disturbances.

The incoming beam is steered into the first orbit of a stage by an achromatic bending-magnet system. One possible system of three magnets is illustrated in Fig. VI. 7, another system is discussed in Section VI. E. 4. To avoid expensive elevation changes in the inter-stage beams and minimize excavation, the incoming beam to the second stage is brought over the machine but to the third stage, under the machine. Ejection at the median plane of the machine is tangential to the final orbit and readily accomplished by terminating the magnetic guiding system. Means for the emerging beam to pass through one or two cavities and magnet yokes are provided. Quadrupole focussing magnets at about 30' intervals in the interstage tunnels confine the beam and provide matching from the output of one stage to the input of the next.

A machine stage is formed of a circular array of alternating RF cavity resonators and sector magnet assemblies. To allow space for injection a gap is provided in the ring by omitting one cavity.

The magnetic fields which guide and focus the circulating beam are produced by appropriately shaped pole-pieces placed at each orbit. The magnetic flux for all poles in one sector is returned through a common radial yoke. A single pair of coils excites all poles in a sector. Fig. VI.9 illustrates the sector magnet construction schematically. Because the magnetic fields must be defined very accurately to avoid beam spill the pole assemblies must be positioned with respect to each other to within tolerances of the order of a few mills. The bottom yoke will form a stable mounting base and alignment will be done in the shop. Adjustable gaps between the poles and the upper yoke will allow the relative fields to be shimmed. The sector magnets will be checked magnetically as assembled units before mounting in the machine room. Some gross parameters for the different stages are given in Table VI. B. 2.

TABLE VI. B. 2
SECTOR MAGNET PARAMETERS

	<u>Stage 1</u>	<u>Stage 2</u>	<u>Stage 3</u>
Yoke Length (cm)	472.0	834.0	739.0
Yoke thickness (cm)	60.6	112.7	94.4
Yoke spacing (cm)	29.6	25.0	26.7
Mass of steel (ton)	31.1	218	144.5
Mass of copper (ton)	1.06	1.52	1.20
Coil power (kW)	25.2	47.5	38.5
No. of poles	17	31	28

The magnetic field is steady so the coils are powered by D.C. Because the coils must operate in high nuclear radiation fields thin strips of anodized aluminum are used as insulators between adjacent flat strips of copper in the winding. Water cooling passages are provided in the coils to minimize temperature changes in the magnet steel due to the coil.

The RF cavities illustrated in Fig. VI.10 are rectangular boxes designed to resonate at 50 MC/s. Gross parameters required for each stage are listed in Table VI. B. 3.

FIG. VI. 9 Typical Sector Magnet.

FIG. VI. 10 RF Cavity Assembly.

TABLE VI. B. 3
CAVITY PARAMETERS

Unit	No. of Cavities	Height cm	Width cm	Length cm	Surface Area of each cavity (cm ²)	Volume of each cavity (litres)
Stage 1 SOC	12	403.62	25.87	447.74	4.05×10^5	4.7×10^3
Stage 2 SOC	12	321.70	114.55	826.47	7.95×10^5	3.04×10^4
Stage 3 SOC	32	325.32	160.35	771.95	8.54×10^5	4.02×10^4

The interior of the cavity is lined with oxygen free, high conductivity (OFHC) copper bonded to 3/8" thick mild steel plate for strength. Plates forming the box will be welded to form a vacuum tight enclosure. The support structure is fabricated from standard I-beams with rigid corner joints which will limit deflections of the mid points of the vertical walls caused by atmospheric pressure. The irregular pitch of the proton beam tubes along the horizontal centre line of the cavity walls does not allow the I-beams to pass between them. The structural beams are therefore cantilevered from above and below. All structural beams are connected to the plate by resistance welded "Nelson" studs and separated by spacers from the plate about $\frac{1}{2}$ ", so that the walls can be adjusted to maintain size and flatness under vacuum to compensate for deflections of the beams. The walls are penetrated by a 24" manhole, RF coaxial line and coupling loop and two 18" diameter vacuum pump ducts. Cooling channels run the full perimeter of the cavity between vertical structural support beams.

Each cavity is mounted on a structural girder of the same width as the cavity. A tube at each orbit, curved to conform with the proton beam path through the magnets, completes the vacuum envelope between cavities. These tubes have bellows joints at the cavity connections to permit deflections of the joints and provide mechanical isolation between the cavities and magnets.

A section of the magnet-cavity arrangement is shown in Fig. VI.11.

Each magnet assembly rests on seven screw jacks fixed to the concrete ring beam. A set of thrust bearing balls is located between the magnet yoke bearing surface and the jacks to facilitate final adjustments in the horizontal plane. The magnet is moved horizontally and locked in position by horizontal screw jacks on steel base plates permanently set in the concrete. The RF cavities are located and locked in position in a similar manner.

FIG. VI. 11 SOC Magnet Cavity Arrangement.

In stages 2 and 3 the vacuum ducts extend through the inner shielding walls to a central circular region of the building with sufficient shielding to permit immediate access to the vacuum pumps during shut-down. To assure clean surfaces in the high electric field regions sputter-ion pumps are selected to evacuate the accelerating structures.

Because of the close tolerances on sector magnet location, essential to avoid beam spill, special means will be provided for positioning them during machine assembly to within a probable error of the order 0.01 inch. The cavities need to be positioned to lesser accuracy, of the order 1/8". A four-legged gantry, equipped with tooling bars, transits and scales and spanning the cyclotron ring will be moved around the ring to locate or check the assembled magnets and cavities initially. It will be available for any realignment subsequently needed but it may be necessary to provide means for remote reading after operation.

5. Beam Transport System

Little work has been done on the engineering design of this system. A preliminary conceptual layout is illustrated in Fig. VI. 3 and its basic provisions have already been mentioned. The beams will have to be transported over many hundreds of feet. Quadrupole focussing magnets located about every 30' are illustrated schematically in Fig. VI. 12. Surveys of the most economical design have yet to be made and conceptual designs of beam splitters and septum and bending magnets prepared. To minimize beam spill considerable attention to reduction of aberrations will be needed.

6. Services

About 130 MW of electrical power is needed to supply the accelerator system, the biggest single load being the RF generators. About 1 MW of emergency power will be needed for safe shutdown and other essential standby services.

Demineralized, closed-loop cooling water systems service the RF amplifiers, cavities and magnets; the cavity system is closely temperature controlled to reduce the tuning control needed. The machine vaults will require close temperature control to minimize dimensional changes in the structures. These and other mechanical services are grouped together in service buildings close to the areas served and are discussed in more detail in Chapter IX.

FIG. VI. 12 Typical 60' Section of Beam Transport System.

C. ION SOURCE AND PREACCELERATOR

The ING ion source will be either a modified duoplasmatron^{17, 18} or a hollow cathode discharge¹⁹ and the beam will be pre-accelerated to 750 kV and bunched before entering the linac. Two preaccelerators are planned because experience in other laboratories²⁰ has shown this to be a most unreliable component in an accelerator:

The choice of 750 kV is a compromise. There is need in the initial acceleration for a high voltage to satisfy the linac requirements for radial transit time factor²¹ and to diminish the effect of space charge. (Beam blowup due to space charge varies as $(\text{energy})^{-3/2}$.) A low pre-accelerator voltage is necessary to allow air insulation of the terminal and easy access to the source. High gradient columns (up to 50 kV/cm on the Brookhaven test stand - see Fig. VI.13) are therefore used to minimize the time spent at low voltages. Re-entrant design reduces the gradient on the outside of the column.

The accelerator design calls for an RF current of 65 mA with a momentum normalized emittance (emittance invariant[†]) of not greater than 10π mm mrad. At 750 kV, $\epsilon = 250\pi$ mm mrad. A smaller emittance would be desirable because beam quality deteriorates up to 10 MeV^2 . The source must deliver more than 65 mA because of attenuation due to unwanted mass components in the beam (mainly H_2^+) and the phase acceptance of the linac. A second harmonic two-gap buncher (efficiency of 83%)⁵ precedes the linac to increase the beam current in the acceptable phase of each RF cycle. The proton component of duoplasmatron beams is $\sim 60\%$, hence the required source current $I_s = \frac{65}{.83 \times .80} = 130 \text{ mA}$. We will take $I_s = 180 \text{ mA}$ to allow for contingencies. Sources are in operation that satisfy these requirements for current and emittance.^{17, 18, 19}

† The emittance invariant $V = \beta\gamma\epsilon$ where $\beta = \frac{v}{c}$, $\gamma = (1-\beta^2)^{-1/2}$, ϵ = two dimensional transverse phase area. Cylindrical symmetry is assumed.

¹⁷ L. W. Oleksiuk, Recent Measurements on the Duoplasmatron Source, proc. conf. on Proton Linear Accelerators (Midwestern Universities Research Ass'n.), MURA 714, 447 (1964)

¹⁸ R. C. Davis, et al., High-Current Ion-Beam Production and Injection, Thermonuclear Division Semi-annual Progress Report, ORNL-3652, 84 (1964)

¹⁹ P. Henning, et al., Bull. Amer. Phys. Soc. Series 2, 10, 725 (1965)

²⁰ C. S. Taylor, High Current Performance of the CERN PS Linac, proc. intl. conf. High Energy Accelerators (Dubna USSR) 616 (1963)

²¹ A Final Report on the Design of a Very High-Intensity Proton Linear Accelerator as a Meson Factory at an Energy of 750 MeV, TID-21282 (1964) (ref. 67, VII. C. 4. 4. 2)

²² Th. Sluyters, Nuclear Instr. & Methods 27, 301 (1964)

FIG. VI. 13 Brookhaven High Gradient Column.

All high current ion sources operate by extraction from a plasma boundary. Figure VI.14 shows the essentials of a hollow cathode discharge source (a duoplasmatron is similar - the main differences are a filament cathode and shaped magnetic field).

FIG. VI. 14 Hollow Cathode Ion Source (Schematic).

Hydrogen is bled into the hollow tungsten-rhenium cathode and ionized in the several ampere arc discharge. An axial magnetic field of a few hundred gauss inhibits radial diffusion of the plasma. An axial pressure gradient forces the plasma through the anode aperture to the plasma boundary where the large potential gradient (Pierce configuration)²³ extracts a space charge limited proton current.

The anode aperture limits the gas flow into the accelerating region, $\sim 1/3$ of the atoms fed in appear as ions in the extracted beam. For a 180 mA beam $\sim 2 \times 10^{18}$ hydrogen atoms must be pumped out every second. Ignoring the diatomic nature of hydrogen, a pumping speed of ~ 5000 l/s at the top of the column will maintain a pressure of 10^{-5} torr.

Several ion source requirements peculiar to ING will call for development work.

(a) Source Lifetime: The sources referred to above are either pulsed¹⁷ or operated continuously for periods of hours.^{18, 19} The ING source should be capable of continuous operation for days, which may be beyond

²³ J.R. Pierce, Theory and Design of Electron Beams, D. Van Nostrand Co. (1954)

present filament technology. (The hollow cathode discharge source is superior in this respect). Deterioration of other source components may also be significant over such periods.

(b) Regulation: Since about 90% of the RF power delivered to a cavity is absorbed by the beams, the latter has an important effect on the cavity voltage, which will change with changes in the beam if not regulated. This might cause beam spill. It is cheaper to regulate the beam current than the RF power supplies. The time constant for this regulation is not unreasonable. It is determined from the loaded cavity Q (10,000) and the operating frequency (50 MHz).

$$\text{Thus: } \tau_R < \frac{Q}{f} = \frac{10^4}{5 \times 10^7} = 2 \times 10^{-4} \text{ s.}$$

Two possible methods of regulation requiring adjustment of source parameters have been outlined²⁴. The range of such regulation is however restricted by the necessity of optimizing the parameters in tuning the source. Significant deviations from optimum values would result in unfavourable ion optics.²⁵

A third method would be to regulate the beam current by varying the RF amplitude of the buncher. The linac will accept only ~25% of an unbunched beam while a single gap buncher alone increases this to ~70%²³ - almost a factor of three.

(c) Plasma Oscillations: Under favourable operating conditions, a characteristic of these sources is a current modulation of 5-10% which is attributed to ion acoustic waves in the plasma²⁵. The frequency of these oscillations is ~10-30 MHz which should interfere little with the beam current regulation since $f \gg \tau_R^{-1}$. If, however, the oscillation frequency is near the fundamental or a subharmonic of the accelerator frequency, beating could cause a regulation problem.

(d) Current Buildup: When the machine is turned on a gradual increase in accelerator current will be required in step with the cavity RF power level. Programming the source parameters to realize this current variation is unacceptable for the same reason as is regulation by this method. A coarse current control could be obtained with a cooled iris. The current regulator would supply the fine control. Here again, the wide range of the buncher regulator would be advantageous.

To summarize, sources exist capable of delivering the current required for ING within phase space boundaries acceptable for the design. Development will be required to satisfy the special source requirements of ING, especially that of long life, but all advances beyond present technology appear feasible.

²⁴ J. H. Ormrod, ING Ion Source, report FSD/ING-15 (1965)

²⁵ A. Van Steenberg, IEEE trans. Nuclear Sci. NS-12 (3) 746 (1965).

D. INJECTOR LINAC

The beam from the 750 keV pre-accelerator is accelerated by the injector to 10 MeV. An Alvarez linac operating at 50 MHz will be used. The principles of such a machine are discussed in Section XIV.B.1. Proton linacs have been built for pulsed operation at 200 MHz^{26,27} and their characteristics are well known. One 50 MHz CW linac has been designed but not built (the MTA C-50)²⁸ and a CW deuteron linac, the A-48, was built²⁹.

Pulsed linacs operate at high voltage gradients to keep the total length to a minimum. Because they are pulsed high RF power losses may be tolerated and breakdown problems usually limit the gradients. In a CW linac RF costs are high and the length giving least cost may be considerably greater than that of a pulsed linac.

The total cost for a specified energy gain may be expressed in the form

$$\text{Total Cost} = A + BL + C/L$$

where

L is the length

A represents fixed costs (instrumentation, etc)

BL represents costs of the tunnel and accelerator

C/L represents RF costs.

The length for minimum cost is $\sqrt{C/B}$.

Cost estimates were scaled from 200 MHz accelerators^{26,27} to find the optimum length. Using $B = \$100,000/\text{m}$ and $C = \$3,500,000 \text{ m}$; the following minimum cost design is obtained (Table VI.D.1). No check has been made of sparking problems as this requires a detailed investigation of the fields at the drift tubes.

²⁶ A. Carne, K. Batchelor, NIRL/R/55, (1964)

²⁷ D. Young, BNL-6511, p. 76 (1962)

²⁸ LRL 102, (1954)

²⁹ E.O. Lawrence, Proc. Int. Conf. Peaceful Uses of Atomic Energy, Vol. 16, p. 62 (1955).

TABLE VI. D. 1

<u>INJECTOR LINAC PARAMETERS</u>	
Input Energy	0.750 MeV
Output Energy	10 MeV
Cavity Length	580 cm
Cavity Diameter	400 cm
Drift tube diam	65 cm
Drift tube hole diam	6 cm
Gap/cell length	0.2 to 0.3
$\cos \phi_s$	0.9
T (av)	0.77
E_o	2.3 MV/m
E_g (av) at gap	11 to 8 MV/m
Shunt Impedance (ZT^2)	22 $M\Omega/m$
Power loss	830 kW
Beam power	615 kW
Total power	1445 kW

A detailed study of the injector has not been done. It will follow existing practice, where considerable experience exists. Space charge effects must be examined but it is thought there should be no serious problem; the CERN injector linac has been successfully operated at 75 mA (pulsed) with satisfactory emittance.²² *

If 10 MeV proves to be too low an injection energy for a SOC, the linac may be extended to higher energy. The cost of a 65 mA linac is shown in Table VI. D. 2 as a function of output energy. This cost is for capital plus the present value of operating for 5 years but does not include the fixed costs (item A).

TABLE VI. D. 2

LINAC INJECTOR COSTS

<u>Output Energy</u> <u>MeV</u>	<u>Cost</u> <u>M\$</u>	<u>Rate</u> <u>M\$/MeV</u>
6	0.97	0.185
8	1.31	0.181
10	1.63	0.176
12	1.97	0.175
14	2.29	0.172

* Verbal reports indicate 130 mA has been achieved using a new injector system (May, 1966).

The cost per MeV energy gain of the Stage 1 SOC is M\$.19 so, although the linac cost estimates are very rough, there appears to be no reason against increasing the injection energy.

E. SOC STAGES

1. Selection of Parameters

The most significant SOC parameters are listed in Table VI. B. 1. Some are related to specifications, some are chosen to minimize system costs and some may be derived once the others are chosen. Most of these parameters cannot be chosen independently and in some cases an iterative process was required. For example, the beam diameter, which determines the pole tip size and the minimum orbit separation, can only be determined after a machine design has been formulated.

A brief description of the selection process is given in this section and details may be found in appendices VI. 1, 2 and 3 or in the references.

The parameters to be chosen for the SOC stages are:

- Output energy
- Current
- Frequency
- Staging energies
- Synchronous phase angle
- Central magnetic field
- Beam apertures
- Minimum orbit separation
- Pole tip size
- Clearance between magnets and cavities
- Number of segments
- Harmonic number (RF cycles per proton revolution)
- Cavity size
- Accelerating voltage
- Number of turns
- Magnet yoke size
- Field gradients

1.1 Output Energy and Current

The selection of energy and current is discussed in Appendix VI. 1. The basis of this selection is the provision of required thermal neutron flux, $10^{16} \text{ cm}^{-2} \text{ s}^{-1}$ in D_2O as cheaply as possible. To provide this flux it is estimated that the neutron source strength should be $8 \times 10^{18} \text{ s}^{-1}$. Possible choices of current and energy are given in Appendix VI. 1. Of these choices the low energy, high current ones may cause space charge problems. The most prudent choice is 1 GeV, 65 mA.

1.2 Frequency

The largest cost items in the accelerator are those associated with the generation of RF power. Most of this power appears in the output proton beam so most of the SOC parameters have only a small influence on the total cost. Frequency is an exception. The capital and operating costs of RF equipment do not depend simply on frequency but vary also with the types of tubes used and circuit design but, in general, the cost rises with frequency.

The frequency range which can be considered for the SOC is 30-200 MHz. Neither limit is sharply defined. Cavity size depends on the RF wavelength so the limitations reflect the usable range of cavity sizes.

According to Lee-Whiting's³¹ calculations the cost of a high energy stage would decrease with decreasing frequency even if the cost of the RF were assumed independent of frequency. He, however, ignored limitations due to admittance so that his cheapest design is without adequate beam handling capabilities. With these added the trend he finds does not occur, particularly at lower energy.

At low frequency his apparently cheapest designs have relatively few sectors and a low ratio of path length in the magnetic field to path length outside it. Both characteristics are objectionable because they influence stability limits and require use of weaker focussing. The low magnet-to-straight-section ratio increases deviations from the equilibrium orbit, by the lack of focussing in the field-free straight sections. To ease beam handling problems at low frequency we would then have to increase the aperture, reduce the cavity width and increase the number of sectors, changes which would considerably increase the cost. In addition the reduced cavity width would require an increase in injection energy, as discussed below.

It is not considered practical to have a shift of frequency part way through the acceleration, as has been proposed for linear accelerators (LAMPF³², YALE²¹). With SOC the low energy stages would prefer a higher frequency than the high energy stages (the converse of the linac). Space charge problems in the low energy stages would then be more serious.

The SOC does not appear to be satisfactory below 10 MeV and will require an injector such as a linac (Section VI. D). The linac diameter is proportional to wavelength so if injector costs are significant they will bias the choice toward higher frequency.

³¹ G.E. Lee-Whiting, SOC Parameters by Cost Minimization, report FSD/ING-10 released as AECL-2267 (1965).

³² D.E. Nagle, The LASL Meson Factory, proc. Conf. on Proton Linear Accelerators (Midwestern Universities Research Association), report MURA-714, 94 (1964).

The choice of 50 MHz was based on a conservative estimate of the low frequency limit. The choice of frequency needs further study.

1.3 Staging Energies

The SOC, as described in this report, is limited in energy gain per stage. Attempts to design a SOC with a greater gain result in massive magnets and inefficient cavities. It may however be possible to increase the gain by using tapered cavities and a more economical magnet design (see Appendices VI.2 and 6).

The low energy limit is imposed by the cavity shape. The height of the cavity is approximately $\lambda/2$ and the width $\beta_{\min} \lambda/2^*$. ($\beta = v/c$, v proton velocity, c velocity of light). At low β the cavity becomes inefficient and physically awkward. The lower limit appears to be $\beta = 0.145$ (10 MeV).

The ratio of output to input β of a single stage was originally estimated to be 2. This gives the system 10-40-200-1000 MeV. Detailed cost estimates favour the system 10-50-300-1000 MeV (see Appendix VI.2). The reason for this change is that most of the accelerator cost is in the high energy stage and it is economical to reduce its cost at the expense of the other stages. Research requirements prefer 10-50-400-1000 MeV because a beam of the intermediate energy 400 MeV would be more useful than 300 MeV (see section V.A). The cost premium for this appears small but such a system has not been examined in detail.

A two-stage system appears to be impractical and four stages offer little advantage even if the added complexity is not considered.

1.4 Synchronous Phase Angle

Operation so that a synchronous particle crosses the cavity before the RF voltage reaches its peak is necessary for phase focussing (see Appendix VI.3). The bunching force may be increased either by increasing the energy gain per cavity or by increasing the synchronous phase angle ϕ_s . For ϕ_s below 45° the increase in cavity power loss per energy gain due to a change in ϕ_s is less than that due to a change in energy gain which would cause the same increase in bunching force. Provided ϕ_s is less than 45° only ϕ_s should be altered to provide the bunching.

*

For this discussion the coaxial cavity modification³³ will not be considered.

³³ E. D. Hudson, et al., IEEE trans. Nuclear Sci. NS-12 (3) 489 (1965).

A synchronous phase angle of 30° is adequate in all of these respects but it is not clear what the minimum acceptable angle would be.

* These values use the admittances of the final design.

1.7 Minimum Orbit Separation

Orbit spacing is not constant in the SOC but is smallest near injection and extraction. If there were no limitations on the orbit spacing RF costs could be traded for magnet costs and an optimum spacing found. For the available cost estimates this spacing is always unreasonably small so the smallest practical spacing is used.

The magnetic fields can be shaped adequately with a separation of 1.6 beam diameters but 2 diameters are required to allow space for making beam-tube joints with the cavities.

1.8 Pole Tip Size

The pole tips must be wide enough to provide a uniform magnetic field gradient over the diameter of the beam tube. Widths used are:

stage 1	10.13 cm
stage 2	9.07 cm
stage 3	8.00 cm

1.9 Clearance Between Magnets and Cavities

The tightest clearance occurs between the outside of the magnet coil and the RF cavity at turn one of each stage. 20 cm has been set as the minimum to allow cavity wall stiffening and access to joints on the beam tubes.

1.10 Segment and Harmonic Numbers

The number of segments must be odd to allow magnets in adjacent turns to have gradients of opposite signs. (see Section VI. E. 1.15) This arrangement is desirable for minimum turn separation. The harmonic number need not be the same as the number of segments and for each segment number several harmonic numbers give possible designs.

A computer program is available (see Appendix VI.2) which calculates the cost of SOC designs for specified segment and harmonic numbers. The combination which gives the minimum cost is adopted provided it has adequate acceptance and no other undesirable features.

1.11 Cavity Size

The cavity length and width were determined by the cost minimizing program described in Appendix VI.2. The height was determined by the resonance condition

$$\frac{4}{\lambda^2} = \frac{1}{a^2} + \frac{1}{d^2}$$

where λ is the wavelength
 a is the length
 d is the height

1.12 Accelerating Voltage

The accelerating voltage is determined by the condition that the orbit spacing exceed a minimum value.

1.13 Number of Turns

The number of turns was found by having the computer program follow a particle until it reached the required energy.

1.14 Magnet Yoke Size

The magnet yoke dimensions were calculated by the cost minimizing program. Two parameters were considered free for optimization and the others derivable from them. The procedure is discussed in Appendix VI.2.

1.15 Field Gradients

The field index $n = - \frac{dB}{dr} \frac{\rho}{B_0}$ is often quoted rather than the gradient.

$\frac{dB}{dr}$ is the gradient

ρ the radius of curvature in the field B_0

B_0 the central magnetic field.

In an alternating gradient (strong focussing) system, n is greater than one and alternates in sign from magnet to magnet.

The magnet gradient structure chosen was alternating triplets (see Appendix VI.3 1.6). This structure offers some advantage over singlets or doublets^{34, 35} although difficulties from edge effects may arise³⁶. Singlets and doublets remain as alternatives.

The field index was found which gave the largest admittance to the stage (see Appendix VI.3.1.3) and this index was used for the entire stage. A constant index for a range of energy (and so radius of curvature) means a varying gradient and pole tip shape. Since this may make the tips expensive the possibility of simulating a changing gradient by a combination of high and zero gradient components is being investigated (see Section VI. E. 3).

³⁴ R.E. Worsham, IEEE trans. Nuclear Sci. NS-12 (3) 644 (1965).

³⁵ R.E. Worsham, Lens Systems, Transverse Emittance Matching and Effective Magnet Errors, proc. AECL Symp. on Separated Orbit Cyclotrons and Their Uses in Neutron Generation (Chalk River, 1964) 15, (1965).

³⁶ R.S. Lord, private communication, (1965).

2. Accelerating Cavities

2.1 Introduction

The accelerating cavities are rectangular boxes resonant in the TE_{101} mode at 50 MHz. Dimensions have been given in Table VI. B. 3. Power is fed into each cavity through a loop coupled to the magnetic field and the cavity is kept in tune by two tuning devices - a slow tuner for manufacturing variations and slowly varying effects and a fast tuner of smaller range for short period variations. The cavities are very sharply selective, the unloaded Q 's being 9800 for stage 1, 72,600 for stage 2 and 83,500 for stage 3. In the operating mode the electric field in the cavity is parallel to the width and varies semisinusoidal with length and height. The electric field at the centre of the cavity is of the order of one megavolt per metre. Apart from those connected with the tuning and coupling devices problems may arise in the effect of higher modes of oscillation on the beam.

For satisfactory operation of the machine the electric field must be so controlled in amplitude that the standard deviation of all cavity voltages from the ideal is less than 30%, and tilt in the distribution is less than 20% from end to end of the cavity (see Section VI, Appendix VI.3).

A perfectly rectangular cavity with perfectly flat sides and no penetrations can support other spatial modes of oscillation at frequencies given by

$$f = \frac{1}{2} c \left[\left(\frac{\ell}{a} \right)^2 + \left(\frac{m}{b} \right)^2 + \left(\frac{n}{d} \right)^2 \right]^{1/2}$$

where ℓ , m , n are integers and a , b , d are the height, width, and length of the cavity. The TE_{101} mode, corresponding to $\ell = n = 1$ and $m = 0$, is excited by a driving voltage having the appropriate frequency. The driving voltage may also contain harmonics of the resonant frequency. Other modes of the cavity will also be excited by the driving voltage, both by its fundamental and its harmonics. The amplitude of each such excitation depends on the difference between the natural frequency of the mode and the frequency of the exciting voltage, on the Q of the mode, on the amplitude of the exciting voltage and on its coupling with the mode in question. The beam itself will also act as an exciting voltage and, since its harmonic content will certainly be greater than that of the driving voltage, the excitation of unwanted modes by the former will probably be more serious than their excitation by the latter. Such excitations are undesirable both by causing energy losses in the cavity walls and by deflecting the beam.

An actual cavity may be considered as a perturbed form of the ideal rectangular cavity, with a set of modes which is a perturbed form of the ideal set. Perturbations of the cavity which will certainly exist are

a) the coupling loop by which the driving voltage is applied, b) tuning devices, c) beam tubes and vacuum ducts penetrating the cavity walls and d) distortions of walls from the ideal plane rectangles. All these will vary with time: tuning devices will normally be in operation and the coupling loop may be rotatable for power matching. Their effect on the excitation of unwanted modes may be considerable since, the Q 's of all modes being high, a small perturbation of a mode frequency may greatly influence its excitation by any harmonic of the driving voltage or by the beam.

With the tuners mounted in the top wall of the cavity and providing only a small range of adjustment (0.001 slow, 0.0001 fast) there should not be any serious tilt in relation to the tolerance, but it may be necessary from mode shifting considerations to split the tuning function between two or more devices. The effect of the beam tubes should not be serious and will be determined experimentally. Due to the method of construction the walls of the cavity under vacuum will resemble a large number of rectangular panels joined together at the corners, each panel deflected inward by the external atmospheric pressure. The perturbations so produced may or may not have favourable effects on the distribution of spatial modes in the cavity. It is considered better to have the cavities with nominally flat walls and rectangular shape and to tune by separate devices rather than to tune by deforming the cavity walls.

Troubles which it will be impossible to predict in detail by calculations which replace an actual cavity by an ideal, unperturbed cavity are: a) unwanted modes which, in the ideal cavity are not strongly excited by harmonics (including the fundamental) of the driving voltage or by the beam itself may, in the actual cavity, be strongly excited, b) the resulting departure of the actual field distribution from the ideal may be such that the tolerance on tilt is exceeded, c) transverse fields in the actual cavity, resulting from unwanted modes, may be such that the beam is destroyed.

These effects are not yet fully analyzed and their study will be a major part of the RF test cavity programme.

2.2 Construction

Cavity construction is illustrated in Fig. VI.15. The sides are formed from six plates running the full length. Four plates are bent to form longitudinal corners so that a smooth surface is maintained. The two end plates are corner welded. Especial care must be taken with the welds since the available sizes of plates make it impossible to avoid having some welds crossing current paths.

The welded joints on the cavity walls will be copper to copper, the steel being milled back as shown in Fig. VI.15. This method should minimize distortion and allow all welding to be done from outside the cavity. The gas tungsten arc process will be used. The welds will be leak tested with helium.

END PLATE
NOT SHOWN

FIG. VI. 15 Assembly of Cavity Wall.

Each cavity is mounted on a structural girder base of width equal to the cavity - Fig. VI.16. This base has pads on its top and bottom surfaces machined parallel within a close tolerance. Pads on the outside faces of the girder are also machined to provide rigid and accurate connection for the vertical support beams. The initial piece of structure thus formed may be used advantageously as a jiggling fixture for the assembly and welding of the cavity walls. (see Fig. VI.16).

The cavity walls are supported from the I-beam structure by Nelson studs resistance welded to the copper lined plate. Spacers provide a gap of about $\frac{1}{2}$ inch between the cavity walls and the support structure. This type of structure offers the following advantages:

- a) Parts of the supporting structure can be removed to give access to the cavity walls for repair of weld seams.
- b) Separation of beams and plates provides the fabricator with a method of aligning the weld joints and compensating for the flatness tolerance of plate and I-beam.
- c) The cavity walls can be adjusted to nominal flatness and perpendicularity under vacuum, since the walls can be drawn outward to compensate for deflections of the structural supports.

2.3 Cavity Cooling

A small change in temperature causes a small change in the frequency of the wanted mode but, the Q of the cavity being high, this change significantly affects the excitation of the mode by the driving voltage. The cavity walls will be cooled by a closely servo-controlled system maintaining the mean temperature constant to $\pm 0.5^{\circ}\text{C}$. Cooling channels run the full perimeter of the cavity between the vertical support beams. All channels connect to common inlet and outlet headers.

The cooling channels are made as wide as possible to minimize temperature variation over the cavity surface. Centre stud supports are used to reduce the necessary metal thickness. Thin plate can be welded to the outside of the cavity without distorting the walls. Piping and channel cross-sections are varied to obtain flow roughly corresponding to the distribution of heat in the cavity walls.

2.4 Cavity Penetrations

Penetrations through the cavity walls are:

2.4.1 Man-Hole

A man-hole is provided at one end of the cavity for cleaning and inspection. Continuity of current paths across the man-hole is ensured through an RF seal.

FIG. VI. 16 Cavity Base and Vertical Beam Support.

2.4.2 Coupling Loop Connection

The coupling loop assembly on the end of the cavity is held in place by a clamping ring and bolts installed outside the cavity. An RF seal is provided at the inner surface of the cavity wall.

2.4.3 Tuning Assemblies

A fast and a slow tuner are provided for each cavity.

2.4.4 Sensors

Voltage and phase sensors are installed.

2.4.5 Beam Tubes

Stainless steel beam tubes are located along both sides of the horizontal centre line of each cavity. The ends are machined for the installation of slip-on high vacuum type flanges. To ease assembly the tube stubs are $\frac{1}{4}$ inch larger in diameter than the matching beam tubes in the magnet sector.

2.4.6 Vacuum Port

Large stainless steel ducts are located near the bottom of the inside ends of the cavities. Slotted copper screens, to provide good RF conductivity without significant reduction of duct conductance, cover the inner openings.

2.5 Fabrication Tolerances

It is reasonable to expect a constructional accuracy of 2 to 3 millimetres in length and height of the cavity. This corresponds to a frequency variation of $\pm 0.05\%$.

2.6 Choice of Surface

Although consideration of wall losses would indicate that a surface roughness of 2.5 microns RMS should be adequate various considerations of voltage breakdown in vacuum indicate that a better surface than this is desirable³⁷. At present the specification is 0.5 micron RMS with the surface irregularities of small curvature. The surface must be clean metal and abrasives or grinding compounds must not be used for cleaning welds and penetrations. The surfaces must not be plated.

³⁷ W. Watson, Surface Finish for Cavity Resonators, FSD/ING-60 (1966).

2.7 Achieving Accelerating Voltages

The major problems in achieving the necessary cavity voltages are (a) voltage breakdown and (b) multipactoring.

2.7.1 Voltage Breakdown

It is not expected that sparking or voltage breakdown will be a problem once the cavities have been held at the design field gradient for some time. In all stages the gradient is more than an order of magnitude below Kilpatrick's criterion³⁸. There will, however be some problems, particularly in running up for the first time³⁹. One is the local increase of gradient in the vicinity of the edges of the beam tubes, estimated to be 50 % with the beam tube end curved to a 1/8 inch radius. A further possible source of breakdown on initial tests is the pressure in the cavity. Although 10^{-6} mm of Hg is believed adequate (section VI. E. 5) according to some sources⁴⁰ this is just on the limit at which breakdown may be expected to occur with 10^6 volts per metre, approximately the SOC cavity gradient. A third problem is the heavy outgassing which can be expected on first application of RF fields. This may lead to breakdown due to ionized gas molecules³⁹. A further source of electrons which may lead to sparking or breakdown is multipactoring.

2.7.2 Multipactoring

The phenomenon of multipactoring (secondary electron resonance) is a function of the cavity geometry, the frequency, and the electric field. Consider the parallel plate geometry below.

³⁸ W. D. Kilpatrick, A Criterion for Vacuum Sparking, report UCRL-2321 (1953).

³⁹ W. Watson, Voltage Breakdown in SOC Cavities, FSD/ING-54 (1966).

⁴⁰ A. H. W. Beck, (editor), Physical Electronics (Part 1), Handbook of Vacuum Physics (MacMillan) 108 (1965).

If an electron is present at one surface of the gap when the applied voltage is at time phase ϕ and the conditions are such that it is accelerated across the gap in exactly $(2n-1)$ half cycles of the RF voltage and arrives with enough energy to cause secondary emission of electrons from the surface, then the newly emitted electrons will be accelerated back across the cavity. If the secondary emission yield is greater than unity the process will very rapidly build up until limited by available RF power. The result is that the build up of gap voltage is effectively stopped at the multipactoring voltage.

Now in any given case multipactoring will occur only if the energy gained by the electron in transit, V_0 , lies between the limits for the secondary electron yield δ to exceed unity. For copper $200 \text{ eV} < V_0 < 1500 \text{ eV}$. The process is considered in detail in reference⁴¹ and Fig. VI. 17 shows the calculated energy gains for electrons versus phase angle. The possible multipactor regions are shown for each stage. It is known that ETH (Zurich) have had considerable trouble with multipactoring and breakdown in a cavity which should not support stable multipactoring lower than 3rd order or higher than 6th order⁴².

During machine run up the conditions are quite different from those applying in operation. Owing to the high Q of the cavity the field at the centre passes rather slowly through the multipactoring range (the time constant is about 1 millisecond and the time to pass through the range is about 15 microseconds or 1500 half cycles of RF). In all likelihood there will be short bursts of lower order multipactoring and stable higher orders.

Means must be provided either to drive rapidly through this region or to treat the surface so that the secondary emission yield is below unity. A thin layer of titanium prepared by evaporation has been suggested and is being investigated.

These problems will be aggravated during initial commissioning of the cavities because of heavy outgassing on the application of RF fields.

2.8 Excitation and Tuning of Cavities

The devices considered here are (a) the coupling loop (b) a slow speed tuner and (c) a high speed tuner. It must be remembered that the values obtained for such parameters as coupling loop area are only

⁴¹ W. Watson, Multipactoring in SOC Cavities, report FSD/ING-55 (1966).

⁴² A.H. Willax, private communication, (April, 1966).

FIG. VI. 17 Electron Energy Gain in Multipactoring.

approximate, various assumptions being implicit in the development of the basic formulae (e.g. radius of curvature of loop at each point is large compared with radius of conductor⁴³).

2.8.1 Coupling Loop Areas

The cavities will be excited by loops located at the mid-point of the outside end of the cavity and accommodated within the limits of a 9 inch coaxial feed line i.e. one dimension of the loop should not exceed say 17 centimeters. The peak loop voltage is determined from $V_L^2 = 100 P_B / N$ for a 50 ohm line where P_B is the beam power for the stage and N the number of cavities. From the known cavity voltage and dimensions the loop area S_{ab} is calculated (see Appendix VI.7) and Table VI.E.1 gives the results of this calculation. Losses in the cavity, loop and tuning devices is not included.

TABLE VI. E. 1

STAGE	P_B MW	$V_L \times 10^{-3}$	$V_C \times 10^{-3}$	$S_{ab} \text{ m}^2$	Dimensions cm
1	3	5	0.317	0.0058	7.5 x 7
2	20	12.9	1.342	0.029	17 x 17
3	57.4	13.39	1.453	0.036	17 x 21.4

Because efficiency in the RF system is important, care is taken to optimize the loops for the operating conditions. One problem arises from the wide range of powers required between zero current and full power operation. (This is 3.6:1 for stage 1, 9.3:1 for stage 2, and 14.3:1 for stage 3).

The loop area required to keep an impedance of 50 ohm varies as the square root of power demand. It is possible to design fixed coupling loops and arrange the transmission line lengths in such a way that excessive voltages or currents are avoided at, or during run up to, any particular power level. However, there will be some loss of efficiency at levels other than that for which the coupling loop was optimized and this is undesirable for prolonged operation at such levels. It is hoped that the use of rotatable loops and input matching arrangements will keep the loop matched during slow power changes.

⁴³ S. Ramo, et al., Fields and Waves in Communications Electronics, (Wiley), 309 (1965).

2.8.2 Capacitative Loop for Fast Tuning

The fast tuner is located close to the centre of the top surface of the cavity, where the magnetic field is maximum.

The function of this tuner is to maintain the cavity resonant in the presence of fairly rapid environmental changes such as sudden fluctuations in barometric pressure, seismic disturbance, or shock excited panel vibrations of parts of the cavity walls. Such disturbances cover a range from a few seconds per cycle to about 36 cycles per second for panel vibrations⁴⁴. It is necessary to control the resonant frequency to about 1 part in 10^6 and hence undesirable to place too great a range on this fast control. The tuner will give a frequency variation of $\delta\omega/\omega = 0.0001$. For this type of tuner a loop is installed near a maximum of the magnetic field close to the wall of the cavity. The loop is closed through a capacitor. The effect of the tuner is analogous to pulling the frequency of a resonant circuit by coupling to it another circuit resonant at a different frequency.

An approximate theory is developed in Appendix VI.7 and Table VI.E.2 gives a set of parameters calculated on the basis of coaxial capacitors.

TABLE VI.E.2

STAGE	AREA S m^2	COAX I.D. m	COAX O.D. m	COAX L m	COAX GRADIENT $\text{V/m} \times 10^{-6}$
1	0.0094	0.19	0.20	0.05	2.41
2	0.0135	0.29	0.30	0.03	4.11
3	0.0115	0.29	0.30	0.05	4.52

⁴⁴

H. Underhill, private communication (April, 1966).

Diagrammatically the loop is

A tuner such as this has been tried successfully at ETH (Zurich) on a 1:5 scale model of a cavity somewhat similar to the SOC cavities⁴⁵. It used a parallel plate capacitor, but a coaxial design should be better mechanically and electrically.

2.8.3 Slow Post-Tuner

Slow-Tuning is achieved by a cylindrical metal post located close to the centre of the top surface of the cavity, where the magnetic field is greatest.

The cylindrical metallic post tuner is required for slow changes, such as long period barometric pressure variations and starting the machine from cold, and also to cover cavity to cavity variations in manufacture and possible effects of wall distortions.

⁴⁵ P. Lanz and U. Schryber, Aufbau des 1:5 Kavität-Modells II mit Leistungsstufe und daran ausgeführte Messungen, Eidg. Technischen Hochschule Internal Report, (December, 1963).

Diagrammatically the tuning post is

Environmental changes can be allowed for⁴⁶ with $\delta\omega/\omega = \pm 5 \times 10^{-5}$, but the unknown effects of wall distortions make it desirable to have a greater range. At the moment the value chosen is twice the value corresponding to manufacturing tolerances (0.05 %) or $\delta\omega/\omega = 0.001$.

Such a tuner has been examined experimentally over a tuning range of 3%⁴⁷ and proved satisfactory. An approximate theory for the post tuner is given in Appendix VI.7 and Table VI.E.3 shows the dimensions calculated for the SOC.

TABLE VI.E.3

STAGE	RADIUS m	PENETRATION m
1	0.10	0.135
2	0.20	0.139
3	0.25	0.130

⁴⁶ G.E. Lee-Whiting, private communication (February, 1966)

⁴⁷ J.R. Macdonald, Rev. Sci. Instr. 26, 433 (1955).

2.9 Sensors for Cavity Control

Three quantities require to be controlled for each cavity, namely (a) tuning, (b) electric field, and (c) phase of cavity voltage with respect to an external reference. Little work has been done on the development of sensors for these control functions. Tuning will most likely be determined by measurement of reverse power at the fundamental frequency from the coupling loop. The development of a two loop reflectometer will allow the determination of both amplitude and sense of the reactive component, which is the input information needed by the servo loop. The electric field will be measured directly either by measuring the torque on an ellipsoid or the coulomb force on a surface normal to the field. The latter method has been used on a cavity at ETH (Zurich)⁴⁵ and is proposed here. The force exerted on a surface area S by an alternating field $E_0 \sin \omega t$ is given by $F = \epsilon E_0^2 S/4$. In this machine with fields about 10^6 volts/metre the force will be about 0.22 grams per square centimetre. This sensor then consists of a small diaphragm replacing part of the cavity wall on the horizontal centre line. The deflection of the membrane by the coulomb force is converted by a transducer into a voltage which is compared with an external reference. The comparator output is the error signal input to the level servo-loop. Problems are foreseen in the development of the transducer, due to the high nuclear radiation fields which will be present near the cavity. Phase will probably be monitored by a loop coupled to the magnetic field.

2.10 Full Scale Experimental Cavity

In the preceding subsections references have been made to problems which either cannot be resolved by theoretical studies or which require development work before engineering design can begin. To resolve those problems a full scale test cavity is to be built and a 400 kilowatt RF generator provided to drive it. This work will be done at 40.68 MHz which is an ISM frequency. The prime areas of experimental work will be:

- a) obtaining and maintaining the cavity voltage. This includes the problems of sparking, voltage breakdown and multipactoring. The test cavity will be provided with three observation windows for viewing or camera work. Part of the work on multipactoring will be the determination of the necessary rate of rise of voltage and examination of the need to pulse the RF generator in order to drive through the multipactoring region.
- b) coupling loop studies, including matching for a given power level, maximizing efficiency, mechanical design and variable power operation. This latter test will determine whether loop rotation, variable area or multiple loops is the optimum approach.
- c) tuning devices.

- d) field, phase and tuning sensor development.
- e) mode distribution and the effect on it of various perturbations.
- f) vacuum requirements and outgassing.

3. Magnetic System

3.1 Magnetic Field Requirements

3.1.1 General

Because the magnetic field is steady, the machine magnets are powered by DC. There are no eddy-current losses and solid iron sections can be used for the magnetic flux paths. Layouts showing the general arrangement of the magnet sectors of stages 1 and 2 are shown in Fig. VI.18, 19 and 20. The pole tips in these figures are discussed later.

3.1.2 Flux Density Requirements

The radius ρ of a proton travelling perpendicularly to a magnetic field is given as a function of energy E and flux density B in the following table.

TABLE VI. E. 4

E (MeV)	10	50	300	400	1000
$B\rho$ (kG-cm)	458.2	1035.3	2695.4	3183.1	5657.3
ρ (cm) at 7.5 kG	61.1	138	359.4	424.5	754.3

A value of mean flux density of 7.5 kG has been chosen for all stages of the machine as reasonable when the field shaping requirements for focussing are taken into account. The values of ρ , the proton path radius at this value of flux density, are also shown in Table VI. E. 4.

To focus the proton beam magnetic field gradients of alternating sign are required⁴⁸. By having an odd number of sectors, as in all these machine designs, the flux gradients alternate in sign radially, as shown in the sections on Figs. VI. 18 and 20.

⁴⁸ E. D. Courant and H. S. Snyder, Annals of Physics, 3, 1-48 (1958).

FIG. VI. 18 Stage 1, SOC Sector Magnet.

FIG. VI. 19 Stage 2, SOC Sector Magnet (Plan).

SECTION "A.A."
of Fig. VI-18

of fig. VI-18

WIMS 1/4" x 1/8"

POLE TIP DETAIL

FIG. VI. 20 Stage 2, SOC Sector Magnet (Section).

The flux gradient required for focussing is related to the field index, n , which also determines the machine's admittance. The field index is defined by

$$n = - (dB/Bo) / (dr/\rho) \quad (\text{see Section VI.E 1.15})$$

and has the values 10, 11 and 80 for the stage 1, 2 and 3 SOC's. These indices determine the values, given in Table VI.E.5, of the flux gradient at injection to the three stages.

TABLE VI.E.5

SOC stage	1	2	3
n	10	11	80
ρ min (cm)	61.1	138	359.4
$\frac{dB}{dr}$ (kG cm)	1.227	0.598	1.7

In our SOC concept the multiple pole tip arrangement shown in Fig. VI.21 is used.

FIG. VI. 21 Multiple Pole Tip Arrangement.

This combination, within each sector, of zero-gradient sections with non-zero gradient sections allows the effective field index to be kept constant by varying the effective value of the flux gradient. The same pole tip profiles, producing fixed values of flux gradient, can then be used throughout a stage.

3.1.3 Tolerances

The necessity of keeping the beam spill low and avoiding coupling of horizontal and vertical oscillations of the beam sets close tolerances on the magnitude and position of the magnetic field. A further treatment is given in Appendix VI.3, where Table VI.10 gives pertinent values. Table VI.E.6 gives the tolerances in inch units-inches:

TABLE VI.E.6

Linear Displacement	Allowable Standard Deviation		Allowable Max. error
	$\pm \sigma$		$\pm 3 \sigma$
	inches		inches
Pole tip subunits	- radial	0.002	0.006
	axial	0.002	0.005
Pole tip assemblies	- radial	0.012	0.036
	axial	0.016	0.047
	tangential	0.035	0.106
Magnet yoke segments	- radial	0.020	0.059
	axial	0.039	0.118
	tangential	0.059	0.177
Rotation about axis	Allowable Standard Deviation		Allowable Max. error
	$\pm \sigma$		$\pm 3 \sigma$
	radians		minutes
Pole tip subunits	- tangential	0.0002	42
			2.1
Pole tip assemblies	- radial	0.002	420
	axial	0.0015	310
	tangential	0.0003	62
Magnet yoke sectors	- radial	0.002	420
	axial	0.0008	170
	tangential	0.0001	21

3.1.4 Singlets, Doublets, Triplets

Following Worsham³⁵, only triplets have been studied until recently. However, at the radial inner ends of the sectors the triplet sections are too short to establish the required field properly (see Fig. VI.18). The pole tips are 3" long, and the end effect is $2.4 \times 2" = 4.8"$.

Doublets (+ - followed by - +) or singlets (gradients of alternate signs in successive sectors) have also been considered. A preliminary study suggests that lower field gradients, greater admittance and easier tolerances may result. Table VI.12, App. VI.3 lists comparative machine characteristics estimated for singlets, doublets and triplets.

3.2 Pole Tip Design

3.2.1 General

The shaped magnetic fields described in section 3.1.2 are produced by shaping the pole pieces of the magnet. The zero gradient section could be produced by two wide parallel pole surfaces. Where, however, the required width of the uniform field is comparable to the gap between the pole tips it becomes necessary to shape the pole tips, reducing the gap at the sides, to compensate for the leakage or fringing field. Similarly, two planes at a small angle to each other will provide a gradient in the magnetic field, and it appears that such an arrangement can be used to provide the gradient of about 0.6 kG/cm which is required by stage 2 of this design. But for higher gradients an arrangement of essentially hyperbolic pole surfaces is required in order to maintain a linear gradient. Since the flux density B_y is inversely proportional to the pole tip separation y , and the equation of the surfaces is $xy = \text{constant}$, the gradient $\frac{dB_y}{dx}$ is also a constant. This is the basis for the pole tip shapes which are used in quadrupole focussing magnets for ion beam transport^{48a}. Unfortunately modifications to this ideal hyperbolic shape are necessary when, as in this case, only one-half of the quadrupole is present. To determine the pole tip shapes necessary we have used conducting paper analogue techniques, experimental models and computer programmes which are specifically designed for such magnet problems. These are described in subsequent sections.

3.2.2 Conducting Paper Analogue

FSD/ING-52⁴⁹ describes the use of a conducting paper analogue for determining field gradients and beam tube size of the first reference design in AECL-2177³. The same technique has been used for the present design

^{48a} A. Septier, Electronics and Electron Physics, XIV, 85 (1961).

⁴⁹ A. Harvey, Determination of SOC Magnet Pole Tip Shapes by Conducting Paper Analogue, report FSD/ING-52 (1966).

and some of the results are shown in Figs. VI.22 and VI.23. Compensation for the varying orbit separation has still to be studied.

3.2.3 Model Magnet Studies

An experimental magnet has been constructed, full scale for the middle of a sector of the third stage. It has been used to determine experimentally the flux density distribution produced by pole tip shapes derived from the conducting paper analogue studies. The measuring system used was a Hall probe. Some of the results are given in reference⁴⁹.

This magnet has been used for a preliminary survey of the linearity of the field gradients obtained, of end effects, and of the vertical component of the magnetic field on the median plane. Results show that linearity of $\pm 1/2\%$ can be achieved and end effect, with gradients of 3.75 kG/cm, between two adjacent sections of opposite gradients is $2.4 \times$ beam tube diameter. For a zero gradient pole, the extrapolated length (beyond mechanical end of the pole tip) = $2 \frac{1}{4} \times$ beam tube diameter. The accuracy of construction of the magnet and the Hall probe positioning system were not adequate to provide meaningful answers on the verticality of the field. To provide information on the tolerances, it will be necessary to construct full scale model magnets using machining and alignment techniques such as will be required for the SOC machine magnets, and greatly improved measuring facilities. Typically the radial and axial positioning accuracies must be of the order of $\pm 1/10,000$ inch and the rotational accuracy of the probe positioning boom 4 seconds of arc. The sensitivity to a horizontal flux component has to be 0.6 of a gauss in a vertical field of 7.5 kG.

3.2.4 Computer Studies

In parallel with the experimental programme, a computer programme is being prepared to assist in pole tip design and examine the effect of such factors as the tolerances of manufacture on the resulting field distribution. The programme will be initially two-dimensional but capable of being extended to three dimensions. Figure VI.24 shows a plot derived from TRIM⁵⁰ for our pole tip design which gives 3.75 kG/cm flux gradient.

⁵⁰ J.S. Colonias and J.H. Dorst, Magnet Design Applications of the Magnetostatic Program called TRIM, proc. Intl. Symp. Magnet Technology (Stanford University) 188 (1965).

FIG. VI. 22 Stage 2, SOC Pole Tips & Field Distribution.

FIG. VI. 23 Stage 3 SOC Pole Tips & Field Distribution by Conducting Paper Analogue

FIG. VI. 24 Flux Plot by "Trim".

3.3 Yoke Design and Assembly

3.3.1 Yoke

Figures VI. 18, 19 and 20 illustrate stage 1 and 2 sector-magnets schematically. Stage 3 magnets are similar to stage 2. The pole-stems, carrying the shaped poles, are mounted on massive upper and lower yokes. Yokes at the inner and outer radial ends of the sector complete the flux return path. This yoke type is referred to as the end-yoke, or Hudson-Lord, magnet. An alternative design of yoke takes the flux from each pole pair to the sides of the sector where it is returned in a yoke set between the pole tips and the adjacent cavities. This magnet design, the side-yoke, or "picture-frame" magnet, is treated further in Appendix VI. 6.

It has been decided that the reluctance of the yoke circuit shall not exceed 25% of the total reluctance of the magnetic circuit. So that variations in steel permeability do not have an uncontrollable effect on the flux density.

The large amounts - 8,000 tons for the three stages - and large sections of steel required for the end yoke design will involve manufacturing and handling difficulties.

It is necessary to compensate for the varying reluctance of the path lengths from the middle of the sector to the ends. This is accomplished by means of a variable shim or air gap between the pole stem and the yoke. This may be also regarded as a Purcell filter⁵¹, which will help in homogenizing the flux density through the pole tip.

3.4 SOC Magnet Support

Each magnet support structure must be sufficiently rigid and stable, in itself and with respect to every other magnet support in a SOC stage, to maintain machine alignment tolerances as described in Appendix VI. 3. The individual tolerances pertinent to the support structure for a magnet sector are given in Table VI. E. 7.

The tightest tolerance on magnet yoke positioning is radial displacement.

⁵¹ E. M. Purcell, U. S. Patent 2, 962, 636.

TABLE VI. E. 7

Type of Error	Standard deviation σ	3σ limits	Yoke displacement inches σ	Resulting direction of beam displacement
Yoke sector displacement with respect to any other sector				
1. Radial displacement	0.02 in	0.059 in		radial
2. Axial displacement	0.04 in	0.118 in		axial (vertical)
3. Tangential displacement	0.15 in	0.177 in		radial
Yoke sector rotation about a specified axis				
1. Radial rotation	0.002 rad	0.006 rad	0.08 on width	axial (vertical)
2. Axial rotation	0.0008 rad	0.0024 rad	0.21 on length	radial
3. Tangential rotation	0.0001 rad	0.0003 rad	0.28 on length	axial (vertical)

The magnet yoke rotational tolerances can best be appreciated by converting the angle of rotation to linear displacement of the magnet yoke edges. As indicated by Table VI.E.7, the tightest tolerance would involve maintaining all yokes within 3σ limits of 0.084 inches ($\sigma \approx 0.028$ inches), this measurement being the difference in yoke elevation between the inner orbit and outer orbit with respect to any other yoke. The above tolerances have been assigned by assuming all other errors are zero.

To isolate effects of earth tremor, foundation creep and shrinkage a floating ring is used to support the magnets and cavities as shown in Figs. VI.7 and 8. The ring floats on a spring system which provides nearly uniform support to prevent ring warpage or distortion. Tilting or elevation change of the entire ring could be tolerated within the limits of acceptance of the beam transport magnets leading from the SOC.

Thermal effects on the magnet support foundation are summarized in Table VI.E.8 for the third stage SOC. Allowable temperature gradients have been estimated to maintain alignment tolerances.

TABLE VI. E. 8

Foundation Temperature Effect	Resulting Magnet Displacement inches/ $^{\circ}$ F	SOC Tolerance Allowable Temperature Change-Standard Deviation σ
1. Uniform temperature increase or decrease of foundation ring	SOC diameter change of 0.007 inch/ $^{\circ}$ F	This is a uniform change that does not disturb the proton beam appreciably
2. Temperature difference between magnet sectors	Causes a radial displacement of pole tip units 0.0007 inch/ $^{\circ}$ F (max)	Assuming random ΔT between sectors $\sigma \approx 17^{\circ}$ F
3. Temperature difference between magnet sectors	Causes vertical displacement of magnet sectors. Order of 0.0006 inch/ $^{\circ}$ F	Assuming random ΔT between sectors $\sigma \approx 65^{\circ}$ F
4. Radial temperature difference along a magnet sector	Causes a tangential rotation of the magnet yokes (vertical tipping) order of 0.0006 inch/ $^{\circ}$ F	Assuming random ΔT between sectors $\sigma \approx 45^{\circ}$ F

There does not appear to be any necessity for critical temperature control of the foundation. The most important thermal effects are caused by temperature differences between magnet sectors, but this foundation tolerance will most likely be overridden by yoke operating temperature limits required to maintain the internal sector magnet flux density tolerances.

3.5 Alignment

The present concept is to have the magnet pole tips for a complete sector made as a subassembly, which can be magnetically mapped in the magnet test area, and provided with alignment targets which are then used to position the tips in the machine. Screw adjustment of the position of this subassembly may be adequate but it is possible that a further study of the problems of maintaining the accurate alignment of the magnetic field may show a live servo-controlled positioning system to be necessary.

Because the limiting accuracy is in the ability to measure a distance or angle rather than to position a part to that measurement, the errors are normally distributed with a standard deviation $\pm \sigma$ and maximum error of $\pm 3\sigma$. Consequently, 68.3% of all magnet components must be positioned within the σ limits, while 31.7% may be between σ and 3σ limits. The errors given in Table VI.E.6 are each for one condition only, with all other conditions assumed exact.

Within the operating life of the machines, facilities must be provided to detect, correct or compensate any misalignment due to differential settlement, earthquakes or other causes.

Each stage does not have a single centre from which to make radial measurements. Instead the radial centre line of each accelerating cavity and magnet sector intersects the machine's X or Y axis at a different point. This irregular layout, together with the difficulty of aligning, or possibly remotely aligning, magnet components hemmed in between two much higher accelerating cavities, results in a difficult alignment problem.

To accommodate this multi-centred cyclotron layout a five to ten foot long X and Y axis tooling bar, equipped with a movable theodolite and optical center, is located at the cyclotron's hub. Concrete columns to bedrock provide sufficient stability for this movable center and its reference points, while openings in the building structure permit sighting to the machine components. Together with a telescope to read one end of an optical tooling tape, this equipment is expected to locate all radial center-lines to their required azimuth within one second of arc and all radial distances to within 0.010 inch.

Magnet pole tip subunits are assembled and checked within 0.001" on a surface table equipped with optical instruments and a digital micrometer. These subunits are then shop positioned with small screw jacks on the bottom half of their magnet yoke, using arbitrary X and Y axis optical tooling bars set six feet from the yoke. A separate optical tooling level and electronic levelling instrument provide alignment in the horizontal plane. After the sector pole tips are completely shop assembled, tested magnetically and pole tip assemblies adjusted as required, the radial centreline is referenced on the outside of the assembly.

A four wheeled gantry, equipped with tooling bars, transits and scales, spanning the cyclotron ring above the cavities, is moved to any position around the ring. When located in azimuth by the centre theodolite and radially by tape, this gantry provides the location of the magnet sector and all its pole tip assemblies from a single set up. Although it may not be essential for initial installation of the magnets, it will prove useful for final or subsequent in-place alignment of pole tip assemblies. In addition, this alignment gantry or beam provides the means to check components optically by remote control, should the need arise.

Accelerator cavity alignment is easily achieved with the same equipment since the allowable errors are much greater than for the magnet sectors, namely, beam holes 0.197 inch, radial and tangential position in the ring 0.79 inch, and axial position 1.97 inches.

Regular checking, both optical and electronic, will indicate any movements of magnet sectors or accelerating cavities during normal operation. The size and frequency of such movements, are almost impossible to predict, but undoubtedly depend on foundation conditions. For example, radial displacements of the magnets of up to 0.12" at CERN⁵², built on limestone, forced re-alignment after four years of operation; settlement of 0.016" was expected at BNL⁵³, built on glacial moraine, in the first six months after the magnets were installed; whereas the ZGS accelerator, supported on columns to bedrock settled only 0.002" on one side. Founded on vibration dampeners and concrete columns to bedrock, the SOC stages are expected to remain in alignment for many years.

3.6 Permeability

A factor of considerable concern in the design of both yokes and pole pieces is the permeability of the iron or steel used and its homogeneity. The variation of permeability with temperature determines the temperature stability required of the machine room.

⁵² J. Gervaise, A High-Precision Device for Length Measurements, CERN 64-39, (1964).

⁵³ O.S. Reading, Precise Survey of the 25 BeV Synchrotron at Brookhaven National Laboratory, BNL 4082 (1959).

The reference design is based on unannealed SAE 1010 steel, the most readily available suitable steel. Considerable savings will be possible with higher permeability steel.

To achieve maximum permeability, low carbon steel is desirable. There should be no difficulty in achieving carbon contents as low as 0.06% in the large ingots required. Annealing at temperatures up to 1500°F also produces a large improvement in permeability. Figure VI.25 shows typical values for steel with a nominal carbon content of 0.1%. If annealed SAE 1010 steel is used, the yoke steel requirement is reduced by 6 or 7%.

3.7 Coil and Power Supplies

3.7.1 Coil

The basic coil design to produce the ampere turns required to energize the magnets is provided by the optimization programme SEEKSOC (see Appendix VI.2), assuming a copper coil, with water cooling and a packing factor of 0.5. The principal problem with this coil is the high nuclear radiation field in which it must operate, estimated to be about 100 R/hr (see Section VI.1.3). It is proposed to use as the insulator aluminum in the form of thin strips anodized on both sides. between adjacent flat strips of copper in the winding. Ground insulation will be by means of flat blocks of aluminum oxide firmly clamped so that they are in compression at all times. A cross-section of the coil construction is shown in Fig. VI.26. The water cooling passages provided are separate from the conductor. Having these at the outside of the coil will help protect the magnet steel from temperature changes due to the coil. It would also be possible to use aluminum strip as the coil conductor, and this becomes more attractive as the copper market becomes more difficult. It would, however, still be desirable to use thin strip as the insulator rather than anodization of the conductor itself since its lower radius of gyration makes cracking of the insulation on the outside radius of a bend less of a problem.

A radical alternative to this coil construction is offered by superconductors, which require no running power in order to energize them⁵⁴. An economic assessment of their usefulness is underway, but a demonstration of the practicability of superinsulation to contain the liquid helium surrounding the superconductor and of a practical flux pump⁵⁴ to generate the required magnetic flux, will be necessary.

⁵⁴ H. Van Beelen, et al., Physica 31, 413 (1965).

FIG. VI. 25 SAE 10-10 - Steel Permeability.

STAGE 3 3.94" WIDE x 3.68" DEEP 37,900 AMPÈRE TURNS

18 CONDUCTORS $0.125'' \times 3.5'' = 0.44 \text{ in.}^2$

1,110 A/CONDUCTOR, i.e. 2520 A/in.^2

FIG. VI. 26 Sector Magnet Coil Cross-Section.

3.7.2 Power Supplies

Silicon controlled rectifier power supplies are the most probable choice for supplying the magnet DC power. Alternatives are transformer regulated silicon diode bridges, which are comparable in cost for unit sizes exceeding 300 kW, and motor generator sets, which, because of lower efficiency and higher capital costs, are being superseded by the solid state devices.

The capital cost of silicon controlled rectifier supplies does not vary appreciably with unit size⁵⁵ and should not exceed 20¢/watt, the value used in SEEKSOC. The choice of voltage and current is important and should be considered in the design of the magnet windings since the use of a low voltage and high current, i.e. one or two turns/coil, is more expensive than that of a medium voltage and medium current.

The unit size will be dictated by the location of magnets. Sector magnets could be grouped and fed from large common supplies, with the addition of current trimming controls to each sector magnet. One arrangement is shown in Table VI. E. 9

TABLE VI. E. 9

Stage	No. Magnets	Magnet Power kW	Power Supply	Magnets/ Power Supply
1	13	328 Total	1 at 350 kW	13
2	13	619 Total	2 at 350 kW	6 & 7
3	33	1268 Total	4 at 350 kW	8 & 9
		2, 215 kW Total		

Beam transport magnets, which will be spaced out along the beam path, will probably be fed from individual units. The choice of common or individual DC power supplies will depend on performance and economics not yet worked out.

Regulation of 0.01% is achieved in present commercial designs. A current feed-back loop is supplied to compensate for changes in load due to magnet coil heating and feed-forward loops are used to counteract supply voltage changes.

⁵⁵ A. Otter, private communication (April 4, 1966).

3.7.3 Magnet Regulation

Controlling the exciting current in the magnet coils does not in itself guarantee repeatable control over the magnetic flux density, since this is also affected by the rate of increase and decrease of current⁵⁶. A standard nuclear magnetic resonance probe, or rotating coil gaussmeter which has been calibrated by NMR, will be used to check the field. Once the field is established the current regulation of 0.01% is adequate to maintain it. The gaussmeter will be movable, to enable it to serve several sectors and to protect it from the radiation field during operation.

⁵⁶ C.A. Harris and J.K. Cobb, Establishing the Magnetic Field of a Solid Pole Magnet to Within $\pm 0.01\%$ Proc. Intl. Symp. Magnet Technology (Stanford University) 823 (1965).

4. Injection and Extraction

The transport system must meet several requirements. First a reasonable path must be found for the central path. Next the system must be made achromatic. Finally the emittance ellipse must be in the required orientation (see Appendix VI.3). The bending magnets must not disturb adjacent orbits in the SOC.

Two achromatic injector systems have been considered but no mechanical analysis has been done for either. Injection system No. 1 (see Fig. VI.27) deflects the beam by 180° and has been assumed in the general layout drawings for stages 2 and 3. The injection path indicated in the drawings for stage 1 (Fig. VI.4) demands a horizontal deflection of 90° and a vertical shift. An achromatic system to do this has not been considered.

System No. 2 (see Fig. VI.28) deflects the beam only enough to clear the accelerating cavity. The requirement that the injector be achromatic is achieved by a pair of quadrupoles placed symmetrically between the two bending magnets. Simultaneous focusing in both planes is obtained by adding a third quadrupole of the opposite polarity in the central drift space.

With the injector chosen the SOC emittance requirement may be transferred to an emittance requirement at the injector entrance. The match is done in the straight portion.

The injection system has not been settled but system No. 2 appears more attractive. Specifications for possible systems are given in Table VI. E.10.

Extraction could be done in a manner similar to injection for the first two stages but is less attractive for the third stage. The magnetic rigidity of the protons increases from input to output in all stages, but in stages 1 and 2 the space available for the deflecting magnet increases as well so the field required is not excessive. In stage 3 the field free gap increases from 228 cm at input to only 255 cm at output while the rigidity doubles.

Tangential extraction can be done in all stages by omitting the bending magnets and allowing the beam to continue in a straight line from its last cavity traversal. This scheme has been accepted for all three stages. One magnet yoke and at least one cavity will be intercepted by the emerging beam and a path must be provided through them. Extraction need not be done in the cavity free section used for injection, so this section is available for instrumentation or future development.

FIG. VI. 27 Injection System No. 1.

FIG. VI. 28 Injection System No. 2.

TABLE VI. E.10
INJECTION SYSTEMS (see Fig. VI. 27, 28)

	Stage 1	Stage 2	Stage 3
Deflecting magnet No. 1			
Field (kgauss)	10	10.4	15
Deflection	80°	45°	45°
Arc length (cm)	64	78	141
Drift space (cm)	110	66	137
Quadrupole No. 1			
Gradient (kgauss/cm)	2	2	2
Length (cm)	7	13	25
Drift space (cm)	36.4	56	54
Quadrupole No. 2			
Gradient (kgauss/cm)	2	2	2
Length (cm)	6.7	11	25
Drift space (cm)	36.4	56	54
Quadrupole No. 3			
Gradient (kgauss/cm)	2	2	2
Length (cm)	7	13	25
Drift space (cm)	110	66	137
Deflecting Magnet No. 2			
Field (kgauss)	10	10.4	15
Deflection	80°	45°	45°
Length (cm)	64	78	141

The straight portions of the interstage transport systems have quadrupoles to contain the beam and provide emittance matching.

5. Vacuum

The vacuum required in the accelerator is primarily determined by that required to prevent electrical breakdown in the cavities⁵⁷. As a design criterion a vacuum of 10^{-6} torr has been used.

The effect of a residual gas pressure at 10^{-6} torr on activation of the machine due to beam scattering (discussed in Section VI. I.1) is not important.

To meet the requirement conservatively, the system is designed for pressures of 8×10^{-7} torr in each RF cavity. This is achievable with commercially available components without baking.

The volumes and surface areas for each stage are given in Table VI. E. 11.

TABLE VI. E. 11

SOC VACUUM PARAMETERS

Unit	Volume Litres	Surface Area of OFHC Copper cm^2	Surface Area of Stainless Steel cm^2
Stage 1	5.64×10^4	4.86×10^6	0.72×10^6
Stage 2	3.648×10^5	9.54×10^6	1.56×10^6
Stage 3	1.28×10^6	27.328×10^6	4.16×10^6
TOTAL	1.7012×10^6	41.728×10^6	6.44×10^6

Each stage of the SOC is a large vacuum chamber consisting of a number of accelerating cavities linked in series by a number of beam tubes of relatively low conductance. Several hundred vacuum tight mechanical joints have to be made to link all these units into one common chamber. A means of isolating each cavity for the purpose of tracing leakage will not be used because the molecular conductance of the beam tube between cavities is sufficiently low that any leak in the system would influence most the pressure in the nearest cavity.

Entry into the SOC rooms will probably not be possible during operation nor, for the second and third stage SOC rooms, immediately following a shutdown. It is important that the vacuum system

⁵⁷ S. R. Conviser, IEEE trans. Nuclear Sci. NS-12 (3), 699 (1965).

operate with minimum shutdowns for maintenance. For this reason the vacuum pumps are located, outside the high radiation areas, in the inner circular rooms of Stages 2 and 3 SOC buildings as illustrated in Figure VI. 29. The radiation fields in Stage 1 SOC will be considerably lower and its pumps are located close to the cavities.

5.1 Selection of High Vacuum Pumps

To assure clean surfaces in the high electric field regions sputter-ion pumps are used to evacuate the accelerating structures. Pumps, such as diffusion pumps, which may contribute to backstreaming of organic vapours are avoided. The experience of accelerator groups^{58, 59} is that such vapours, when condensed on high gradient surfaces, tend to lower the breakdown voltage and/or contribute to multipactoring type discharges at relatively low RF gradients. Also, because a contaminated cavity would be extremely difficult to enter and clean due to high levels of radioactivity, the ion pump is the logical choice.

Other advantages of the ion pumps are:

- a) They require no maintenance over extended periods.
- b) They do not require baffles or traps which add impedance to the system.
- c) The pump current depends on gas density and therefore pressure can be read from a calibrated current meter.
- d) The system remains under vacuum in the case of power failure.
- e) They have no moving parts, are silent and vibration free.
- f) Accidental let up to air does not damage the pumps.

A high vacuum unit is necessary for each RF cavity because of the relatively low molecular conductance of the beam tubes between cavities.

5.2 Capacity of High Vacuum Pumps

The capacity required of the high vacuum pump is entirely dependent on the following:

- a) the outgassing rate of the chamber walls,
- b) the pump down time,
- c) the air leakage into the system.

⁵⁸ B. Austen, et al., The Design of Proton Linear Accelerators for Energies up to 200 MeV, report MURA-713 (1965).

⁵⁹ L.C. Teng, 200 MeV Injector Project for the Zero Gradient Synchrotron, ANL Document, April, (1965).

FIG. VI. 29 Arrangement of Cavity and High Vacuum Pumps.

The outgassing rate of the chamber walls is dependent on the smoothness and cleanliness of their surfaces. The lowest outgassing rate from a surface is obtained when it has been highly polished, ultrasonically cleaned and baked for several hours at about 400°C under vacuum. This is not practical, so the walls will be cleaned and baking will be confined to pumping low pressure steam through the cooling channels. Cleaning methods have not yet been determined and will depend on the surface finish necessary (see section VI. E. 2. 6).

A test model cavity was constructed and pumped down to vacuum to obtain the outgassing rate of OFHC copper (see Figure VI. 30). The copper surface was polished to a 25 microinch finish and chemically cleaned. It is not anticipated that these rates will be improved appreciably but the RF current will probably speed-up outgassing of the surfaces.

Figure VI. 31 indicates the pumping speeds required (based on Fig. VI. 30) for each of the largest RF cavities for a range of pump down times. The cost of the vacuum system is largely determined by the specified rate of pump down.

High pumping speeds are necessary only for the first 100 hours of pumping. A Titanium Sublimation Pump to supplement the ion pumps is used during the pump down cycles from 1×10^{-3} torr to 8×10^{-7} torr. This pump is a cheap means of removing getterable gases in a system. The pumping speed of the sublimator for each cavity pump header ranges between 1500 and 5000 l s^{-1} , depending on the temperature of the condensing coil on which the titanium is collected. The condensing coil will be cooled by liquid nitrogen so that the pumping speed is close to 5000 l s^{-1} .

The titanium filaments in the sublimator have a total operating life of about 24 hours but, being used only intermittently, they should serve for long periods. An isolation valve is necessary between the pump and the header to enable renewal of filaments.

It is inevitable that air leaks will exist which cannot be traced. Allowance for this is included in the required pumping speed of the ion pumps. The quantity of leakage is based on the assumption that leak rates greater than $5 \times 10^{-6} \text{ cm}^3 \text{ s}^{-1}$ of atmospheric air will be readily traced and repaired. There are about 100 mechanical joints in each cavity. Assuming each leaks at a rate of $5 \times 10^{-6} \text{ cm}^3 \text{ s}^{-1}$ a constant pumping speed of 400 l s^{-1} will be required at operating pressure.

FIG. VI. 30 Outgassing Rate of OFHC Copper (non-baked, chemically cleaned, surface finish 25 micro-inches).

FIG. VI. 31 High Vacuum Pump Speed for each RF Cavity to reach 8×10^{-7} torr.

Considering a high-vacuum pump-down time of 5 hours, the resistances of the pump throat, the ducting and the RF screen in the cavity wall, it is calculated⁶⁰ that two 1200 l s^{-1} ion pumps are required for each RF cavity in Stage 2 and Stage 3 SOC's.

When the outgassing rate of the cavity walls has reached 2×10^{-10} torr litres per second per square centimetre, the operating pressure in each cavity could be maintained by one 1200 l s^{-1} ion pump.

Similarly two 500 l s^{-1} ion pumps and one Titanium Sublimation Pump 5000 l s^{-1} are required for each cavity in Stage 1 SOC.

5.3 Roughing System

The type and capacity of the roughing pumps are based on reaching a pressure of better than 10^{-3} torr in about 5 hours. A two stage mechanical booster pump of 1600 cfm free air displacement backed by a single stage rotary piston pump of 500 cfm will pump down 4 accelerating cavities to this condition.

Regardless of the capacity of the pump the maximum number of cavities which can be pumped by one unit to the minimum pressure requirements is governed by the conductance of the beam tubes between the cavities. A booster pump unit will be connected to every fourth high vacuum pump header.

To prevent oil vapours backstreaming from the pumps into the cavities a cold trap is installed between the backing pump and booster pump and likewise a molecular sieve between the booster pump and the pump header. The molecular sieve will remain at room temperature until a pressure of about 10^{-3} torr is reached. At this stage the sieve will be cooled by liquid nitrogen to induce cryogenic pumping of condensable vapours and thus further reduce the pressure.

A high vacuum valve between the molecular sieve and the pump header is necessary to isolate the complete roughing unit from the system after the ion pumps are started. A 6" diameter all metal valve will be used in preference to an organic sealed valve to avoid loading the ion pumps with a considerable and continuing amount of additional gas.

⁶⁰ S.B. Hodge and K.H. Griffiths, Measurement of the Outgassing Rate of Oxygen-Free High Conductivity Copper, report FSD/ING-11 (1966).

F. R.F. System

The RF system is required to supply a total output of just over 80 megawatts to 57 loads comprising:

- a) Injector linac approx. 1.5 MW,
- b) 12 first stage cavities at approx. 350 kW each,
- c) 12 second stage cavities at approx. 1.7 MW each,
- d) 32 third stage cavities at approx. 1.7 MW each.

The above unit sizes include some spare capacity to allow for the possibility of one amplifier being inoperative. The block diagram in Figure VI.32 is an outline of the system.

The RF system will dominate the cost of the machine and the power bill will be most of the annual operating cost⁶¹.

For the reference design the capital cost per watt as a function of amplifier output power was assumed to follow the slope of the Mosko⁶¹ curve, re-normalized so that the cost per watt at the two megawatt level was 50¢ per watt. This allows for conversion to Canadian dollars, escalation and 10% for AC distribution and switch gear.

A recent review of costs indicates that, while the slope of Mosko's curve appears to be correct, a more realistic figure at the 1.7 megawatt level is 28 cents $\pm$ 20% per watt⁶². This figure is being used in the project cost estimates until a better figure is generated. A more detailed study of these costs is in progress.

Economical achievement of the required reliability of the RF system requires detailed studies of the over-all system, the sub-systems and individual components. These studies have not been made. By providing sufficient excess capacity in the amplifiers advantage can be taken of the inherent tolerance of the SOC to failure of one amplifier chain. The analysis in Appendix VI.3 indicates one cavity can lose all its excitation and, provided the cavity is detuned, the machine will continue to function at some loss in phase acceptance. Transient conditions at the time of failure have not yet been analyzed.

⁶¹ A.G. Ward, The Radio-Frequency System for the Intense Neutron Generator (ING), proc. AECL Symp. The Generation of Intense Neutron Fluxes (Chalk River), AECL-2177, paper 6 (1965).

⁶² F.J. Heath, Memorandum on RF Power Costs, report FSD/ING-49 (1966).
J.O. Cann (C.G.E.) private communication (June 2, 1966).

FIG. VI. 32 Block Diagram of the Radiofrequency System.

1. Possible R. F. Generators

Two basic types of device that could be used are the familiar "Power Grid" tubes (triodes, tetrodes and pentodes) and the transit-time devices, such as the klystrons, travelling wave tubes and crossed-field amplifiers.

Klystrons have been designed for multimegawatt pulsed operation at frequencies of 400 MHz and higher. CW klystrons are available for frequencies of 225 MHz and up, with output ratings up to 100 kW. Klystron designs scaled down to the 50 MHz range would in principle deliver large CW powers. The structure would, however, be large. Current klystron designs have efficiencies of about 45%, with maximum predicted efficiencies of about 65%. This is considerably poorer than the performance of triodes and tetrodes.

The amplitron^{*}, or crossed field amplifier, is discussed in Chapter XIV. Its development is relatively recent, and it rivals the klystron as an amplifier to produce both CW and pulse power at short wavelengths. When scaled to the range of 50-200 MHz the amplitron should also produce considerable power, and has a potential efficiency of 80% or better. It will operate with a cold cathode and would be expected to have a very long service life.

It has some disadvantages, a low power gain, less than 10 db, and would allow reflected power from the load to pass back through the tube into the driver stage. This could prove very embarrassing, although the use of a Magic "T" or a circulator may reduce the severity of this problem.

Its selection at this time would involve a considerable gamble concerning the efficiency and the emergence of a satisfactory solution to the circuit design problems⁶³.

A conventional triode has been selected for the reference design in spite of the frequency of 50 MHz for the reference design being very near the upper limit of operation for such tubes. Published ratings are usually specified for a "Maximum frequency of 30 MHz", and it is noted that "Reduced output can be obtained at higher frequencies."

^{*} "Amplitron" is a registered trademark of the Raytheon Company.

⁶³ The Amplitron and its Use in an RF System for a CW Proton Linear Accelerator, Raytheon Technical Report No. MPO-023; FSD/ING-50, (1966).

The largest tube available with sufficient published data to permit a performance analysis is the Machlett ML 8549. It has a maximum output rating of 2.5 megawatts. It is structurally simpler than other tubes of similar capability, due to the use of magnetic focussing of the electron beams. This magnetic focussing has also resulted in wide spacings and correspondingly large mechanical tolerances. This tube was designed originally as a pulse modulator, operating at 60 kV plate voltage and providing output current pulses of 1100 A. As an amplifier it has been tested at a maximum of 700 kW at 13.5 MHz.

RCA⁶⁴ has a series of "super power" tubes, which have been designed especially for ultra high frequency operation. They have suggested the largest of these (the A15186C) for use in this application. Although its published C W rating is only 750 kW they have suggested it could be used at 1.5 to 2.0 MW output. The tube could be redesigned to be twice its present length to operate with a better margin of safety. These tubes are made with extremely close spacings, the separation between grid and cathode being only 0.015 inch. Such close spacings and correspondingly close tolerances result in high manufacturing costs. The close spacings are necessary for operation at frequencies of 400 to 600 MHz and are of no significant advantage at 50 MHz.

Tube life is in principle intrinsically a function of filament temperature, as indicated by figure 6 of reference ⁶¹. Tubes are usually designed for a filament life of the order of 10,000 to 20,000 hours. The life expectancy of a filament operated at 1950°K is almost 10 times that of a filament operated at 2050°K. This increase in life is obtained at the expense of halving the emission. Since it is anticipated that the ML8549 will be operated at about one third of its design emission capability it should be possible to extend its expectancy to at least 30,000 hours. In commercial Radio and Television service tube life of 10,000 to 20,000 hours is quite common and a figure of 15,000 hours has been used in the replacement cost calculations. However, troubles with developmental tubes have been encountered in the use of triodes for linear accelerators. Such tube failures are usually due to manufacturing defects or application problems, rather than to the emission life of the cathode. The experience of others suggests the need for a tube development program to insure reliable amplifier performance.

In the operation of a high power tube an arc which short-circuits the anode to the grid or cathode occasionally develops. To prevent damage to the tube the high voltage is bypassed by an electronic switch, or "crowbar", and the power supply is de-energized. Within a few seconds the plate voltage is re-applied and normal operation of the amplifier resumed⁶¹.

⁶⁴ M. V. Hoover, IEEE trans. Nuclear Sci. NS-12 (3), 76 (1965).

The possibility that such a disturbance to the RF supply may stop the whole machine provides a strong incentive to avoid flash arcs if possible.

The detailed mechanism responsible for starting flash arcs is not known. Many mechanisms have been suggested for the initiation of electrical breakdown in high vacuum. These include surface regeneration processes, the clump hypotheses and electron beam effects. Recent papers^{65, 66} favour field emission from sharp points. The points apparently grow spontaneously on the negative electrode under the influence of high electric fields. If such a mechanism is indeed responsible for flash arcs then the Machlett tube with its much larger electrode spacings would be less susceptible to flash arcs. One must, however, assume that flash arcs will develop and therefore provide a system such as an "electronic crowbar" to protect the tube against damage.

2. RF Amplifier Chain

A four stage amplifier chain will provide power for the three S.O.C. stages and for the injector Linac. The following block diagram indicates the tube types, and power levels involved.

The first two tube types are available from both Eimac and Machlett. The third tube is available from Eimac, and was originally announced as the X2062A. The fourth tube is the Machlett magnetically beamed triode, mentioned above.

The first three stages are grounded cathode amplifiers while the final stage is operated in the grounded grid configuration.

The anticipated efficiency of the amplifier chain at 50 MHz is tabulated in Column I of Table VI. F. 17.

It should be noted that this efficiency does not allow for the anticipated improvement in performance to be expected from wave shaping techniques, such as the Tyler circuit, which is discussed in section VI. F. 1. 7. 2.

⁶⁵ D. Alpert, et al., J. Vacuum Sci. and Tech. 1, (6), 35 (1964).

⁶⁶ R. P. Little and S. T. Smith, Electric Breakdown in Vacuum, IEEE Trans. on Electron Devices ED-12, (2), 77 (1965).

TABLE VI. F. 17
RF SYSTEM EFFICIENCY

Frequency	50 MHz	40.68 MHz	27.12 MHz
PA Plate Efficiency	75%	79%	85%
	kW	kW	kW
Output Power	1600	1600	1600
Trans. Line Losses .6%	9	9	9
Coupling & Matching Ckt. Loss 1%	<u>16</u>	<u>16</u>	<u>16</u>
Total Tube Output	1625	1625	1625
Plate Losses (PA & IPA)	546	436	290
PA Grid Ckt. Loss	15	15	15
Fil Power PA & IPA	21	21	21
Plate Supply Losses 3%	65.4	62	57.7
IPA Grid Ckt. Loss	3	3	3
IPA Screen 1500V 1.5A	2.2	2.2	2.2
1st IPA Fil	1	1	1
1st IPA Plate Loss	3	3	3
1st Amp.	.5	.5	.5
Water Pump & Blower Power 5+1	<u>6</u>	<u>6</u>	<u>6</u>
Total Input Power	2288.1	2174.7	2024.4
	<u>1600.</u>	<u>1600.</u>	<u>1600.</u>
	2288.1	2174.7	2024.4
Overall Eff.	70%	73.6%	79.2%

2.1 Power Amplifier

At 50 MHz it is desirable to replace the usual circuit elements by resonant transmission lines. The wavelength is small enough that they are of reasonable physical dimensions. When properly built these lines have low losses and a large circulating voltampere capability. They also have a self shielding characteristic which eliminates many of the RF radiation problems.

The mechanical structure of the tube must also be taken into account since the structure itself takes the form of a length of transmission line. Using the ML8549 as the reference tube, the following is pertinent:

Interelectrode capacitance

Grid	-	Plate	-	280 pF
Grid	-	Cathode	-	730 pF
Plate	-	Cathode	-	25 pF

Strapped resonant frequencies

Grid	-	Plate System	-	56 MHz
Grid	-	Cathode System	-	64 MHz

Fig. VI. 33 shows the schematic of the final amplifier and Fig. VI. 34 shows its physical outline.

The amplifier is operated as a grounded-grid amplifier^{67, 68, 69} in which the control grid acts as a shield between plate and cathode to reduce feedback capacitance. This, without neutralization, reduces the possibility of self oscillation and gives maximum stability. Despite the high power requirements for the drive when operating in the grounded-grid mode the additional power is not lost. During conduction the voltage developed across the input circuit is in series with the voltage developed across the plate circuit, thus increasing the resultant RF output voltage and consequently the output power. During non-conduction the RF cathode voltage subtracts from the RF plate voltage, thus reducing the possibility of flash arcs.

Because the operating frequency is near the strapped resonant frequency in the plate-grid system the output and input circuits will be operated in the 3/4 wave mode, which will provide the necessary space for output coupling and tuning.

⁶⁷ E. E. Spitzer, *Electronics*, 19, (April 1946).

⁶⁸ J. Dain and I. A. D. Lewis, Design Notes on Grounded Grid Power Amplifiers with Coaxial Line Circuits, AERE-GP/M-159 (1953).

⁶⁹ E. Zaccheroni, *Nuclear Instr. and Methods* 5, 78-79 (1959).

FIG. VI. 33 Schematic of the 1.7 MW Amplifier.

FIG. VI. 34 Physical outline of 1.7 MW Amplifier.

Calculations, using transmission line theory^{70,71} without consideration of mounting problems, have been made for a 3/4 wave resonant transmission line for both the input and output tank circuits. One of the disadvantages of a 3/4 wave resonator is that the structure becomes quite long.

Various methods can be used to minimize the overall length of the cavity resonator.

- a) Contain the grid cathode line within the plate gride line⁶⁹.

Containing the input circuit within the output circuit is inconvenient at 50 MHz. Tuning of the input circuit becomes a problem because one has to resort to plungers which are awkward when dealing with such large cavities.

- b) Change the characteristic impedance of the line either by decreasing or increasing the radii of the inner and outer conductors for appropriate lengths, to give an overall minimum length, or by slotting the inner conductor as in the "spoke effect" used by Mosko⁷². This longitudinally slotted inner conductor may be considered a degenerate form of helical conductor.⁷³

This slotting technique will be used in the input and output circuit to increase the characteristic impedance along the appropriate length of line.

In slotting the inner conductor the area per unit length is cut in half but the electrical path length has been shortened. The overall effect of the slotting on the losses has not been calculated.

If we slot the ends of the inner conductor of the cathode input line into 8 strips 2" wide with 2" spacings between them, the characteristic impedance of the slotted section increases to 47.1 Ω from 10.9 Ω . Since this is a 3/4 wave resonant line the requirement for minimum overall length is met by having a high Z_0 at either end of the cavity and a low Z_0 at the center. By use of transmission line equations a minimum length of 69.4" was calculated for the cathode circuit in the following proportions.

⁷⁰ W.C. Hollis, *Electronics* 20, 130 (May 1947).

⁷¹ F.E. Terman, *Electrical Engineering*, p.1046 (July, 1934).

⁷² S.W. Mosko, ORNL, Private communication (October 25-26, 1965).

⁷³ W.W. McAlpine and R.O. Schildknecht, *Proc. IRE* 47, 2099-2105, (1959).

- 0.0786 λ of slotted transmission line at the cathode terminals
- 0.0747 λ of slotted transmission line at the shorted end
- 0.1408 λ of complete inner conductor transmission line in the center.

A developed view of the cathode inner conductor is shown below.

In the input circuit, the coupling capacitors must be capable of passing approximately 760 A and have a voltage rating of 5 kV. About 1800 pF of capacity is required for proper coupling. In order to avoid internal resonances and to obtain the required current rating, 100 pF or 150 pF units will be used in the appropriate quantities.

The tuning capacitors require a rating of approximately 0.21 A/pF and a voltage rating of 5 kV. A variation of 30 or 40 pF will give a reasonable tuning range.

Capacitors satisfying the above requirements for coupling and tuning are commercially available.

Because of the low input impedance of the tube when operating as a grounded grid amplifier a $\lambda/4$ transformer matching section might be adequate⁷⁴.

The operating input impedance at the terminals of the tube, when the mechanical structure of the tube is taken into consideration, is approximately 1 Ω . If a transmission line matching transformer is used the characteristic impedance of the $\lambda/4$ transformer matched to a 50 Ω line will be 7 Ω . A quarter wavelength at 50 MHz is 59". This is about half the length of the original cavity but can be used as part of the

⁷⁴ T. Morino, Microwave Transmission Design Data, Dover Publication Inc., New York (1958).

transport system from driver to PA input. Since a characteristic impedance of $7\ \Omega$ might make the inner to outer conductor spacing too small three or four lines with a higher characteristic impedance could be used in parallel, as was done with the output coupling in the CERN⁶⁹ amplifier.

The slotted conductor technique can also be used in the output circuit to shorten its length. If we slot the inner conductor of the plate line into 8 strips 7" wide with 7" spacings the impedance of the slotted section increases to $40.3\ \Omega$ from $17.25\ \Omega$. Since the impedance at the plate terminal is inductive, on account of the transmission line effect of the tube structure, the requirement for minimum length is met with a line having a low characteristic impedance at the plate terminal and a high characteristic impedance at the shorted end. The overall minimum lengths, as determined by the transmission line equations, for this particular cavity is found to be 71.1" consisting of 48.5" of line with a characteristic impedance of $17.25\ \Omega$ and 22.6" of slotted inner conductor transmission line with a characteristic impedance of $40.3\ \Omega$. A developed view of the plate inner conductor is shown below.

When slotted inner conductors are used in the input and output circuit the dimensions of Fig. VI. 34 become $L_{in} = 69.4''$ and $L_{out} = 81.3''$ to give an overall length of 153.7". The overall height of the tube alone is approximately 46".

The coupling and tuning capacitors in the output circuit require components of higher rating than those in the input circuit. The coupling capacitors must be capable of passing approximately 1300 A with a voltage rating of 55 kV. About 1500 pF of capacity will be adequate. Again, as in the input circuit, an appropriate quantity of small size capacitors will be used to avoid internal resonances and to meet the required current rating. The tuning capacitors require a rating of approximately 6.6 A/pF and a voltage rating of 55 kV. A variation of 30 or 40 pF will give a reasonable tuning range. Capacitors with high current and high

voltage ratings usually have a wide capacity variation so that the rating per pF at maximum capacity is not very great. This problem can be solved by using mechanical stops to limit the maximum capacity to the required value.

The input and output coupling for the amplifier will be done by using a capacitor divider network which will enable efficient operation at all levels. (See Figure VI.33). The loading resistance on the amplifier is varied by changing the ratio of capacitance and the loading reactance is varied by changing the effective reactance of the series combination.

A number of problems are likely to be encountered in development of the high power amplifier.

- a) Parasitic oscillations are due to unwanted resonances in the tube structure or associated circuits. A grounded-grid amplifier will minimize the possibility of such occurrences and is most commonly used at high frequencies for this reason. It is rare indeed for oscillations of this sort to occur in a grounded grid amplifier. Should they do so, it might be necessary to couple damping resistances to the offending circuits, if they cannot be retuned to eliminate the possibility of oscillation. Sometimes an additional (negative) feedback path can be introduced to eliminate the problem.
- b) On account of the relatively high voltages and frequency the avoidance of overheating from RF currents will require extra care in the choice of components. In some cases extra cooling may be required, in others the replacement of single by multiple units, to eliminate series resonances.
- c) Corona is visible evidence of excessive voltage gradients. It can usually be avoided by suitable mechanical spacing and contouring of circuit elements which are exposed to high fields.
- d) The measured efficiency is the final criterion of an amplifier. Sometimes the measured efficiency falls short of predicted values, and it is then necessary to look for spurious responses in the system, which give rise to undesirable wave-shapes on the tube elements. Suppression by means of loading resistors is often the most effective cure for such problems. The resistors may absorb only small amounts of power, but have a very marked effect on efficiency.

The prediction of efficiency in the 50 MHz frequency range is somewhat uncertain, but we anticipate a plate efficiency of 75%, with conventional circuitry⁷⁵.

⁷⁵ H.D. Doolittle (Machlett), private communication (1965).

2.2 Driver for 1.7 MW Amplifier

The grounded grid 1.7 MW amplifier requires almost 350 kW of drive power. The Eimac 4CW250,000 (formerly designated X2062A) is used as the driver amplifier tube. It is capable of providing over 500 kW of output power, and good life and high efficiency can be anticipated at the required output level. It operates in a conventional grounded cathode configuration and is operated "Class C" for maximum efficiency.

Alternatives to the Eimac 4CW250,000 are the RCA6949 and the Machlett ML8546. The RCA tube is very costly, because of the close spacings and intricate construction used. It is a triode and has the advantage of being a proven design but it would be less efficient than either of the other two tubes. The ML8546 is a tetrode of recent design. It is in use in production transmitters but has not yet been used at high frequencies. It is the least expensive of the tubes being considered but its output may be marginal.

While the RCA6949 is nominally a triode, the beam former electrode operates very much like the screen-grid of a tetrode, so that the output circuits for all three tubes are very similar and will not be very different from that used on an amplifier of similar output capabilities designed by S. Mosko, of Oak Ridge National Laboratory⁷².

2.3 Lower Powered Amplifiers

Lower powered amplifiers will use tetrode tubes, the largest of which is the 4CX15000A widely used in television transmitters. This tube is capable of supplying up to 36 kW in the class "C" mode, or 28.5 kW in linear class AB operation. Since it will be used to supply about 10 kW it is expected to have a very long life.

The 4CX350A is a high-gain tube capable of supplying the required drive power for the 4CX15000A. It can be driven by a transistor amplifier or by a low-power electronic phase shifter.

The use of three tetrode stages, operating well within their maximum operating conditions, will provide the required gain and stability of operation.

The RF circuits for the lower stages have not been designed in detail; their design is conventional.

3. RF Power Distribution System

3.1 Transmission Lines

Transmission lines about 100' long are required to connect the 1.7 MW RF Amplifiers to the cavities. These lines must be rated to withstand normal operating stresses, and occasional high standing wave conditions, caused by cavity breakdowns, etc.

Transmission line power ratings are limited by voltage breakdown between conductors and by heating of the inner conductor (in the case of coaxial lines). The continuous power ratings are limited by voltage breakdown at frequencies below 3 megacycles and by heating at higher frequencies.

The continuous power ratings decrease with increasing frequency, because of the increasing losses due to skin effect. For example, 9 inch line is rated at 3 MW peak power but its CW rating is 700 kW at 27.7 MHz, 510 kW at 50 MHz and 200 kW at 250 MHz. Continuous power ratings can be increased by improvement in the heat transfer conditions. By using a black finish on the inner and outer conductors, to improve radiation of heat and SF₆ gas at 2 atmospheres pressure, to improve conduction, the continuous power rating at a given frequency can be increased by a factor of 2.4, based on an inner conductor temperature of 212 °F, and an ambient temperature of 40°C. Water cooling of the outer conductor would permit a further increase in rating by a factor of 1.4⁷⁶.

The peak power rating can be increased by a factor of 15 by use of SF₆ while dry air at 2 atmospheres increases the peak power rating by a factor of 2.5.

The reference design uses 9-inch line with a water-cooled inner conductor and is pressurized with SF₆. The water cooling overcomes the problem of over-heating the inner conductor and the SF₆ provides the additional peak voltage insulation, which may be necessary under conditions of high VSWR.

Alternatives which will be given further consideration are:

- 1) Fourteen-inch line, pressurized with SF₆ at two atmospheres pressure. (Recommended by the Andrew Antenna Co.).
- 2) An external cooling system, which could be used with a circulation system for the SF₆ in either of the above installations.

⁷⁶ Andrew Antenna Catalog No. 23 (p.88, 95).

to maintain the temperature in the line below (say) 20°C . The amount of heat to be removed is 9 kW for the 9-inch line or 6 kW for the 14-inch line, assuming a good impedance match to the cavity.

This system would eliminate the need for water cooling the inner conductor of the nine-inch line and would thereby eliminate the risk of water escape.

The Andrew Antenna Co. recommends the use of 14-inch line, pressurized with 2 atmospheres of SF_6 , for 2 MW at 50 MHz. If water cooling of the inner conductors is used and the line is pressurized with SF_6 a 9-inch line will be quite satisfactory. It has the advantage of smaller physical size and the use of standard fittings.

3.2 Coupling and Mismatch Problems

The problem of coupling to high-Q loads, such as the SOC accelerator cavities, has been the object of a number of investigations. The difficulty arises from the fact that a load having a Q of 10,000 to 100,000 represents a short circuit at frequencies very close to the operating frequency. From the point of view of amplifier stability the line connecting the cavity to the amplifier should be an integral number of half wavelengths in electrical length. On the other hand such a line length results in a short circuit appearing across the amplifier plate circuit in the event of a cavity breakdown. To minimize the effect of a cavity breakdown on the tube the line should be an odd number of quarter wavelengths in electrical length⁶⁹.

The problem is not unlike that encountered in television transmitters, where earlier designs used high-Q cavities coupled to the output circuit of the final amplifier to short circuit the energy at unwanted sideband frequencies. Recent designs use a hybrid technique⁷⁷ whereby the power is reflected by cavities in two branches of a hybrid circuit and the reflected power is dissipated in a dummy load. (Such a unit presents a voltage standing wave ratio of less than 1:3 to the amplifier, when properly adjusted). This technique can be readily applied to the feeding of pairs of cavities in the SOC.

Hybrid combining units will fill a dual role, providing isolation between the amplifier output circuits and the cavities, for the protection of the tubes, and at the same time providing the desired diversity

⁷⁷ W. F. Goetter, Television Transmitters in Parallel Operation, G. E. publication GER-2057 (1965).

of drive power sources*. Typical RF connection between a pair of cavities and a pair of amplifiers is shown in Fig. VI.35. Two amplifier chains will have their outputs combined and then divided to drive a pair of cavities. If the pair of cavities is similarly matched any reflected power will be absorbed by dummy load No. 1. In the event of either cavity arcing over the other will continue to operate normally and the reflected power from the arcing cavity will be dissipated by both dummy loads. If either of the amplifier chains fails the other will continue to operate with half of its power being lost in dummy load No. 2 while the remainder of its output will be divided equally between the two cavities. A slight increase in output from the remaining RF chains in the affected stage will compensate for the reduced power in two cavities. Operation of the machine with two cavities having only one-quarter power applied has not been analyzed.

The Block diagram, Fig. VI.32 indicates the connections between the RF Power supplies and the accelerator cavities.

To achieve the complete diversion of reflected power into the dummy load (assuming equal reflection coefficients for the two cavities) it is necessary that they operate with a phase difference of 90° . This is very nearly the case in the final stage, where the phase difference per sector is 273° . In the second stage the phase difference per sector is 498° , making a difference between alternate sectors of 84° . In the first stage the phase difference between sectors is 194° , making a difference of 84° for six sectors. (Refer to Table VI. B.1).

Since one can always find a pair of cavities that have close to a 90° phase difference one can, by adjusting the transmission line length, easily obtain the 90° phase difference at the output of the hybrid.

The hybrid combining units each have output connections which must be terminated in dummy loads which, under normal conditions, dissipate very little power. Under transient conditions it is possible for either one of them to be subjected to the combined output of two

* Since the phase difference at terminal 4 and 1 of the hybrids in Fig. VI.35 is the desired value of 90° for hybrid operation, power being fed to these terminals (reflected or incident) will combine at terminal 3 and cancel at terminal 2. Conversely if power is fed into terminal 3 it will divide equally between terminals 4 and 1. If terminals 4 and 1 are matched the power will be absorbed by the matched loads. If they are not matched some of the power will be absorbed and the remainder will be absorbed by the matched load at terminal 2. If power is fed into either one of terminals 4 or 1 the power will divide equally between terminals 3 and 2.

FIG. VI. 35 Connections between Amplifiers and Cavities.

amplifiers (3.4 MW). In the event of failure of one amplifier chain the dummy load in the combining hybrid may be subjected to 850 kW dissipation for an indefinite period. These loads will be rated at 1000 kW continuous, 3.4 MW for ten seconds.

The hybrid combiners and dummy loads will be located between the RF amplifiers with which they are associated. Since these are relatively light in weight, and are unlikely to require frequent servicing, they will be hung, out of the way, from the roofs of the RF galleries.

4. RF Control System

4.1 Frequency Control

It is required to maintain the frequency of operation of the SOC within ± 1 part in 10^6 on a short term basis. Although crystal oscillators used in radio and television broadcast transmitter work are only required to maintain the frequency to within ± 10 parts in 10^6 the performance of such oscillators is usually within ± 1 part in 10^6 ; this will be no problem.

4.2 Phase Control

The phase of the voltage in each cavity must be maintained to within ± 0.3 radians of the reference phase regardless of beam loading and assuming all other parameters are at zero tolerance.

Various types of phase shifter can be used to control the drive phase to satisfy this requirement. (About 14° of shift is required to compensate for beam effects).

- a) Adjustable lengths of coaxial line are frequently used for phase shifters at 50 MHz and higher frequencies. A change in line length of $1/4$ wavelength will produce a phase shift of 90° . "Delay lines" are frequently used, to reduce the physical size of the phase shifting sections.
- b) A T-section, consisting of two coils and a capacitor may be used to achieve phase control. Control of $\pm 15^\circ$ may be achieved by adjustment of the capacitance, without changing the inductances of the T.
- c) Electrically adjustable delay lines are available, consisting of several T-sections in which the inductance or capacitance can be changed by means of a control voltage, thereby changing the phase shift through them. The inductances are made of ferrite cores saturated by dc in auxiliary windings. The capacitance is provided by varactors controlled by variation of a d.c. bias voltage.

In controlling the phase of the cavity it is necessary to have both slow and fast controls. For initial set-up a manually adjusted delay line is available to adjust the phase of the drive voltage to the correct value. The reactive component of the beam loading, as the beam current is increased, will be compensated for by the tuning control and the phase shift through the amplifier plate circuit by the amplifier loading control. The cavity input matching adjustment will be one that does not affect the phase of the driving current.

An electrically operated phase control will be used for fast control with a speed of response well in excess of the cavity response, which limits the response of the overall system. It may be necessary to limit the speed of response of this phase control system in order to prevent undesirable amplitude modulation of the cavity voltage.

While an absolute measure of phase for each cavity will be available for control and drive purposes, it will also be necessary to control the phase on a stage basis. Such control will facilitate adjustment of the accelerator to compensate for different flight times between stages.

4.3 Amplitude Control

4.3.1 Beam Current Compensation

Variations in beam current will result in corresponding variations in the amount of power required to maintain the voltage amplitudes in the accelerator cavities at the specified levels. An amplifier loading or power output control is required for each amplifier. It must be adjusted during the start-up cycle of the SOC, to maintain the voltages in the cavities within the specified limits of amplitude variation as the beam current is increased slowly from zero to its full operating value. This means that the power output of the amplifiers must be varied from 10% of maximum at zero beam current to maximum at full beam current.

The amplifier loading control takes the form of a capacitive voltage divider, consisting of two variable capacitors in series. The load resistance on the amplifier is varied by changing the ratio of the capacitances and the load reactance by changing the effective capacitance of the series combination. This control permits the operation of the amplifier with maximum RF voltage at its plate for all load levels, thus maintaining maximum amplifier efficiency for all power output requirements. The accelerator cavity input matching control will maintain the transmission line standing-wave ratio at its minimum value for all power levels.

It is planned to employ motorized control of these capacitors but, if more rapid response should be required, they could be

operated by solenoids or "loudspeaker" type driving units, which will operate at mechanical frequencies up to about 30 cycles⁷⁸.

It is anticipated that the beam current will be so controlled that there will be very little variation in beam current from the set value. There may be some incidental modulation of the beam current at frequencies of the order of 10 MHz. Such variations will not affect the cavity voltage significantly unless their sidebands happen to coincide with unwanted cavity resonances. The bandwidth of the fundamental mode response of the cavity is approximately 5 kHz, under full load conditions. It is assumed that variations in the 10 MHz range will not affect the cavity voltage significantly.

4.3.2 Line Voltage Compensation

Line voltage variations may be as great as $\pm 7\%$. They may be compensated for by means of inductrol regulators, silicon controlled-rectifiers or by adjustment of the amplifier loading control. Silicon controlled-rectifiers (SCR's) will provide the required compensation with minimum disturbance of the amplifier output power, as they will react to changes in supply voltage with sufficient speed to correct the rectifier output voltage before the disturbance is observed at the output of the power supply filter.

4.3.3 A.M. Type (Heising) Modulator

The power input to the plate circuit of an amplifier delivering 1.7 MW, assuming a plate efficiency of 75%, is 2.27 MW. For 100% modulation the modulator would be required to deliver 1.14 MW. For 10% modulation, the modulator is required to deliver only 11.4 kW - a very insignificant amount of power.

4.3.4 Amplitude Control Range

In summary, the amplitude control system is required to control the amplifier output power in order to maintain constant cavity voltage. It must control the output power of the amplifiers over a power range of approximately 10 to 1, in order to compensate for variations in:

- 1) Beam Loading
- 2) Line Voltage.

The system response covers the frequency range from 0 to 10 kHz, although the overall response will be limited by the accelerator cavity response to a much narrower range. There are three means of control, each effective over a limited range of the total bandwidth:

⁷⁸ M.A. Green, IEEE trans. Nuclear Sci. NS-12 (3), 65 (1965).

- 1) Amplifier loading controls:
Frequency Range 0 to 0.1 %
Control Range 10% to 100% (Power)
- 2) Silicon controlled-rectifiers:
Frequency Range 0.1 to 50 Hz
Control range $\pm 10\%$ (voltage)
- 3) AM type (Heising) modulator
Frequency range 50 to 20,000 Hz
Control range $\pm 10\%$ (voltage)

In effect (2) and (3) compensate for fast disturbances, giving (1) time to catch up with changed conditions.

4.3.5 Snap On Voltage Control

Due to the phenomenon of "multipactoring" it may be necessary to turn the transmitter on as fast as possible in order to drive through the multipactoring voltage. This can be done with considerable speed, limited by the bandwidths of the amplifier and the cavity. Since the unloaded cavity only requires 10% of the maximum power the transmitter can be very easily pulsed to its maximum CW rating to increase the rate of rise of the voltage through the multipactoring region.

4.3.6 Protective System

Interlocks will be provided to monitor flow rates in all air and water cooling systems, and alarm indications given when the rates of flow fall below preset minima. Temperature alarms will also provide an indication of coolant discharge temperatures exceeding specified limits. Electrical and mechanical interlocks and shorting switches will be used to protect operators from exposure to high voltages, high currents, and from RF radiation.

Overload relays will be used to protect amplifier and power supply circuits from excessive currents. In the case of the final amplifiers and their drivers high-speed fuses and vacuum gap "crowbar" devices⁷⁹ will be used to provide rapid shut-down of the plate supplies in order to protect the tubes. It is anticipated that the voltage will be removed within 3 to 5 μ s of the detection of a fault.

When the beam current in the accelerator is suddenly shut off the amplifier output must also be cut off so that the voltage does not rise too far to cause the entire system to crowbar and drawing a large short circuit current from the AC line. The following are possibilities:

⁷⁹ Ignitrons in Capacitor Discharge and Crowbar Service, G.E. publication, PT 57 (1961).

- a) The RF drive to the amplifiers can be cut off immediately and their bias reduced to a suitable value, following which the bias can be slowly increased to cut-off. This will result in immediate removal of RF power output from the amplifiers. The plate input to the amplifiers will be almost unchanged, initially, and the power will be dissipated on the plates of the tubes. As the bias is increased the power input will be reduced to zero. The tubes will be subjected to a short period of higher-than-normal dissipation but have sufficient thermal inertia to absorb it. This system is used in some broadcast transmitters for "lightning trip" protection.
- b) With the hybrid feed system proposed the phase of the driving voltage to one amplifier can be shifted by 180° and the combined output of the two amplifiers fed into a dummy load, instead of into the accelerator cavities. The drive can then be reduced gradually and the dummy load will have absorbed a burst of power for a short period.
- c) The amplifier system can be driven from a different master oscillator, at a frequency (say) 50 Kc off-set from normal. This will result in complete reflection at the input of each cavity, with the power dissipated in a dummy load, while the output from the amplifiers is gradually reduced.

5. A.C. and D.C. Power for Amplifier Chains

The 60 cycle primary power distribution system is a 3 phase 34.5 KV system, which supplies power via vacuum-type circuit breakers to the primary windings of the main power amplifier plate supplies. Over 98% of the power required by the power amplifier is supplied from this source.

Eight high voltage D.C. plate supply rectifiers, each capable of an output of 15 MW, will supply power to groups of six-amplifiers⁸⁰. This arrangement has the advantage of reducing the cost of rectifiers by reducing their number while retaining the advantages of a degree of redundancy. Several transformer winding configurations are possible for a rectifier of this size. The Δ -Y system is in effect two rectifier systems connected in series. Each transformer phase has two rectifier windings, one set connected in Y the other in Δ . The winding voltages are adjusted so that each set provides one half of the required D.C. voltage through a full-wave bridge rectifier. The two outputs are connected in series to provide the total output voltage. The ripple frequency is 720 cycles, and the ripple voltage is 1.1% (RMS) of the D.C. output, without additional filtering.

⁸⁰ R.K. Elliott, AC Power Requirements for the Intense Neutron Generator, report FSD/ING-19 (1965).

The use of a vacuum spark gap to protect the tube and associated components, in the event of a flash arc or overload of one amplifier, requires a means for isolation of the crowbarred amplifier from the rectifier output. Fast fuses have been developed suitable for this function⁸¹. These require replacement before the amplifier can be put back into service. More sophisticated devices for breaking D.C. circuits of this size are being developed and may be available by the time they are needed⁸¹.

Vacuum spark gaps will trip within 1 microsecond of receipt of a trigger signal and are capable of drawing a peak current of 100,000 amperes. Special precautions are required to control the transients⁸² resulting from such steep wave-fronts and high currents.

Non-linear resistors, or resistor-rectifier combinations, are often used to control such transients, with excellent results. In this connection it must be recognized that even a few feet of cable has significant inductance and distributed capacity, so that transients must be controlled at both ends of the cable, if the control is to be complete.

6. Amplifier Cooling Requirements

A water cooling system with a heat exchanger and water purification system will be required to supply a flow of purified cooling water for the P.A. and driver tubes⁸⁰. The water cooling requirements for the ML8549 is 100 gpm at a water jacket pressure of 30 psi. The water cooling requirements for the X2062A driver tube is approximately 88 gpm at a pressure of 65 psi. A central combined cooling system is anticipated rather than one using individual cooling loops for each amplifier chain.

Transmission lines and dummy loads will require water cooling and will be integrated into the combined cooling system. There is also the possibility that the amplifier cavity will require water cooling of approximately 5 gpm at 20 psi but, until further detail design is done, the exact cooling requirement is not known.

The ML8549 and the X2062A will require additional forced air cooling of the grid and filament terminals. Forced air cooling will also be required to maintain each chain of amplifiers within the normal operating temperature range.

⁸¹ C. Stairs, C.G.E., private communication, (1966).

⁸² Ignitron Excitation Circuits and Their Requirements, G.E. Publication PT50, (1961).

7. Departures from Reference Design

7.1 System Operating Frequency

The case for shifting to a lower operating frequency was first discussed in FSD/ING-22. This is based in part on an anticipated improvement in PA plate efficiency of the ML8549, 75% at 50 MHz, 79% at 40.68 MHz and 85% at 27.12 MHz. Estimated overall system efficiencies are given in Table VI. F. 17.

The possibility of interference with other services should not be overlooked when selecting an operating frequency. Should such interference occur it might be necessary to shut down the whole facility for a considerable length of time, while the problem was being cleared up. Operation at a frequency assigned for industrial, scientific and medical use will minimize the probability of interference with other services. Two such assigned frequencies are 27.12 MHz and 40.68 MHz. The lower frequency is to be preferred from the point of view of amplifier efficiency, and should be considered. In the event that 27.12 MHz cannot be used the frequency of 40.68 MHz is recommended.

The dimensions of the ML8549 structure are such that, at 50 MHz, the usual $\lambda/4$ cavity does not leave enough space outside the tube envelope to provide the desired coupling and tuning facilities. For this reason the reference design is based on a $3\lambda/4$ cavity, which is quite large.

At 40.68 MHz the $\lambda/4$ cavity is much more satisfactory and can readily be applied. It has a radial width of 18 inches for a 5-inch length, while the 50 MHz cavity has a width of only 7 inches for the same length.

7.2 High Efficiency Circuits

The Tyler circuit⁸³, or a modification of it, offers the possibility of improved amplifier efficiency by means of plate and grid-voltage wave shaping. An improvement of 6% to 8% in plate efficiencies of 10 kW and 50 kW AM Broadcast transmitter amplifiers, operating at 1.2 MHz, has been achieved by this means⁸⁴.

Some experimental work employing this technique has been done at 4 MHz by Eimac with encouraging results⁸⁵. No work is

⁸³ V. J. Tyler, A New High-Efficiency High-Power Amplifier, The Marconi Review No. 130, XXI, 3rd Quarter (1958).

⁸⁴ C. G. E. Transmitters, models BTC 83 and BTC 50.

⁸⁵ B. Sheppard, (Varian Associates), private communication, (May, 1966).

known at frequencies as high as 50 MHz, but, while there will be added problems at the higher frequencies, they do not appear to present insuperable obstacles. The use of third harmonic voltages at the tube grid and plate terminals in the wave shaping techniques must be taken into account in selecting the operating frequency, a consideration which provides an additional incentive to choose 27.12 MHz in preference to 50 MHz.

For high efficiency the plate voltage must be at a minimum value all the time the electrons flow from cathode to anode. One might consider satisfying this condition by using a very narrow anode current pulse, so that the voltage will be substantially at its minimum value for the whole of the pulse duration. If the average current is to be maintained at its original value the peak current must be then increased and the filament power increased accordingly.

Since the voltage drop through the tube is proportional to the peak current, the efficiency improvement will be limited by the increased loss from this source. The Tyler circuit takes advantage of the fact that, if the anode voltage waveform is flattened at the negative peak, a broad current pulse can be used without loss in efficiency. This is done by adding a third harmonic to the anode voltage to flatten the wave and by injecting a third harmonic voltage into the grid circuit.

The Tyler circuit results in higher than normal grid currents and grid dissipation, so that some tubes are not suitable for this type of operation. In this respect, the Machlett ML8549 appears to be a good prospect as its grid dissipation rating is 9 kW, well beyond the anticipated dissipation level of 2 kW.

7.3 Amplifier Tube Change

Machlett has proposed a tetrode tube based on the ML8549, which would be capable of operation at 2.5 megawatts output with only 10 kW of drive power. Such a tube would eliminate the need for the 350 kW amplifier tube in the 1.7 MW amplifier chain, with a consequent saving in materials and improvement in system reliability.

7.4 Amplitude Control

The "fast" amplitude control system described for the reference design is of significant cost. It is required to compensate for anticipated fluctuations in the beam current and might be eliminated if the beam current can be adequately controlled.

7.5 Individual Plate Supplies

There are economies to be achieved through the use of "group" supplies, but this leaves us with the problem of isolating the crowbar of a defective amplifier, following a crowbar actuation. At the moment a fuse seems to be the only practical answer that is immediately available, although suitable "dc commutation" devices⁸¹ are being developed.

The use of individual supplies has the advantage of complete isolation and permits the use of high-speed vacuum breakers to clear a fault. Such circuits can be re-activated without the down-time associated with a high-voltage fuse replacement.

G. CONTROL SYSTEM

1. Overall System

The control system, although very large and elaborate, is not considered to be of primary importance in determining the basic feasibility of the accelerator. It has therefore received little attention. Only a basic outline is given here.

The function of this system will be:

- a) To provide signals to establish the operating parameters of the accelerator. This includes sequencing control signals for run-up from shut-down to beam on.
- b) To monitor the operation of the accelerator and to provide information to the operations crew on the status of parts of the system.

It is a matter of design philosophy that digital techniques will be employed where possible. Considerable experience with computer process control has been gained at CRNL from NRU computer control experiments.^{89, 90, 91}

Figure VI. 36 illustrates a possible computer control system. Because of the large number of readings of sensors that must be monitored during operation this task is divided between four computers designated monitor computers. Input from the various sensors to the monitor computer is accomplished through a multiplexer and an analogue to digital converter. Figure VI. 37 illustrates the arrangement for a typical monitor computer.

This computer continually scans all inputs and compares the readings with stored set points. If a reading exceeds preset limits an interrupt alarm signal is sent to the central control computer which registers the alarm either on a teletype print out or on the CRT displays. Corrective action may also be initiated by the control computer through one or all of the monitor computers, which will in turn effect changes in the operating parameters.

⁸⁹ C.G. Lennox and N.P. Vakil, A Digital Computer Control Experiment on a Nuclear Reactor, AECL-1970 (1964)

⁹⁰ K.R. Morin, The NRU Monitor Computer and Self-Powered Neutron Flux Detectors, AECL-2216 (1965)

⁹¹ K.R. Morin and C.G. Lennox, A Solid-State Multiplexer for use with Self-Powered Neutron Flux Detectors, AECL-2217 (1965)

FIG. VI. 36 Outline of Computer Control System.

VI. G

FIG. VI. 37 Outline of Typical Control System for SOC Stage.

Magnetic drums associated with each monitor computer will maintain a record of the current readings of each sensor as well as time average values. Such information will be particularly valuable in the detection of malfunctions. The information stored on each drum can be called up by the central control computer where the values of any particular parameter can be printed out or displayed on one of the CRT displays. The information may also be used in computing parameter changes for the machine.

The response time of the computer control is not expected to be less than 100 ms. For parameters requiring faster control closed loop analogue servo systems will be employed. See below for a description of some typical loops of this type.

Fault signals that require immediate shut-down will also bypass the computer control.

2. Cavity Control Servo System

To maintain proper accelerator operation the magnitudes and phases of the RF fields in the cavities must be held at predetermined values, and the resonant frequency of the cavities kept at the design frequency.

The basic block diagram for the RF phase and amplitude control system is shown in Figure VI. 38. The reference signals are common to all cavities. The cavity variables ϕ and G representing respectively the phase and the amplitude of the RF electric field inside the cavity are measured by suitable sensors and compared with the corresponding reference quantities.

The phase error signal, after suitable compensation and amplification, is fed into a phase shifter device which drives the phase output of the power amplifier. The amplitude error signal, after compensation and amplification, is fed into a modulator whose output controls the amplitude of the RF voltage from the power amplifier.

The transient behaviour of the cavity is an important element in the design of the control loops. A simplified transient analysis has been made on the basis of an equivalent circuit for an unloaded cavity⁹². The more difficult case for the beam loaded cavity remains to be done.

⁹² G. Porcelli, Transient Analysis of a Resonant Cavity for a Separated Orbit Cyclotron, FSD/ING-59, (1966).

FIG. VI. 38 RF System Control Diagram.

The bandwidth of the loaded cavity is expected to be about 1000 Hz. Since the bandwidths of all other elements in the phase and amplitude servo loops, including the RF power amplifier, will be approximately ten times larger, the cavity determines the effective bandwidth of the loop. Disturbances whose spectra lie outside the system bandwidth are of no concern such as, for example, the modulation of the beam intensity in the ion source, expected to have a frequency of the order of mega-cycles.

An automatic tune control loop in each cavity is required in order to maintain proper tuning of the cavities in the desired mode. The main factors that would affect the tuning of the cavities are variations of temperature and barometric pressure.

An estimate of the detuning effects produced by temperature variations of $\pm 1/2^\circ\text{C}$ (it is assumed that the temperature of the cavity can be controlled to within $\pm 1/2^\circ\text{C}$) in the reference cavity is

$$\frac{\Delta f}{f} \cong 0.6 \times 10^{-5}.$$

The estimated detuning produced by a barometric pressure variation of $\pm 4\%$ from the mean is

$$\frac{\Delta f}{f} \cong 1.5 \times 10^{-5}.$$

Now the bandwidth of the resonance curve of the cavity is of the order of $1/Q$. Since for an unloaded cavity $Q \cong 10^5$ both the temperature and pressure variations are large enough to produce a drastic effect on the cavity fields. Thus a tune control system is necessary. It is desirable to divided the operation between two tune control loops, one slow for coarse control, the other fast for fine control.

The bandwidth of the fast loop may be of the order of 10 Hz, sufficient to cover the bandwidth of the effective disturbances of the cavity tune. That of the slow loop may be ~ 0.1 Hz. The frequency range of the fast loop may be smaller than that of the slow loop, but, in order to keep the fast loop always ready for corrections in either direction, the slow loop will have to take over from the other any tuning load that falls within its bandwidth. This is readily accomplished if the fast loop is of proportional type and the slow loop of integral type, as shown in Figure VI. 39, in which the tune control loop of Figure VI. 38 is given in more details.

FIG. VI. 39 Tuning Control Loop.

If the cavity is not in tune the fast loop corrects the error with a tuning device of proportional type. This leaves a residual error which is gradually eliminated by the action of the slow tuner actuated by the integral of the error itself.

The detection of tuning errors for tuning control should be done outside the cavity, in the feed line. In fact the beam load is expected to affect the phases of the field quantities in the cavity, thus creating ambiguity if one tries to use such phases as an indication of tuning errors. However, the phase relationship between field quantities in the feed line should not be affected by the load, if proper matching with the cavity is achieved. In fact such phase relationship should be strictly dependent on the tuning of the cavity and could be used for tuning error detection as shown schematically in Figure VI.38.

H. BEAM TRANSPORT

A beam transport system must be able to carry particles from one place to another with negligible loss and deliver them in an acceptable configuration.

The most convenient way to think of a beam of particles is in terms of the emittance ellipses introduced in Appendix VI. 3.

A beam emerging from a SOC stage has x and y emittance ellipses as shown in figure VI.50 page 172. If the beam drifts in a field free region the ellipse will shear to the right keeping its area constant. (The θ_x co-ordinate of each particle remains constant and the x co-ordinate increases at a rate proportional to θ_x). If the beam passes a thin lens the ellipse shears vertically - again with its area remaining constant (x co-ordinate unchanged θ_x changed proportional to x). The problem of designing a transport system - for example from the output of stage 1 to the input of stage 2 - is to choose a system of lenses which manipulates the emittance ellipse so that it never has a width greater than the confining tube and arrives at stage 2 with the correct orientation. The problem would be straightforward except that the beam is astigmatic and the lenses used (quadrupoles) defocus in one plane while focusing in the other.

For a discussion of emittance matching see reference⁹³.

1. Primary Beam Transport

The beam emerges tangentially from Stage 3 and, after clearing the last cavity, travels 17' to the accelerator exit tunnel. This tunnel is 135' long and takes the beam to the high activity tunnel. The beam is focused to a small waist at the meson target No. 1. From here the beam is taken through an RF beam splitter. This switches the beam rapidly to one of 3 exit paths. To allow separation of the deflected and undeflected beams the emittance ellipse must be shifted clear on the phase plot. This will allow it to be separated in position subsequently. The separated beams may be taken along the primary channel or along one of the two parasitic beam channels. (See figure VI.3).

Beam No. 1 continues to a small waist at the meson target No. 2 and through it to the end of the tunnel (total length 315'). Here it is deflected 20° by an achromatic bending magnet and sent down the thermal neutron facility tunnel (345') to the target building. At the entrance to the

⁹³ K.G. Steffen, High Energy Beam Optics, Interscience, New York (1965)

target building the beam is bent up by a 20° bending magnet. At the center of the building (90' horizontally from the edge) it is deflected down into the target by a 110° magnet. This magnet is not required to be achromatic.

Beam No. 2 is taken off at 90° into the meson experiment building.

Beam No. 3 is taken off at 45° into the advanced power technology building and the resonance-neutron time-of-flight facility.

Detailed design of the transport system has not been completed but the tentative design calls for 4" diameter quadrupole doublets every 30'. This gives the following number of doublets.

Injector to stage 1	2
Stage 1 to stage 2	5
Stage 2 to stage 3	9
Accelerator exit tunnel	7
High activity tunnel	9
Thermal neutron facility tunnel	10
Thermal neutron bldg.	3
Total	52

2. Beam Splitters

It is desired to provide beams of protons of the full energy from the accelerator but of reduced intensity to the various experimental facilities located between the accelerator and the thermal neutron facility. It is proposed to accomplish this by the sideways deflection of micro-pulses at a sub-harmonic of the accelerator frequency.

The problem to be solved here is similar to but not identical with that encountered in the travelling wave separators now in use at several high energy accelerators. The travelling wave separator is required to deflect sideways from a mixed beam of secondary particles emerging from a momentum analyzer, particles of a given mass. The device is filled with a travelling wave of micro-wave energy for a time exceeding the macro-pulse width from the accelerator. The filling time of any such device would however be much too long to employ in the deflection of a single micropulse.

The micropulse structure emerging from the last stage of the SOC operating at 50 MHz may be visualized as follows:

In order to deflect a single micropulse the deflecting field must be applied after the next preceding pulse has left the device and before the next following enters it, i. e. within a time $\tau + T = 38.2 \text{ ns}$. This implies the use of a non-resonant travelling wave device in which the field can be built up and removed in a few nanoseconds at most. The simplest device would be a parallel plate transmission line driven by a high voltage pulse.

Panofsky and Wenzel⁹⁴ have shown that in a travelling wave system operating in a transverse electric (TE) mode (this includes the TEM mode) the net deflection of a particle having the wave velocity is zero, because the deflecting impulse of the magnetic field always cancels the impulse of the electric field. If, however, the particles ride upstream against the wave the electric and magnetic impulses are parallel and additive. This reinforcing effect has been proposed for use in a beam deflection system for the CERN synchrocyclotron⁹⁵. In this system the deflecting force is

$$F = eE + eVB = eE(1+\beta)$$

where βc is the particle velocity.

The angular deflection imparted to the particle is given by the ratio of the perpendicular to the longitudinal momenta. Hence

$$\theta = \frac{p_{\perp}}{p_{\parallel}} = \frac{E(1+\beta)S}{\beta^2 Mc^2}$$

⁹⁴ W.K.H. Panofsky and W.A. Wenzel, Rev. Sci. Instr., 27 967 (1956)

⁹⁵ H. Beger, et al, Nanosecond High Voltage Pulses for internal Cyclotron Beam Deflection, report CERN 62-25 (1962)

where E is the field strength in MV/cm, S is the distance travelled in the field, and Mc^2 is the total energy of the particle in MeV. If the travelling wave is moving in a direction opposite to the particle and if a single micropulse is to be deflected the length of the electrodes, S , is restricted to $S \leq L/2$. That is, the voltage pulse is to be applied to the downstream end of the deflector as soon as the preceding micropulse leaves it and the voltage must be removed from the upstream end just before the following micropulse arrives.

The splitter is to be placed in the beam transport line, which consists of quadrupole doublet lenses spaced approximately 10 meters apart. Referring to Fig. VI. 40 it can be seen that, if the splitter is placed at the beam focus, the maximum deflection occurs at the quadrupole doublet. Conversely if the splitter is placed at the doublet the maximum deflection occurs at a focus. Neither of these is practical. The best that can be realized is a lesser deflection given by displacing the splitter a distance ℓ_s from the center of the doublet. The deflection d is then

$$d = \theta(D/2 - \ell_s)$$

The beam will be displaced within the splitter by an amount

$$d_s = (1/2) \frac{E(1+\beta)S^2}{\beta^2 Mc^2}$$

The total deflection at the focus is then

$$d = \frac{E(H\beta)S}{\beta^2 Mc^2} \left\{ (S+D)/2 - \ell_s \right\}.$$

The maximum value of the length S is $L/2 = 239$ cm. D is assumed to be 10 meters and ℓ_s chosen to be 100 cm. The calculated values of the deflection d , the applied voltage and the power delivered to the device are shown in Figure VI. 41 as functions of the field strength. In calculating the power delivered it was assumed that 1% of the micropulses (5×10^5 per second) were to be deflected and that the deflection system was equivalent to a 200 ohm transmission line with a matched terminating load. It is clear that deflections of 4 to 8 cm can be achieved with pulse voltages less than 200 kV with the delivered power less than 1.5 MW.

At the focus where the deflection is between 4 and 8 cm a septum magnet is placed to deflect the beam further so that it enters the first quadrupole lens of the appropriate beam transport system.

FIG. VI. 40 Beam Transport Optics at the Beam Splitter.

FIG. VI. 41 Beam Splitter Performance.

If the separation of the beams at the downstream quadrupole lenses is taken to be 50 cm the septum magnet must produce a deflection of 0.1 radian. The deflection

$$\theta = \frac{P_1}{P_{11}} = \frac{cB\ell}{M\beta C} = 1.84 \times 10^{-7} B\ell$$

where ℓ is the length of the magnetic field and B is the field strength in Gauss. This gives

$$B\ell = 5.4 \times 10^5 \text{ G cm.}$$

A 10 kG magnetic field would have to be 54 cm in length. A cross section of a conventional septum magnet is shown below

The current sheet across the opening of the "C"-shaped core reduces the fringing field in the region of the main beam to a very small fraction of the field in the gap of the core. The change in the field across the current sheet is

$$\Delta B = 0.4 \pi j$$

where j is the current per unit length in the direction parallel to the field⁹⁶. For a field of 10 kG a current of 8000 amperes per cm is required. If the septum thickness is limited to about 1 cm the current density would be

⁹⁶ E.B. Forsyth and C. Lasky, The Fast Beam Extraction System of the Alternating Gradient Synchrotron, report BNL-910 (1965)

dangerously high. The field could be reduced to about 2.5 kG by extending the length of the magnet to 216 cm. The feasibility of a superconducting septum magnet has been studied by M. A. Green⁹⁷. If the field is less than 15 kG an iron core can be used in a non-saturated condition. Green describes a 5 kG septum magnet with 8000 ampere-turns in Zr-Ni superconducting ribbon or wires. The current density is about 10^5 A cm^{-2} . As this current density has been achieved in Zr-Ni it would appear feasible to consider a 10 kG superconducting septum magnet in which the current sheet is developed in several turns of wire. Shielding will be required on the upstream side of the septum magnet to limit the production of heat in the sheet conductor by proton bombardment.

The layout of the proposed beam splitter assembly in the main beam tunnel is shown in Fig. VI. 42 . The upper part of the assembly would be used to divert 1% of the main beam into the intermediate energy experimental area, the lower part to divert a smaller fraction into the resonance neutron and nuclear power experimental facilities.

3. Meson Beams

Most of the material presented in this section is drawn from the meson factory proposals of Los Alamos⁵, Yale⁹⁸ and UCLA⁹⁹ as well as other unpublished reports. Transport of these secondary beams is illustrated in Figure IX. 9.

3.1 Pion Beam

The principal requirements of this beam are:

- a) a small emittance,
- b) a moderately small momentum ($< 10\%$) and
- c) short length, so that a large fraction of the pions can be directed onto a target before they decay in flight.

⁹⁷ M.A. Green, The Feasibility of a Low-Field Superconducting Thin-septum Magnet, report UCRL-16346 (1965)

⁹⁸ A Final Report on the Design of a Very High-Intensity Proton Linear Accelerator as a Meson Factory at an Energy of 750 MeV. TID-21282 (1964)

⁹⁹ Pion Facility - A High Energy Cyclotron for Negative Ions, UCLA, TID 20522 (1964)

FIG. VI. 42 Layout of Beam Splitter Region in High Activity Tunnel.

These requirements can be met by a set of three 90° bending magnets with field gradient index $n = 0.5$. The maximum field in the gap is 20 kG and the radius of curvature 3.75 ft. This system has the advantage of being achromatic for small angles of incidence. One stop, placed before the first magnet, defines the acceptance angle and a second, near the center of the second magnet, defines the momentum spread. With a total length of 40 ft. about 50% of 200 MeV pions would decay in flight.

The three magnets placed within the shield wall between the main beam tunnel and the experimental room would conduct the pions in a zig-zag path. At the end of each straight section beam stops are provided to improve the shielding against neutrons.

3.2 Fast muon beam

This beam requires a moderately broad spectrum of pions to be injected into a channel composed of quadrupole lenses, such as is used at CERN¹⁰⁰. There pions from a target in the proton beam are magnetically analyzed and then pass into a channel composed of 24 quadrupole lenses, each 22 cm long and with an aperture of 20 cm. In the total length of 13 meters 45% of pions of 400 MeV/c decay in flight.

3.3 Stopped Muons

A channel optimized to accept 10 to 100 MeV pions is suitable for maximizing the density of stopped muons¹⁰¹. The channel would contain 22 quadrupole magnets each with an aperture of 20 cm and pole tip of 20 cm. A field strength of up to 10 kG would be required. At the end of the channel the muons are stopped in a carbon absorber of 5 cm maximum thickness. The pion contamination in the beam is selectively stopped at a smaller value of the range.

¹⁰⁰ A. Citron, et al., The High Intensity Muon Beam with Low Pion Contamination at the CERN Synchrocyclotron report CERN 63-35 (1963)

¹⁰¹ Conference on High-Energy Cyclotron Improvement (College of William and Mary, Williamsburg, Va.) NASA-CR-56934 (1964)

I. SHIELDING AND ACTIVATION

1. Introduction and Beam Spill

One of the more important considerations in establishing the feasibility of ING is the spill rate of high energy protons from the accelerator and beam transport system. Losses arising from imperfections in the magnet system are not yet well enough understood to predict either the absolute spill rates or the distribution of lost protons. At low proton energies, where the worst spill problems are expected, the range of the protons is, on account of the electromagnetic interaction, sufficiently short (0.5 cm in copper at 50 MeV) that only local activation problems are anticipated. In the high energy stages it is assumed, in specifying the shielding requirements, that at most only a few microamperes of proton beam current will be lost in the accelerators.

One source of beam loss is proton scattering by the residual gas in the evacuated beam transport and accelerator systems. The three principal mechanisms are:

- (i) single Coulomb scattering,
- (ii) nuclear interactions,
- (iii) multiple collisions.

The single Coulomb scattering cross-section for direction changes above a certain minimum angle, θ_m has been estimated from the formula given by Blachman and Courant¹⁰². In the energy region 200 MeV to 1 GeV, where activation problems are most serious, the average cross-section is

$$\sigma_{\text{avg.}} \sim 5 \times 10^{-30} / \theta_m^2 \text{ cm}^2 \quad (\theta_m \text{ in radians})$$

The total cross-section for nuclear interactions in the same energy region is

$$\sigma_T \sim 3 \times 10^{-25} \text{ cm}^2$$

This is smaller than the Coulomb scattering for θ_m less than 1 milliradian and comparable for θ_m about 4 milliradians.

Multiple scattering is not an important effect in a SOC because the distance travelled by the protons, about 3200 meters in the 3rd stage SOC, is much shorter than the distances travelled in conventional synchrocyclotrons, where multiple Coulomb scattering can be important.

¹⁰² N.M. Blachman and E.D. Courant, Phys. Rev., 74, 140 (1948)

The vacuum required will depend on the extent to which scattering can produce divergence of the beam beyond the divergence which can be handled by the beam focussing system. If the limiting angle of divergence is 4 milliradians or more the vacuum is set by the acceptable level of nuclear reactions. With 10^{-6} torr the loss rate due to nuclear reaction is 10^{-12} m^{-1} . If the limiting angle is less than this the vacuum is set by the acceptable amount of Coulomb scattering. If, for example, it is 1 milliradian the spill rate, mainly from Coulomb scattering, is $3 \times 10^{-11} \text{ m}^{-1}$, giving a total spill current in the 3rd stage SOC of 6 nA. This is negligible compared to the 0.1 μA /sector spill current which, it is assumed, will result from alignment imperfections in the beam focussing system.

2. Direct Radiation Shielding

As discussed below (section VIII. B) the most important direct radiation component produced when high energy protons collide with matter are high energy (cascade) neutrons. The total number of such neutrons is not very dependent on the material penetrated by the protons and for most of the shielding calculations 2 to 3 neutrons with energies greater than ~ 100 MeV were assumed produced by each proton lost. It was also assumed that no shielding was afforded by equipment around the spill point; for protons lost in the 3rd stage SOC this is conservative, since any lost proton or secondary cascade neutron will likely have to penetrate at least 1 meter of magnet yoke iron before emerging from the accelerator structure.

In most shielding estimates the angular distribution of cascade neutrons was assumed isotropic. This is not a good approximation, since there is a strong correlation between scattering angle and secondary particle energy, but is expected to yield conservative shield estimates when the scattering angle is greater than $\sim 45^\circ$.

Table VI. I. 18 lists some of the cascade neutron source intensities expected at several pertinent spill points in the accelerator and beam transport system based on the assumptions shown of the proton spill rates. Approximate geometry factors for the field points indicated are also shown along with the attenuation factors required for achieving the direct cascade neutron flux levels tolerable at these field points. The final column lists appropriate shield thicknesses for the attenuation factors given, based on Chapter VIII.

For areas requiring continuous occupation (co) $1 \text{ n/cm}^2\text{-sec}$ was taken as the tolerable flux level and for limited access (la) $50 \text{ n/cm}^2\text{-sec}$. In order to control equipment activation (eac) induced by spallation reactions a flux level of $10^6 \text{ n/cm}^2\text{-sec}$ was set; the induced radiation field at the surface of iron after a long irradiation at such a flux will be $\sim 25 \text{ mrem/hr}$ a few hours after shutdown.

TABLE VI.1.18
SHIELDING REQUIREMENTS

Spill Point	Beam Spill	Neutron Source ^(a) n/sec	Field Point Example	Type of Field Point	Geometry Factor (distance)	Attenuation Factor ^(c)	Shield and Thickness ^(d)	
2nd stage SOC	0.1 μ A/sector	5×10^{12}	Control Areas	co	2×10^{-8} (20m)	10^{-5}	4.0m	H. C.
			R.F. gallery	la	10^{-7} (10m)	10^{-4}	3.3m	H. C.
			Vacuum Pumps	eac	10^{-8} (3m)	0.5	0.6m	H. C. (e)
3rd stage SOC	0.1 μ A/sector	10^{13}	Control Areas	co	2×10^{-8} (20m)	0.5×10^{-5}	4.3m	H. C.
			Top of Shield	la	10^{-7} (10m)	0.5×10^{-4}	3.5m	H. C.
			Vacuum Pumps	eac	10^{-8} (3m)	0.1	1.2m	H. C. (e)
Resonance Neutron Facility	13 μ A	2×10^{14}	Control Areas	co	2×10^{-8} (20m)	0.3×10^{-8}	5.2m	H. C.
			Top of Shield	la	2×10^{-7} (6m)	10^{-8}	4.8m	H. C.
			Vault Walls	eac	10^{-8} (3m)	0.5×10^{-2}		
Power Technology Facility	0.06 μ A	3×10^{11}	Control area	co	10^{-7} (10m)	0.3×10^{-4}	1.5m	L. C. (f)
			Exp. Area	la	2×10^{-7} (6m)	0.5×10^{-3}	1.5m	Fe
			Exp. Tank	eac	2×10^{-8} (2m)	1		
Proton Beam # 3 Tunnel	0.1 nA/m	10^{10}	Top of shield	la	2×10^{-7} (6m)	10^{-2}	3.0m	sand
Meson Production Target	130 μ A	2×10^{15}	Exp. Area	co	10^{-7} (10m)	0.3×10^{-4}	3.9m	H. C. (g)
0.1 gm/cm ² of Be	650 μ A	10^{16}	Top of Shield	la	2×10^{-7} (6m)	0.5×10^{-3}	2.7m	H. C.
			Local shields	eac	2×10^{-8} (2m)	2×10^{-4}	1.7m	Fe
Proton Beam # 2 Dump			Exp. Area	co	10^{-7} (10m)	10^{-8}	7.4m	H. C.
			Soil activation		10^{-8} (3m)	10^{-4}	for < 10. curies of soil activity	
Proton Beam # 1 Tunnel	0.1 μ A/m	10^{13}	Top of Shield	la	2×10^{-7} (6m)	2×10^{-5}	6.5m	sand
Proton # 1 Transport at thermal Neutron Fac.	5 μ A/m	10^9	Exp. Area	co	2×10^{-7}	0.5×10^{-2}	1.0m	Fe

(a) Includes a factor for the number of spill points contributing to radiation level at any one field point and an allowance for anisotropic source effects where appropriate.

(b) co means continuous occupation areas, la means limited access areas and eac means equipment activation control.

(c) for high energy neutrons unless otherwise specified.

(d) HC - heavy concrete ($\rho = 3.5 \text{ g cm}^{-3}$), LC-standard concrete ($\rho = 2.3 \text{ g cm}^{-3}$), Fe - iron, Sand - ($\rho = 1.7 \text{ g cm}^{-3}$).

(e) includes an allowance for other activation.

(f) extra shielding outside shielding for limited access area

(g) extra shielding outside shielding for equipment activation control.

3. Operating Radiation Levels

The radiation level in the accelerator and beam transport system when the machine is operating is difficult to predict without some knowledge of the distribution of proton spill. For materials of atomic weight from 15 to 65 a total of about 10 evaporation neutrons are produced by each 1 GeV proton. In lower atomic weight materials fewer evaporation neutrons are produced at each interaction but the mean secondary cascade particle energy is higher, leading to more secondary interactions.

If a 0.1 μ A of proton beam is spilled evenly and at near grazing incidence into the pole pieces and beam tubes of each sector of the 3rd stage SOC, an average plane source of about 10^8 n/cm²-sec of evaporation neutrons will be produced in the magnet yoke cavity. Based on an infinite plane model this source will support a flux in the magnet yoke cavity of about 4×10^8 n/cm²-sec for neutrons with energies greater than 1 MeV and flux of about 10^9 n/cm²-sec for neutrons below 1 MeV. Under these conditions the γ -ray flux from inelastic scattering of the evaporation neutrons in the cavity would be about 100 R/hr. The γ -ray flux from neutron capture γ -rays is more dependent on local geometry and material than the inelastic γ -rays but should not increase this total significantly inside the accelerator magnets.

An estimate of the thermal neutron flux level in the accelerator vault was made using a semi-empirical relation due to Patterson and Wallace¹⁰³ for the flux inside a regular shaped cavity with thick concrete walls. For a vault of surface area S containing a source of fast neutrons Q the unperturbed thermal flux ϕ is given by

$$\phi = 1.3 Q / S.$$

Using this relation for the 3rd stage SOC and assuming a total spill of 3 μ amps and 10 neutrons produced per lost proton the thermal neutron flux level would be

$$\phi \sim 3 \times 10^6 \text{ n/cm}^2\text{-sec.}$$

The capture γ -radiation fields at the surface of an iron slab in such a flux would be about 4 R/hr. This estimate is probably conservative, since the capture into large absorbers such as magnet yokes and cavity surfaces will depress the flux in those areas.

¹⁰³ H. W. Patterson and R. Wallace, A Method of Calibrating Slow Neutron Detectors, report UCRL-8359(1958).

4. Activation Radiation

The beam spill allowed in ING is ultimately determined by the radiation fields from the induced activity in the accelerator and beam transport system. For the case cited above in subsection 3, where 0.1μ amps of the proton beam strike the pole pieces of one sector magnet at near grazing incidence, the residual activity fields from the iron a few hours after shutdown from a long operating period would be a few R/hr. This field is very dependent on the average angle of incidence of the spilt protons since self-shielding can reduce this radiation level by an order of magnitude. Such fields are not likely to present hazards for entry to the accelerator vault since the magnet yokes will constitute very substantial shields for such radiation. If any comparable level of spill takes place at points near the surface of the accelerator structure local activation shielding will have to be provided.

The radiation level from residual activation will have to be controlled throughout the beam transport system, by local shielding around the points that spill a significant fraction of the beam. In particular rather massive shielding will be required around the targets for meson production.

Elastic and inelastic nuclear collisions in the Be targets will remove approximately 0.2% of the main proton beam at each target. No significant fraction of the protons scattered by elastic nuclear collisions are likely to be recovered, but it is assumed that the beam transport system will be capable of accommodating the direction and energy straggle resulting from the electro-magnetic interactions in the Be targets.

Beam scrapers may be required at one or more points in the transport systems to restrict the beam emittance and so control the spill point distribution. For example the main beam transport system in the thermal neutron experimental area must have the particularly low spill rate listed in Table VI. I. 18 or substantially more shielding will be required than that indicated.

The radiation fields from neutron capture products vary over a wide range depending on the material. From the estimated thermal neutron flux in the accelerator vault of $3 \times 10^6 \text{ n / cm}^2\text{-s}$ given above, the field at the surface of a thick copper slab one day after shutdown would be about 25 mR/ hr and for a pure iron slab about 0.7 mR/hr; if, however, the iron contained 1% manganese the field would be about 10 mR/hr five hours after shutdown and 2 mR/hr twelve hours after shutdown. It will be desirable to reduce the thermal neutron flux level in the vault if the beam spill is near that assumed; in the meson target area where the neutron source strengths are much higher it will be essential to control the capture activation by loading the shield facings with an absorber that does not activate.

APPENDIX VI. 1

SELECTION OF CURRENT AND ENERGY

Before the energy and current required to produce the design thermal neutron flux of $10^{16} \text{ n cm}^{-2} \text{ s}^{-1}$ in D_2O can be determined it is necessary to know the following things:

- a) the projectile
- b) the target material
- c) the total neutron yield
- d) the neutron energy spectrum
- e) the relation between the neutron source strength and the flux of thermal neutrons throughout the moderator
- f) the perturbing effects on the flux caused by the insertion of target sheathing material, beam tubes and other absorbers and voids in the actual facility.

The choice of projectile (proton) and target (8" dia. Pb-Bi Eutectic) are discussed in Chapter VII. A. 1. The total measured neutron yields per proton are well fitted by the form $\nu = a + \beta E$, (see Fig. VII. 4) specifically, for 4" and 8" diameter lead targets,

$$\nu = -4.18 + 24.58 E_p \quad 8 \text{ inch}$$

$$\nu = -2.59 + 19.89 E_p \quad 4 \text{ inch}$$

where E_p is in GeV. These results agree with the Monte Carlo¹⁰⁴ calculations but are 10 - 15% lower.¹⁰⁵

Although the measurements¹⁰⁵ were made with targets only 60 cm long, the Monte Carlo calculations show that the total yield increases only slowly with increasing target length beyond this point. To convert the measurements in light water to fluxes in heavy water it is necessary to use calculations such as those described by Kushneriuk, Kennedy and Attree¹⁰⁶. (See also Section VII.A. 2.6). These calculations are readily done only for uniform cylindrical sources of finite length, whereas the Monte Carlo calculation predicts an exponential fall off of source strength with length (see Fig. VII. 2). Nevertheless the measured axial flux distributions 12 cm from the target surface agree well with those calculated using a uniform source 30 ± 5 cm long. With this effective length the source strengths required to produce an unperturbed "midplane" flux of $10^{16} \text{ n/cm}^2 / \text{sec}$ at a distance 12 cm from the surface of a cylindrical target immersed in a heavy water moderator

¹⁰⁴ J. C. D. Milton and J. S. Fraser, A Monte Carlo Calculation of Neutron Production in Heavy Element Targets by Protons in the Range 0.3 - 1 GeV, AECL-2259 (1965).

¹⁰⁵ J. S. Fraser, et al., Neutron Production in Thick Targets Bombarded by High Energy Protons, Phys. in Canada 21, (2), 17 (1965).

¹⁰⁶ S. A. Kushneriuk, et al., Neutron Fluxes in a Moderator Surrounding Targets Bombarded by High Energy Protons, report FSD/ING-5 (1964).

120 cm thick are shown in Table VI. 1, together with the proton current required to give the necessary source strengths.

TABLE VI.1

Target Diameter	Effective Target Length	Neutron Source Strength for $10^{16} \text{ n cm}^{-2} \text{ s}^{-1}$ at 12 cm	Proton Current Required at 1 GeV
20.4 cm	30 cm	$5 \times 10^{18} \text{ n s}^{-1}$	41 mA
10.2 cm	30 cm	$3.8 \times 10^{18} \text{ n s}^{-1}$	36 mA

Thus, using the flux depression factor of 32% from Table VII. A. 5, the required flux in an actual target-moderator assembly can be produced by a 60 mA beam of 1 GeV protons incident on a 20.4 cm diam Pb-Bi target. In fact 65 mA, corresponding to a source strength of $8 \times 10^{18} \text{ n s}^{-1}$ has been chosen to allow for uncertainties.

This set of parameters is not optimized in any way and its choice is still to be justified. For instance, it is clear from Fig. VI. 43 that reducing the target diameter to 10.2 cm (4") gives a gain in unperturbed flux of about 23%. However the geometrical problems of arranging the 4" diameter beam tubes are greater, the tubes interact more with each other and the flux depression caused by the beam tube itself becomes much larger, so that the net gain is likely negligible. Furthermore the target cooling problems, despite the 23% lower heat production would become more difficult (See Section VII. A. 3). Again, since the primary purpose of ING is to produce intense thermal neutron beams at the face of the biological shield, the current requirements could be reduced by decreasing the moderator thickness to about 80 cm. The flux available for irradiation facilities and isotope production would then be lowered, the relative number of contaminant high energy neutrons in the beam would be larger and space would become more cramped. Thus the target and moderator dimensions, though not optimized, are at least reasonable.

A possible method of choosing the current and energy once the target and moderator dimensions are fixed is to minimize the cost necessary to produce the specified neutron flux. This may be done sufficiently well by using a cost formula of the type

$$C = aE + bP$$

With E in GeV and P in megawatts it is convenient to have 'a' in

FIG. VI. 43 Variation of Neutron Yield and Flux with Target Radius.

million \$/GeV and 'b' in million \$/MW. The current in mA required to give S n/s is

$$I = S / (6 \times 10^{15} \nu)$$

With the linear neutron yield formula given above the minimum cost occurs for ν_0 where

$$\nu_0^2 = -a Sb / (6 \times 10^{15} a)$$

Clearly no minimum exists for $a \geq 0$. In writing a cost formula of the type given above it is assumed that at each energy a cost minimization such as that described in Appendix VI.2 is performed for a zero current machine and that the resulting minimized cost is proportional to E. It is further assumed that this minimization is independent of the beam current. Though neither of these assumptions is strictly true, the formula is good enough for the present purpose, which is to obtain a rapid overall view of the trends and magnitudes.

The results for the minimum-cost energies and currents, beam and target powers, are shown as functions of b/a in Fig. VI.44. The coefficients b and a depend not only on engineering considerations but also on financial ones. They may include, for instance, not only the initial capital cost but also the present value of electric power for any desired number of years and interest rate. Typical values are: capital cost b/a = 0.5/20 = 0.025; capital plus present value of 5 years of power at 5% interest, b/a = .73/23.5 = 0.031; capital plus present value of 15 years of power at 4½% interest, b/a = 0.87/25.8 = 0.033. In the latter two cases 60 cycle power is assumed to cost \$37.2/kW year (including an 80% utilization factor), AC to RF conversion efficiency is 70% and a slight correction has been included to take account of the fact that the power to excite the cavities is proportional to the energy. The values quoted are for an SOC but are not significantly different for a linac. Drastic reduction in accelerator cost might double these figures, drastic reduction in RF capital cost halve them. The useful range of b/a is thus 0.01 to 0.07, with a most probable value of about 0.03. From Fig. VI.44, we then obtain the following information (Table VI.1.19).

TABLE VI.2

Minimum-Cost Parameters for $S = 8 \times 10^{18}$ n/sec and Penalty for Operating at Energies other than the Optimum

b/a	E (GeV)	I (mA)	Beam Power (MW)	Target Power (MW)	0.5 GeV Penalty %	1 GeV Penalty %	2 GeV Penalty %
0.01	0.47	179	84.6	65.1	0.1	25	96
.03	.70	103	71.8	45.7	4.1	3.9	33
.07	.97	67	65.7	35.8	12.2	0	10

FIG. VI. 44 Variation of Values of Energy, Current and Beam and Beam Target Powers for Minimum Cost, and of Cost Premiums for Given Energy Choices, as a Function of b/a (defined in text).

The columns headed " x GeV Penalty" show the additional cost in percent, over the minimum, that must be paid to build and operate ING at energy x . They are given as an indication of the curvature of the cost curve in the vicinity of the minimum and are illustrated in the upper part of Fig. VI. 44. It can be seen that, over the conceivable range of b/a values, the 2 GeV penalty is considerable.

Two GeV is still not a useful energy for high energy physics because, although the kaon threshold is 1.1 GeV, the production cross sections rise so slowly that 3 GeV is estimated to be the minimum useful energy. (See also Section XIII. D. 2). At $b/a = 0.03$ the 3 GeV penalty is 66% and it is probable that a separate 3 GeV machine to satisfy high energy physicists could be built for less than this extra cost.

On the other hand, there seems to be no clear way of establishing a preferred energy for meson production in the range 0.5 to 1 GeV. UCLA⁹⁹ preferred the lower energy mainly for reasons of background in coincidence experiments. However, Yale⁹⁸ and Los Alamos⁵ preferred energies of 0.75 and 0.8 GeV. The thick target yield of pions in the 100-200 MeV region is much better at these higher energies. There appears to be little gain or loss in going to 1 GeV. We conclude then that, for reasons of cost and usefulness for meson physics research, any energy between 0.5 and 1 GeV is about equally desirable. If, however, RF capital costs were to drop to \$0.25/watt, making the most probable b/a about 0.015, the 1 GeV penalty might be considered too great.

The lower energy solutions are unattractive for two reasons. The first entry in Table VI. 2 shows that at 0.5 GeV the beam current is about 179 mA and the target power 65 MW. Both of these values are probably too high for a first ING. The high current intensifies beam blow-up and beam-cavity interaction problems while the high target power intensifies the target cooling problem, making necessary higher flow rates, higher temperature differences or larger target diameter or perhaps all three. These three also raise severe problems of erosion, temperature shock, and flux reduction as discussed in Chapter VII.

We conclude that 1 GeV is a reasonable energy for ING. Higher energies are unnecessarily expensive and lower raise unnecessary accelerator and target design problems. Within the accuracy of the estimates 65 mA at this energy will produce the desired thermal neutron flux.

APPENDIX VI. 2

SELECTION OF SOC PARAMETERS

Two of the parameters describing a SOC (see list in VI.E. 1) are restricted to integral values. They are the number of sectors, N , and the harmonic number, H . Furthermore, in order to make the gradients of magnetic field strength have opposite signs in radially adjacent pole pairs, we restrict N to the odd integers. It is obviously convenient to include N and H in an independent set of parameters chosen from the complete list. One method of making the choice is described in the early chapters of reference³¹.

At an early stage we felt a need for at least a crude procedure for determining optimum values of N and H (and some other parameters) by cost minimization. This information is needed before work on the physics of the SOC can be completed, because the studies on orbit dynamics and beam-cavity interaction are pursued largely by numerical calculation; since it is impossible to study all designs by such means, a reasonable idea of where to begin is needed. The analogous optimization procedure for the linac is well known, and can be carried out with a little elementary calculus. Largely because of the curved paths and the required bending magnets the SOC optimization procedure is much more difficult and requires a considerable amount of computer calculation.

Not all the independent parameters were considered suitable for determination by optimization. Because insufficient information about the frequency dependence of the 60 c/s-to-RF conversion efficiency and about the cost per watt of RF-generating equipment was available, no attempt was made to make the program find an optimum frequency. Calculations were carried out for given values of the frequency. The input and output energies, the magnetic flux density at the central orbit, and the magnet gap dimensions were among the parameters treated in the same way. Another important input parameter was the minimum allowable separation between successive orbits; this parameter depends on the design of the magnetic poles.

In addition to N and H we optimized four other independent parameters - two associated with cavities and two with magnets. The cavities were assumed to be rectangular parallelepipeds. Their width and length were treated as free parameters; the height was calculated from a condition of resonance at the assumed frequency. By suitably choosing the voltage and the radial position of a cavity it was possible to ensure that the orbit separation did not fall below the minimum allowable value. The magnet design of Hudson and Lord¹⁰⁷ was assumed, but the field-shaping shims were not included in the calculations. The two free parameters associated with the magnets were the separation

¹⁰⁷ Electronuclear Division, Annual Progress Report, ORNL 3800 (1964).

between the inner surfaces of the horizontal yoke members and the width of the exciting coil; the height of the coil cross-section is related to the first parameter. The treatment of the magnetic system has been improved somewhat over that given in reference 31. The leakage flux is now estimated by comparison with calculations for an infinite sequence of identical, equally spaced, infinitely permeable pole pairs. The yoke thickness is now calculated by a method which takes into account the variation of permeability with flux density; the permeability curve used was that labelled SAE 1010 (as rolled) in Fig. VI.25 of Section VI.E.3. One quarter of the magnetomotive force is allotted to the iron part of the circuit, the rest to the gap.

The optimum values of the free parameters were determined by minimizing the sum of the items of cost which were deemed to depend significantly on the free parameters. The most important items are the capital cost of RF-generating equipment, the cost of making the cavities, the cost of the iron in the magnets, and the cost of a suitable building. Calculations by S. B. Hodge and H. J. Underhill^{10 8} have given costs remarkably close to the \$70 per square foot assumed in reference³¹ for cavity construction. Several additions and changes have been made since reference³¹ was written. The RF capital cost is now made to depend on the size of the unit, following the curve given by Mosko^{10 9} (in 1964), with some renormalization; the beam power is included in the calculation since it affects the rate for RF capital cost. When the calculations here presented were made we were advised by F. Heath (see section VI. F) to renormalize Mosko's curve to 50 cents/watt for a unit of 2 MW capacity; the rate was assumed to be unchanged for units of greater capacity. The corresponding conversion efficiency was calculated to be 70%. Running costs are now estimated for 5 years instead of for 15. Costs for the vacuum system, for machining pole tips and for vacuum-tube replacement have been added. Rough estimates by W. A. Wolfe and other AECL engineers gave \$400 per foot of pole pair as the cost of making, mounting, and aligning the pairs of magnet poles, assuming that conventional machining techniques could be used. New estimates of building costs have been used from Ch. IX; they are roughly double those in Fig. 9 of reference³¹. Rates of costs for three stages of a SOC system are displayed in the upper tables on pages VI. 151, VI. 153, and VI. 155; some are discussed in other sections of this report. Various assumed parameters, and a few derived quantities, are given in the lower tables on the same pages. We wish to call attention to two changes from reference³¹. One cavity has been omitted from each stage, without any other change in the layout, in order to provide room for injection. Also, because we have become more pessimistic about the focusing system, the magnet gaps have been widened to make room for beam tubes of inner diameters 2, $1\frac{3}{4}$, and $1\frac{1}{2}$ inches for stages 1 to 3 respectively.

^{10 8} AECL report in preparation.

^{10 9} S. W. Mosko, The SOC RF System, proc. AECL Symp. on Separated Orbit Cyclotrons and Their Uses in Neutron Generation (Chalk River), FSD/ING-30 (1965).

Not every design found by the cost-minimizing procedure is necessarily physically acceptable. To simplify the program we have ignored a number of inequality-type constraints on the parameters. For example, the calculated cavity voltage could be large enough to cause electrical break-down. It is much easier to seek a minimum without reference to these constraints, and then to take counter-measures only for those that have been violated. In the case of cavity voltage we have been fortunate. The optimum voltage is always much smaller - five to ten times smaller - than Kilpatrick's¹¹⁰ criterion. Similarly the current density required in the magnet coils is not unreasonable. It is assumed initially that the lowest cost will occur when the orbit separations at the initial and final turn are both set equal to the minimum allowable value. In a few cases only it was found necessary to increase the initial separation by a few centimetres above the minimum value; the cost difference was negligible. In most cases, on the other hand, the unrestricted minimum occurs for a configuration in which cavities and magnets overlap in space. It is then necessary to restrict the cavity width to values which give adequate clearance between cavities and magnets. When used for a final-stage SOC, for which it was originally intended, the program usually produces designs which have adequate orbit-dynamical properties - admittance and stability. For lower-energy stages this is often not the case and we have sometimes been forced to move away from the unrestricted minimum. Though it appears highly desirable that these restrictions should be incorporated systematically in the cost-minimizing procedure this has not yet been done.

Sample results for the three stages of a 10-50-300-1000 MeV 65 mA SOC system appear on pages VI.151, 154 and 156; in each case the result sheet follows the appropriate page of input data. We wish to emphasize that the "total costs" shown in the upper part of each sheet is merely the sum of the costs included in the optimization procedure; undoubtedly some items have been omitted, though we hope that they are relatively small and insensitive to the optimized parameters. It should also be noted that some of the cost rates which enter into the calculation are still not very well known. The machines specified by these tables are used as a reference design in this report, even though we know that they are not quite the best that we could do with present information. After a new design is obtained, by cost minimization, there is a considerable time lag while the new information is digested by those concerned with the various components and before new drawings of the system appear. In order to make the various sections of this report agree with one another, we have used the values of N and H of reference³. This means that the design is not quite optimized for present input data. The most extensive calculations of orbits were done at a time when we believed that the beam current should be

¹¹⁰ W. D. Kilpatrick, Rev. Sci. Instr. 28, 824 (1957).

SEEKSOC MARKID

RATES OF COST, ETC.

60 CY TO RF EFFICIENCY	70.0	PER CENT
COST OF POWER	5.31	MIL/KWHR
	3.72	CENTS/YR/60 CY WATT
INTEREST RATE	5.00	PER CENT
RUNNING CAVITIES	5 YEARS 23.0	CENTS/RF WATT
TUBE REPLACEMENT	.90	CENTS/YR/RF WATT (15000 HOURS LIFE)
REPLACING TUBES	5 YEARS 3.90	CENTS/RF WATT
CAVITY WALLS	70.0	DOLLARS/SQ. FT.
VACUUM SYSTEM CAPITAL	38500	DOLLARS/CAVITY
RUNNING	1540	DOLLARS/YEAR/CAVITY
RUNNING VACUUM	5 YEARS 6667	DOLLARS/CAVITY
YOKE STEEL	32.0	CENTS/POUND
POLE TIP PAIRS	400	DOLLARS/FT.
COPPER COIL	3.50	DOLLARS/POUND
MAGNET POWER SUPPLIES	20.0	CENTS/DC WATT
60 CY TO DC EFFICIENCY	90.0	PER CENT
RUNNING MAGNETS	5 YEARS 17.9	CENTS/DC WATT

THE ACCELERATOR BUILDING COSTS

2.1625 +05 PLUS 1.8200 +03 *DIAMETER

PLUS 7.2720 +01*DIAMETER SQUARED DOLLARS

RESISTIVITY OF CAVITY LINING	1.94 -06	OHM CM
RESISTIVITY OF COIL WIRE	1.92 -06	OHM CM

TABLE OF FIXED PARAMETERS

PARTICLE REST ENERGY=	938.256	MEV
PARTICLE CHARGE NUMBER=	1	
STABLE PHASE ANGLE=	30.0	DEGREES
YOKE TO END POLE=	10	CM
MAGNET GAP HEIGHT=	6.03	CM
MAGNET GAP WIDTH=	10.13	CM
COIL PACKING FACTOR=	.50	
MINIMUM CAVITY-MAGNET CLEARANCE=	20.00	CM
OUTER ORBIT SEPARATION=	10.1	CM
INNER ORBIT SEPARATION=	10.1	CM
FINAL PARTICLE ENERGY=	50	MEV
INITIAL PARTICLE ENERGY=	10	MEV
MEAN FLUX DENSITY IN GAP=	7.50	KILOGAUSS
END OF CAVITY TO WALL=	20	FT
BEAM CURRENT=	65.00	MA
BEAM POWER=	2.60	MW
NUMBER OF MISSING CAVITIES=	1	
FREQUENCY=	50.0000	MEGACYCLES/SEC
WAVELENGTH=	599.6	CM

TABLE OF SOC COSTS

(IN MILLIONS OF DOLLARS)

RF CAPITAL	1.088	(AT 86.35 CENTS/RF WATT)	
RF POWER (5 YEARS)	.290		
CAVITY WALLS	.367		
VACUUM SYSTEM CAPITAL	.462		
VACUUM OPERATING(5 YEARS)	.080	2.286	
IRON FOR YOKE AND POLES	.259		
POLE TIPS	.166		
COPPER FOR COILS	.097		
MAGNET POWER SUPPLY	.065		
MAGNET POWER (5 YEARS)	.059	.646	
SHELTER COST		.897	3.829
BEAM POWER CAPITAL	2.245		
TUBE REPLACEMENT (5 YEARS)	.150		
BEAM POWER (5 YEARS)	.598		2.993

TOTAL COST			6.822
TOTAL CAPITAL COST			5.646
ACCELERATOR CAPITAL COST			3.401

TABLE OF VARYING PARAMETERS

NUMBER OF SECTORS=	13				
NUMBER OF RF CYCLES PER PROTON CYCLE=	20				
RADIUS OF FINAL TURN=	599	CM			
RADIUS OF INITIAL TURN=	276	CM			
CAVITY OUTWARD RADIAL INCREMENT=	86.90	CM			
CAVITY INWARD RADIAL INCREMENT=	37.91	CM			
CAVITY WIDTH=	25.87	CM			
CAVITY LENGTH=	447.74	CM			
CAVITY HEIGHT=	403.62	CM	SURFACE AREA/CAVITY=	4.05 +05SQ.CM.	
PEAK VOLTAGE=	.317	KILPATRICK LIMIT=	2.30 +00	MEGAVOLTS	
PEAK ELECTRIC FIELD=	1.2252	MEGAVOLTS/ M			
POWER LOSS:	105.0	KW/CAVITY,	1.26	MW TOTAL	
NUMBER OF TURNS=	17.01				
YOKE WIDTHS: LI=	36.8	LF=	74.0	CM	
	LB=	55.4	LP=	57.4	CM
YOKE SPACING=	29.6	YOKE LENGTH=	472	CM	
YOKE THICKNESS=	60.6CM	TOTAL MAGNET STEEL	405	TONS	
TOTAL FLUX=	1.18 +08 LINES	MAXIMUM AVERAGE B IN YOKE=	17.0	KILOGAUSS	
MMF	GAP	POLE STEM	YOKE HORIZONTALS	YOKE END	TOTAL AMP-TURNS
	3.60 +04	1.09 +02	2.94 +03	8.95 +03	4.80 +04
COIL WIDTH=	14.17	CM	COIL AREA=	1.38 +02	SQ.CM
COIL CIRCUMFERENCE=	7.85 +02	CM			
TOTAL WEIGHT COPPER=	13.8	TONS			
CURRENT DENSITY=	348.1	AMP/SQ.CM	2245	AMP/SQ.IN	
MAGNET POWER	25.2	KW EACH	.3274	MW TOTAL	
ACCELERATOR DIAMETER	45	FT	ROOM DIAMETER	85	FT
INNER CLEARANCE=	26.14	CM	CASE=	2	
INNER COIL CLEARANCE=	18.22	CM			
OUTER CLEARANCE=	80.84	CM			

SFEKSOC MARKID

RATES OF COST, ETC.

60 CY TO RF EFFICIENCY	70.0	PER CENT
COST OF POWER	5.31	MIL/KWHR
	3.72	CENTS/YR/60 CY WATT
INTEREST RATE	5.00	PER CENT
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VACUUM SYSTEM CAPITAL	38500	DOLLARS/CAVITY
RUNNING	1540	DOLLARS/YEAR/CAVITY
RUNNING VACUUM	5 YEARS	6667 DOLLARS/CAVITY
YOKE STEEL	32.0	CENTS/POUND
POLE TIP PAIRS	400	DOLLARS/FT.
COPPER COIL	3.50	DOLLARS/POUND
MAGNET POWER SUPPLIES	20.0	CENTS/DC WATT
60 CY TO DC EFFICIENCY	90.0	PER CENT
RUNNING MAGNETS	5 YEARS	17.9 CENTS/DC WATT

THE ACCELERATOR BUILDING COSTS

2.1625 +05 PLUS 1.8200 +03 *DIAMETER
 PLUS 7.2720 +01*DIAMETER SQUARED DOLLARS

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RESISTIVITY OF COIL WIRE	1.92 -06	OHM CM

TABLE OF FIXED PARAMETERS

PARTICLE REST ENERGY=	938.256	MEV
PARTICLE CHARGE NUMBER=	1	
STABLE PHASE ANGLE=	30.0	DEGREES
YOKE TO END POLE=	10	CM
MAGNET GAP HEIGHT=	5.40	CM
MAGNET GAP WIDTH=	9.07	CM
COIL PACKING FACTOR=	.50	
MINIMUM CAVITY-MAGNET CLEARANCE=	20.00	CM
OUTER ORBIT SEPARATION=	9.1	CM
INNER ORBIT SEPARATION=	9.1	CM
FINAL PARTICLE ENERGY=	300	MEV
INITIAL PARTICLE ENERGY=	50	MEV
MEAN FLUX DENSITY IN GAP=	7.50	KILOGAUSS
END OF CAVITY TO WALL=	20	FT
BEAM CURRENT=	65.00	MA
BEAM POWER=	16.25	MW
NUMBER OF MISSING CAVITIES=	1	
FREQUENCY=	50.0000	MEGACYCLES/SEC
WAVELENGTH=	599.6	CM

TABLE OF SOC COSTS

(IN MILLIONS OF DOLLARS)

RF CAPITAL	1.266	(AT 50.71 CENTS/RF WATT)	
RF POWER (5 YEARS)	.574		
CAVITY WALLS	.719		
VACUUM SYSTEM CAPITAL	.462		
VACUUM OPERATING(5 YEARS)	.080	3.101	
IRON FOR YOKE AND POLES	1.814		
POLE TIPS	.671		
COPPER FOR COILS	.139		
MAGNET POWER SUPPLY	.124		
MAGNET POWER (5 YEARS)	.110	2.857	
SHELTER COST		1.580	7.538
BEAM POWER CAPITAL	8.240		
TUBE REPLACEMENT (5 YEARS)	.730		
BEAM POWER (5 YEARS)	3.736		12.707
TOTAL COST			20.245
TOTAL CAPITAL COST			15.014
ACCELERATOR CAPITAL COST			6.774

TABLE OF VARYING PARAMETERS

NUMBER OF SECTORS=	13				
NUMBER OF RF CYCLES PER PROTON CYCLE=		18			
RADIUS OF FINAL TURN=	1121	CM			
RADIUS OF INITIAL TURN=	539	CM			
CAVITY OUTWARD RADIAL INCREMENT=		174.63	CM		
CAVITY INWARD RADIAL INCREMENT=		70.36	CM		
CAVITY WIDTH=	114.55	CM			
CAVITY LENGTH=	826.46	CM			
CAVITY HEIGHT=	321.70	CM			
SURFACE AREA/CAVITY=	7.95	+05SQ.CM.			
PEAK VOLTAGE=	1.342	KILPATRICK LIMIT=	1.02	+01	MEGAVOLTS
PEAK ELECTRIC FIELD=	1.1711	MEGAVOLTS/ M			
POWER LOSS;	208.1	KW/CAVITY,	2.50	MW TOTAL	
NUMBER OF TURNS=	31.01				
YOKE WIDTHS; LI=	73.2	LF=180.2	CM		
	LB=126.7	LP=126.7	CM		
YOKE SPACING=	25.0	YOKE LENGTH=	834	CM	
YOKE THICKNESS=	112.7CM	TOTAL MAGNET STEEL	2835	TONS	
TOTAL FLUX=	4.38 +08 LINES	MAXIMUM AVERAGE B IN YOKE=	15.3	KILOGAUSS	
MMF GAP	POLE STEM	YOKE HORIZONTALS	YOKE END	TOTAL AMP-TURNS	
3.22 +04	9.04 +01	3.60 +03	7.05 +03	4.30 +04	
COIL WIDTH=	13.51	CM	COIL AREA=	1.08 +02	SQ.CM
COIL CIRCUMFERENCE=	1.44	+03	CM		
TOTAL WEIGHT COPPER=	19.8	TONS			
CURRENT DENSITY=	399.1	AMP/SQ.CM	2574	AMP/SQ.IN	
MAGNET POWER	47.5	KW EACH	.6175	MW TOTAL	
ACCELERATOR DIAMETER	85	FT	ROOM DIAMETER	125	FT
INNER CLEARANCE=	20.05	CM	CASE=	2	
INNER COIL CLEARANCE=	19.94	CM			
OUTER CLEARANCE=	110.39	CM			

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RATES OF COST, ETC.

60 CY TO RF EFFICIENCY	70.0	PER CENT
COST OF POWER	5.31	MIL/KWHR
	3.72	CENTS/YR/60 CY WATT
INTEREST RATE	5.00	PER CENT
RUNNING CAVITIES	5 YEARS	23.0 CENTS/RF WATT
TUBE REPLACEMENT	.90	CENTS/YR/RF WATT (15000 HOURS LIFE)
REPLACING TUBES	5 YEARS	3.90 CENTS/RF WATT
CAVITY WALLS	70.0	DOLLARS/SQ. FT.
VACUUM SYSTEM CAPITAL	38500	DOLLARS/CAVITY
RUNNING	1540	DOLLARS/YEAR/CAVITY
RUNNING VACUUM	5 YEARS	6667 DOLLARS/CAVITY
YOKE STEEL	32.0	CENTS/POUND
POLE TIP PAIRS	400	DOLLARS/FT.
COPPER COIL	3.50	DOLLARS/POUND
MAGNET POWER SUPPLIES	20.0	CENTS/DC WATT
60 CY TO DC EFFICIENCY	90.0	PER CENT
RUNNING MAGNETS	5 YEARS	17.9 CENTS/DC WATT

THE ACCELERATOR BUILDING COSTS

-8.7000 +05 PLUS 1.9500 +04 *DIAMETER
 PLUS .0000 +00*DIAMETER SQUARED DOLLARS

RESISTIVITY OF CAVITY LINING	1.94 -06	OHM CM
RESISTIVITY OF COIL WIRE	1.92 -06	OHM CM

TABLE OF FIXED PARAMETERS

PARTICLE REST ENERGY=	938.256	MEV
PARTICLE CHARGE NUMBER=	1	
STABLE PHASE ANGLE=	30.0	DEGREES
YOKE TO END POLE=	10	CM
MAGNET GAP HEIGHT=	4.76	CM
MAGNET GAP WIDTH=	8.00	CM
COIL PACKING FACTOR=	.50	
MINIMUM CAVITY-MAGNET CLEARANCE=	20.00	CM
OUTER ORBIT SEPARATION=	8.0	CM
INNER ORBIT SEPARATION=	8.0	CM
FINAL PARTICLE ENERGY=	1000	MEV
INITIAL PARTICLE ENERGY=	300	MEV
MEAN FLUX DENSITY IN GAP=	7.50	KILOGAUSS
END OF CAVITY TO WALL=	20	FT
BEAM CURRENT=	65.00	MA
BEAM POWER=	45.50	MW
NUMBER OF MISSING CAVITIES=	1	
FREQUENCY=	50.0000	MEGACYCLES/SEC
WAVELENGTH=	599.6	CM

TABLE OF SOC COSTS

(IN MILLIONS OF DOLLARS)

RF CAPITAL	2.188	(AT 50.60 CENTS/RF WATT)	
RF POWER (5 YEARS)	.994		
CAVITY WALLS	2.060		
VACUUM SYSTEM CAPITAL	1.232		
VACUUM OPERATING(5 YEARS)	.213	6.687	
IRON FOR YOKE AND POLES	3.051		
POLF TIPS	1.324		
COPPER FOR COILS	.276		
MAGNET POWER SUPPLY	.254		
MAGNET POWER (5 YEARS)	.227	5.132	
SHELTER COST		2.828	14.647
BEAM POWER CAPITAL	23.023		
TUBE REPLACEMENT (.5 YEARS)	1.941		
BEAM POWER (5 YEARS)	10.460		35.425
TOTAL COST			50.071
TOTAL CAPITAL COST			36.235
ACCELERATOR CAPITAL COST			13.212

TABLE OF VARYING PARAMETERS

NUMBER OF SECTORS=	33		
NUMBER OF RF CYCLES PER PROTON CYCLE=	25		
RADIUS OF FINAL TURN=	2088	CM	
RADIUS OF INITIAL TURN=	1557	CM	
CAVITY OUTWARD RADIAL INCREMENT=	192.68	CM	
CAVITY INWARD RADIAL INCREMENT=	48.58	CM	
CAVITY WIDTH=	160.35	CM	
CAVITY LENGTH=	771.95	CM	
CAVITY HEIGHT=	325.32	CM	
SURFACE AREA/CAVITY=	8.54	+05SQ.CM.	
PEAK VOLTAGE=	1.453	KILPATRICK LIMIT= 1.43 +01	MEGAVOLTS
PEAK ELECTRIC FIELD=	.9064	MEGAVOLTS/ M	
POWER LOSS:	135.1	KW/CAVITY,	4.32 MW TOTAL
NUMBER OF TURNS=	27.73		
YOKE WIDTHS: LI= 74.1	LF=149.3	CM	
LB=111.7	LP=110.3	CM	
YOKE SPACING=	26.7	YOKE LENGTH=	739 CM
YOKE THICKNESS=	94.4CM	TOTAL MAGNET STEEL	4767 TONS
TOTAL FLUX=	3.20 +08 LINES	MAXIMUM AVERAGE B IN YOKE=	15.4 KILOGAUSS
MMF GAP	POLE STEM	YOKE HORIZONTALS	YOKE END
2.84 +04	1.01 +02	3.31 +03	6.07 +03
			3.79 +04
COIL WIDTH=	10.00	CM	
COIL AREA=	9.35	+01 SQ.CM	
COIL CIRCUMFERENCE=	1.30	+03 CM	
TOTAL WEIGHT COPPER=	39.5	TONS	
CURRENT DENSITY=	405.3	AMP/SQ.CM	2614 AMP/SQ.IN
MAGNET POWER	38.5	KW EACH	1.2700 MW TOTAL
ACCELERATOR DIAMETER	150	FT	ROOM DIAMETER
			190 FT
INNER CLEARANCE=	26.48	CM	CASE= 2
INNER COIL CLEARANCE=	20.00	CM	
OUTER CLEARANCE=	33.97	CM	

SEEKSOCZ TIME 0 MIN 26 SEC

82 mA. The reference design actually corresponds to an optimization performed at 82 mA, with the terms dependent on beam current converted later to 65 mA. We have not considered it important to try to bring all features of the design into agreement with the latest data, because we have in mind several improvements which will probably have an even greater effect on the system. Costs summed over the three stages of the reference design are listed in Table VI. 3.

TABLE VI. 3
COSTS IN MILLIONS OF DOLLARS

Stage	"Total" Cost	Capital Cost	Accelerator Capital Cost
1	6.82	5.65	3.40
2	20.24	15.01	6.77
3	<u>50.07</u>	<u>36.24</u>	<u>13.21</u>
Total	77.13	56.90	23.38

"Total" Cost is Capital Cost plus five-year running costs; Accelerator Capital Cost is Capital Cost minus the cost of the RF-generating equipment needed for the beam power.

The cost-minimizing program has been very useful in studying the effect of varying some of the independent parameters not included in the minimization procedure. Results of this type are contained in the tables at the end of reference³¹. For example, the "total" cost for one particular third-stage SOC rises at the rate of $\$1.4 \times 10^6$ per cm when the minimum allowable spacing between orbits is increased. One of the interesting facts to emerge from these studies is that the "total" cost appears to fall as the frequency is decreased - Fig. 15 of reference³¹. This work was done with constant values for the efficiency and rate of capital cost. Section VI. F suggests that there will be an improvement in both these quantities as the frequency falls. The optimized design has fewer and fewer sectors as the frequency is decreased. This eventually brings us into conflict with the need for adequate admittance and orbit stability but it appears possible that a better design will be found for a frequency below 50 MHz.

Some work has been done on the effects of changing the various staging energies. There would be an experimental advantage in changing the staging energy between the second and third stages from 300 MeV to 400 MeV. Calculations for a system very similar to the reference design gave an increase of 0.27×10^6 dollars in "Total" Cost and in Capital Cost when the staging energy was moved from 300 to 400 MeV;

the Accelerator Capital Cost went down by an insignificant amount. For other systems the penalty in "Total" Cost ranged from 0.4 to 0.9 million dollars. If the staging energy is fixed at 400 MeV, then a lower "Total" Cost can sometimes be found by increasing the final proton energy slightly above 1000 MeV. We conclude that with the present design the penalty for staging at 400 MeV instead of at 300 MeV is small, if it exists at all, and that our calculations are probably not reliable enough to find it. A different conclusion emerges, however, when we try to increase the final energy to 2000 MeV; at constant neutron production the current falls to 29.5 mA. Because the beam power falls from 65 to 60 MW, we save about $\$5 \times 10^6$ on capital costs and about $\$1 \times 10^6$ on running costs. Unfortunately the other running costs rise sufficiently to cancel these savings, mainly because of increased losses in the third stage. The net result is that the "Total" Cost rises by just about the same amount as the Accelerator Capital Cost, by about $\$20 \times 10^6$. The cost of a planar SOC rises rapidly with energy beyond 1000 MeV, because much more energy must be gained per turn in order to keep the separation between orbits up to the minimum allowable value. It is conceivable that a non-planar SOC, as originally suggested by Russell⁴, might have a lower cost. Little work has been done yet on the best values of the staging energies now set at 10 and 50 MeV. It has been demonstrated that, for the present type of design, it would be very much more expensive to go from 50 to 1000 MeV in one stage instead of two. For various reasons it might be better to use the injecting linac to take the protons all the way to 50 MeV, eliminating the first SOC stage. The discussion in Section VI.D suggests that it would also be cheaper.

One reason why the staging problem has not been studied in greater detail is that we hope that better systems will be possible with tapered cavities. The method of separation of variables¹¹¹ allows us to calculate the resonant frequencies and the electromagnetic fields of cavities in which the width or the height or both decreases as one moves toward the centre of the accelerator. Taper of width produces more clearance between the inner ends of cavities and magnets (or, equivalently, a smaller accelerator), and makes the acceleration process more efficient at the low-energy end of the cavity. Taper of height shifts the peak of the voltage distribution outward from the midpoint; this ought to give rise to a shorter and more efficient cavity. At the moment attempts are being made to incorporate the tapered cavity into the cost-minimizing program. Until this is done one cannot be sure that the RF savings will not be eaten up by increased magnet costs. One preliminary result for a cavity with tapered height alone reduced the RF losses from 6.1 to 4.5 MW and lowered the "Total" cost by about $\$2 \times 10^6$. One other type of change of cavity shape from the rectangular has been studied, though no plans

¹¹¹ J.A. Stratton, Electromagnetic Theory, McGraw-Hill (1941)

have yet been made to use it. This is an increase in cavity width - the dimension parallel to proton motion - above and below the plane of the orbits. This modification reduces cavity losses without impairing the efficiency of the acceleration process.

There is also some hope of being able to improve the magnet system, by reducing the amount of iron in the yokes. This can be done, with our present criterion for yoke thickness, if we can make the iron more permeable for flux densities near 15 kilo-gauss. In the present calculations SAE 1010 steel (as rolled) was assumed; some improvement can be expected from annealing. It might also be desirable to specify a steel with a more favourable chemical composition. Another way to reduce the weight of iron is to step the yoke thickness near each end; in one test case this resulted in a saving of 9%. A much more radical change in the magnet design is considered in Appendix VI.6.

APPENDIX VI.3

S.O.C. ION OPTICS

1. Orbit Dynamics1.1 Equilibrium Orbit

The SOC designs derived as described in Appendix VI.2 do not give the details of the equilibrium orbit or the exact locations of the accelerator components. Parameters derived as described below are tabulated in reference¹¹² and were used for the magnet layouts illustrated in section VI.E.3.

The equilibrium orbit in the SOC is a flat spiral of comparatively few turns. The exact path may be defined in several ways (see for example reference³¹) but the method described below is convenient for orbit tracing and was adopted for this reason. Other possible layouts differ only slightly and the orbit dynamics are essentially unchanged.

A "segment" consists of a bending magnet between two field-free sections of equal length (see Fig.VI.45). An accelerating cavity is placed in the field free section so that its center lies at the end of the segment. The proton energy is treated as constant within each segment and incremented at its end.

The time for a synchronous particle to traverse each segment is fixed

$$t = H / Nf$$

where H is the harmonic number (no. of RF cycles per proton revolution),
 N is the number of segments per proton revolution,
 f is the frequency.

The proton path length per segment is

$$L = \beta c t = H\beta c / Nf = H\beta \lambda / N$$

where βc is the proton velocity,
 c is the velocity of light
 $\lambda = c / f$ is the RF wavelength.

¹¹² B.G. Chidley, Preliminary Design of the ING Proposal Separated Orbit Cyclotron, report FSD/ING-44 (1966).

FIG. VI. 45 Layout of SOC Orbit.

The magnetic rigidity of a proton of velocity β is

$$10^{11} \beta E_0 / c \sqrt{1-\beta^2} = 3129.68 \beta / \sqrt{1-\beta^2} \text{ kG cm.}$$

The magnetic field on the synchronous orbit has a constant value B in the magnet and zero in the drift space. The proton is deflected by a constant angle in each segment, $(2\pi/N)$. This gives a magnet path length of

$$M = 2\pi\rho / N = 3129.68(2\pi\beta) / [NB \sqrt{1-\beta^2}]$$

The length of the straight section is

$$S = L - M.$$

A segment consists of a straight section $(S/2)$, a curved or magnet section (M) , and a second straight section $(S/2)$. The next segment will have a different value of β due to the energy gained in crossing an accelerating cavity.

If the above pattern is followed a complete orbit may be drawn. It is "accidental" that no negative lengths are required, that the orbit does not cross itself, and that the centers of accelerating gaps lie on approximately straight lines but this occurs for all designs suggested by the cost optimizing program (Chapter VI, Appendix 2).

The choices of exactly constant deflection angle and the two equal straight portions are not unique; this was the simplest case which gave an acceptable layout. The approximation that β changes abruptly at the cavity center rather than continuously across the cavity introduces a negligible error.

This accelerator design has no true center and the cavity center lines are not radial. This may complicate alignment problems as discussed in section VI.E.3. A table of magnet coordinates has been given in reference⁴⁸.

The slight curvature of the cavity center lines is not essential and a negligible error results if it is ignored.

1.2 Focusing

A practical machine must focus particles back toward the equilibrium orbit. In the SOC this is done by "strong" or alternating-gradient focusing similar to that in a strong focusing synchrotron⁴⁸.

In a system with alternating gradient focusing the particle is first focused radially and defocused axially, then defocused radially and focused axially. The average force seen by the particle will be focusing both radially and axially. The motion of the particle will be approximately sinusoidal with a fine structure imposed on it by the change of gradients. The motion is stable provided the oscillation in either direction is less than a half-cycle per focusing-defocusing unit. The stability criterion for a system with no straight sections is illustrated in the "necktie diagram" below.

"Necktie" stability diagram for an accelerator of $2N$ segments with field indices n_1 and n_2 and no straight sections. The stable region is shaded.

The presence of straight sections will reduce the stable region so that smaller field indices must be used. This implies a reduction of admittance.

In the SOC the operating point is chosen on the diagonal ($n_1 = -n_2$) at the point which gives the maximum admittance (see next section).

The stability region of an alternating-gradient synchrotron is crossed by a network of bands where resonance effects will destroy the beam. In an ideal synchrotron couplings should not exist between radial, axial, and revolution motions but in a practical machine they do and, if the oscillation frequencies are harmonically related, energy may be coupled between the motions. The operating point must be stationary to avoid crossing one of these bands. The analogous problem is almost non-existent in the SOC because particles never retrace a path and the total number of oscillations is small.

In the SOC phase-focusing is necessary to keep particles synchronized with the RF in spite of small energy errors. This is accomplished by designing the accelerator so that synchronous particles arrive at the accelerating cavity with the voltage rising. Low energy particles take longer to traverse the intercavity space and reach the cavity with the accelerating voltage high and receive an above-normal energy increment. The net effect is a longitudinal focusing force toward the synchronous stable phase and the particles oscillate about this phase. There is some coupling between radial and longitudinal motions and, although the natural frequencies of the two motions are sufficiently different that no resonance effects occur, it is important that the amplitude of the resultant radial motion be small. In some designs where N is small and S/M large, requiring n to be small for stability, this coupling may become severe and the machine completely unsatisfactory.

1.3 Orbit Tracing

The total path of a particle in a SOC is relatively short and it is feasible to follow a particle step by step through the accelerator using a computer.

A particle may be specified by giving its position and velocity relative to a synchronous particle on the equilibrium orbit (a total of 6 components). A relation then exists between the coordinates of a particle before and after traversing an element of the accelerator (curved section, accelerating cavity, etc.). The choice of coordinate system is arbitrary but because the motion consists of 3 nearly-independent components (radial, axial, and phase motion) it is convenient to define the coordinates as in reference⁴⁸:

X = radial distance from equilibrium orbit,

Y = axial distance from equilibrium orbit,

$\phi = 2\pi S/\beta\lambda$ = phase, where S is the component of the distance to the synchronous particle measured along the equilibrium orbit, $\beta\lambda$ is the distance travelled by the synchronous particle in one RF period,

$$X' = dX/dS,$$

$$Y' = dY/dS,$$

E = the difference between the energy of the particle and the synchronous particle.

Penner¹¹³ has described a convenient method of calculating these coordinates after traversing accelerator elements, assuming small deviations and linear (constant gradient) magnetic fields. Computer programs have been written based on this method to do the calculations necessary to follow particles through the SOC. More exact calculations which incorporate the effects of magnetic field non-linearities¹¹⁴ have been used to check the area of applicability of the above approximation.

This program is convenient for studying the effects of departures from ideal injection conditions. It includes simplified space charge effects, transverse defocusing by the accelerating fields, and deflection by the RF magnetic fields in the cavities. The program can easily be modified to study the effects of departure from ideal parameters, some of which are discussed in VI. 3. 2.

1. 4 Particle Motions in a SOC

The particle motion consists of 3 almost independent components: a radial oscillation (X, X'), an axial oscillation (Y, Y') and a phase oscillation (ϕ, E). For historical reasons the first two are called betatron oscillations and the third synchrotron oscillation. The motions interact slightly - particularly the radial betatron and synchrotron oscillations - but the frequencies are different and little energy is transferred.

Traces for typical particles in stage-3 are shown in Figs. 46, 47, 48. The traces are single lines 28 turns long divided for convenience of presentation into 5 turn lengths. The ordinates are X, Y , and ϕ . Note that the betatron motions are not pure sine waves but have a ragged structure imposed on them by the alternating gradient focusing. The curves show a slight decrease in amplitude and frequency during passage through the stage. Resonance problems are avoided by allowing the frequencies to shift relatively rapidly. The decrease in amplitude is due to adiabatic damping.

The oscillation "frequencies" for the reference design expressed as the number of oscillations per turn are given in Table VI. 4.

¹¹³ S. Penner, Rev. Sci. Instrum. 32, 150 (1961).

¹¹⁴ G.E. Lee-Whiting, Private Communication (1965).

FIG. VI.46 Radial Motion in 3rd stage SOC.

FIG. VI. 47 Axial Motion in 3rd Stage SOC.

FIG. VI. 48 Phase Motion in 3rd Stage SOC.

TABLE VI. 4
OSCILLATION FREQUENCIES

		Radial Betatron	Axial Betatron	Synchrotron
Stage-1	In	2.8	1.5	0.24
	Out	2.7	1.45	0.21
Stage-2	In	2.6	1.5	0.18
	Out	2.4	1.4	0.13
Stage-3	In	5.3	4.8	0.12
	Out	4.2	3.7	0.09

1.5 Admittance

Particles can be lost during transit through the accelerator by acquiring a large enough displacement to touch the beam tube (i. e. the displacement exceeds the aperture) or by being low in energy and falling more than $2\phi_s$ behind the synchronous particle. The condition for successful passage can be expressed as a restriction on the initial parameters.

The X and X' coordinates of admissible particles may be plotted (a so-called phase plot) and the admittance restriction defines a boundary within which particles are accepted and outside of which they will be lost. This "area" is called the radial admittance of the accelerator. Similarly, axial and phase admittance may be defined. The area similarly defined for the particles of a beam is called its emittance. The emittance diagram of a beam may be changed in shape, but not in area, by beam transport elements. For a beam to be accepted by an accelerator its emittance diagram must lie within the admittance diagram of the accelerator.

The exact treatment is complex but useful quantitative results can be obtained from the restriction on X and X' for $Y = Y' = \phi = E = 0$, on Y, Y' for the others zero, and on ϕ , E for the others zero.

The admittance of the SOC may be calculated by two methods. A large number of particles with various initial coordinates may be followed through the stage to determine which are acceptable, or a calculation similar to that used for a synchrotron may be used⁴⁸. The first method is tedious even for a high speed computer and for most cases the synchrotron approximation is sufficient.

In the synchrotron approximation the beam defining magnets are assumed to be periodic. The period is taken from one point where the beam has maximum size to the next (usually the middle of a focusing lens). The coordinates of a particle at the beginning of each period satisfy an invariance condition so the maximum displacement a particle will have during a large number of periods can be derived. Particles whose deviations would never exceed the aperture are considered accepted and the others rejected. The SOC magnets are not periodic and the number of segments which can be treated as approximately periodic is finite but the calculation is a valuable guide.

The admittance of an accelerator is proportional to the aperture squared. (Squared because the maximum beam size and angular deviation may both be increased proportionally).

It increases as N is increased and H decreased. Table VI. 5 shows the admittance of a 10 - 50 MeV stage with a 1" aperture for various N and H. This trend is consistent with the general picture of focusing discussed previously. A systematic study of the effect of S/M has not been done but note that from App. VI. 3. 1. 1

$$S/M = [(H\beta\lambda B / 2\pi) \sqrt{(1-\beta^2)} / 3129.68]^{-1}.$$

so the variation is similar to that with H.

The problems of loss of admittance with decrease in N and increase in S/M are aspects of the machine design not considered in the procedure of App. VI. 2 but having a direct bearing on the minimum cost of a satisfactory machine. In particular the cost minimizing process can give misleading results in the saving achievable by reducing frequency. The apparent minimum cost is achieved at lower frequency by increasing the cavity width (proportionally to wavelength) and reducing N. This will ultimately lead to a design with unsatisfactory admittance.

It has been suggested¹¹⁵ that an "admittance invariant" equal to admittance $\times \beta/\sqrt{(1-\beta^2)}$ is independent of energy and so a more useful quantity. An admittance invariant of 10π mm milliradians has been used for the beam throughout the accelerator. This is a somewhat arbitrary number based on the measured emittance of the CERN injector linac at 75 mA²².

Phase plots of a beam with this emittance at injection and extraction are shown in figures VI. 49 and 50. The SOC stages being capable of handling beams with larger emittances there is space to accommodate some constructional and alignment errors. The limitations on these errors is discussed in Appendix VI. 3. 2.

¹¹⁵ J.M. Kapchinski, et al., Radio Technical Institute NTD-634A Moscow 1963 (per reference 22).

FIG. VI. 49 Radial and Axial Emittances at Injection.

FIG. VI. 50 Radial and Axial Emittances at Ejection.

TABLE VI. 5

ADMITTANCES IN MM MRADIANS FOR STAGE-I BASED ON A 1"
DIAMETER BEAM TUBE TO SHOW VARIATION WITH N AND H

Harmonic No. H	No. of Segments N						
	7	9	11	13	15	17	19
14	39	45		81	94	106	
16	36	18	57				107
18		14	50	64	77	87	98
20			42	58	70	80	
22					64		83
24				47		69	
26						54	72
28				37		60	68
30					46	56	64

The maximum emittance invariants which could be handled by the SOC stages at injection and extraction are listed in Table VI. 6. The phase plots for these beams are ellipses with the same orientation as for the 10π mm milliradian beams shown in figures 49 and 50 but with both axes increased by a factor $\sqrt{(\text{max emittance}/10)}$. This implies for example that at the exit from stage-3 the beam may be shifted by $0.6(7.4 - 1) = 0.99$ cm before loss will occur.

TABLE VI. 6

MAXIMUM EMITTANCE INVARIANTS OF BEAMS
 (π mm milliradian)

	Injection	Extraction
Stage 1	34	36
Stage 2	32	37
Stage 3	52	74

The output beam from the third stage SOC has X, X', Y, Y' within the areas shown in fig. 49 and ϕ , E restricted to an elliptical region $\phi = \pm 15^\circ$, $E = \pm 7.5$ MeV.

1.6 Pole Tip Structure

To ease alignment problems it may be advantageous to subdivide the pole tips into regions with gradients of opposite sign. The divisions considered are indicated below.

Triplets were chosen for the reference design since the work of Worsham indicated that they give better admittances than singlets and doublets^{116, 117} and because an examination of more complex subdivision found them to offer little advantage¹¹⁸. A recent re-evaluation of singlets and doublets, shown in Table VI.7-9 indicates no disadvantage compared to triplets and they may even be superior. The simpler pole structure is attractive but it must be noted that a complete examination of tolerances has not been done and difficulties may exist.

TABLE VI. 7

PARAMETERS FOR VARIOUS POLE-TIP STRUCTURES (STAGE-1)

	Singlets	Doublets	Triplets
a) Magnet length (cm)		15	7.5
b) Optimum index	Not	4.9	10
c) Gradient (kG/cm)	satisfac-	0.6	1.2
d) Admittance	tory	240	230
e) Radial position tolerance (cm)		0.075	0.050
f) Synchrotron freq.		1/ 4	0.24
g) Radial shift caused by $\Delta\phi = 10^\circ$		0.17	0.27

¹¹⁶ R.E. Worsham, IEEE Trans. Nucl. Sci. 12 (3), 644 (1965).

¹¹⁷ R.E. Worsham, FSD/ING-30 p.15 (1964).

¹¹⁸ B. Chidley, FSD/ING-30 p.32 (1965).

TABLE VI. 8

PARAMETERS FOR VARIOUS POLE-TIP STRUCTURES (STAGE-2)

	Singlets	Doublets	Triplets
a) Magnet length (cm)	64	32	16
b) Optimum index	1.3	5.7	11
c) Gradient (kG/cm)	0.07	0.3	0.6
d) Admittance	98	95	92
e) Radial position tolerance (cm)	0.035	0.130	0.075
f) Synchrotron freq.	1/ 6	1/ 6	0.18
g) Radial shift caused by $\Delta\phi = 10^\circ$	0.47	0.51	0.31

TABLE VI. 9

PARAMETERS FOR VARIOUS POLE-TIP STRUCTURES (STAGE-3)

	Singlets	Doublets	Triplets
a) Magnet length (cm)	68	34	17
b) Optimum index	11.2	38.2	80
c) Gradient (kG/cm)	0.23	0.8	1.7
d) Admittance	83	63	61
e) Radial position tolerance (cm)	0.160	0.120	0.070
f) Synchrotron freq.	1/ 8	1/ 8	0.12
g) Radial shift caused by $\Delta\phi = 10^\circ$	0.37	0.20	0.22

2. Machine Errors2.1 Tolerances

According to the linear orbit theory, if applicable, irregularities in the accelerator structure will cause the beam to oscillate coherently about the equilibrium orbit and the distinct edge of the beam will be retained. Provided the oscillation does not become so severe that the beam touches part of the accelerator no particles will be lost.

The maximum beam shift which can be tolerated is $(R_b - R_a)$, R_a being the maximum beam radius, R_b the beam tube radius. If the beam sticks together, this condition is equivalent to requiring that a single particle on the equilibrium orbit does not gain an oscillation amplitude greater than $(R_b - R_a)$.

This simplified picture has been used as the basis for most of the tolerance calculations.

The definition of tolerance limits is somewhat arbitrary. If the limiting accuracy lies in the ability to measure a quantity then the values are normally distributed with a root mean square deviation σ . (Often 3σ is quoted as the maximum error). If the ability to adjust a quantity is restrictive and any value between min. and max. is accepted with ones outside the range rejected, a second type of distribution results. The two are related by $\sigma = (\text{max-min}) / 2\sqrt{3}$.

In this discussion the errors are assumed to be normally distributed and the limit given is σ .

Tolerances were calculated by following the path of a single particle through an accelerator which had either a parameter in error by a fixed amount or a parameter which took on a different randomly chosen error in each segment of each turn. To guard against an unfortunate choice of random numbers the results given are the averages of 7 sets. Since only one set of errors will be present in an actual machine the tolerances are only meaningful to about $\pm 35\%$.

An orbit can be followed in an inexact SOC by a computer program similar to that for an exact SOC but with the specified components altered¹¹⁹.

It is possible to include several types of misalignments and parameter errors at one time but, except to note how the effects combine, it is usually more instructive to consider one type of error at a time. The results in Table VI.10 were calculated on this basis, so the tolerances are not to be considered design specifications but to represent the leeway available to be shared among all types of error.

The tolerances on cavity position are for all cavities misplaced by the same amount.

The magnet alignment is assumed to be done in three phases: bench alignment of the triplets for each segment of each turn, alignment of the triplets on the yokes for each segment, and alignment of the magnet yokes.

For linear displacements the upper and lower pole tips are assumed to move together. Independent motion is interpreted as a rotation.

¹¹⁹ B.G. Chidley, C.J. Allan, FSD/ING-29 (1965).

TABLE VI. 10
SOC TOLERANCES

RF Errors

Frequency stability	1 part in 10^6	(short term)
Cavity voltage - one unit		100%
Cavity voltage - all units (σ)		30%
Phase - one unit		1.2 radians
Phase - all units (σ)		0.3 radians

Cavity Errors

Voltage tilt	20% end to end
Phase tilt	0.2 radians end to end
Position of beam holes	0.5 cm
Position (except for beam holes)	
radial	10 cm
vertical	10 cm
tangential	10 cm

Magnet Errors

Position		σ
Linear displacement		
Pole tip subunits	radial	0.005 cm
	axial	0.004
Pole tip units	radial	0.03
	axial	0.04
	tangential	0.09
Segments	radial	0.05
	axial	0.10
	tangential	0.15
Rotation about specified axis		
Pole tip subunits	tangential	0.0002 radians
Pole tip units	radial	0.002
	axial	0.0015
	tangential	0.0003
Segments	radial	0.002
	axial	0.0008
	tangential	0.0001
Field (central strength)		0.08%
Gradient	$\sigma = 3\%$ shows no effect	
Gradient non-linearity	$2A_2/A_{1p}$ (see App. VI. 3. 2. 3) 2%/cm	

The error in central field strength varies randomly from one segment to the next but the same error applies for all turns of a segment. A variation of the field gradients will cause emittance mismatch problems.

2.2 Error Compensation

If machine imperfections displace the beam from the central orbit but do not diffuse it, compensation is possible. The beam position could be measured with a non-intercepting beam probe^{120, 121} and the beam re-positioned with correcting coils¹¹⁹. If the beam is re-positioned n times, the tolerances may be relaxed by a factor $1/\sqrt{n}$.

Non-linearities which may arise from pole-tip end-effects or from gradient variations due to pole contour design or fabrication errors will tend to diffuse the beam and reduce the effectiveness of this procedure. Until both the theory is satisfactorily developed and the practical accuracy achievable is known it will not be clear whether tolerances can be relaxed by this technique.

2.3 Magnet Non-Linearities

The tolerances have been calculated with the assumption that the magnetic field varies linearly with distance from the equilibrium orbit.

$$B_z = B_o \{1 + A_1(r-r_o)/\rho\}$$

where $r-r_o$ is the distance from the equilibrium orbit and ρ is the radius of curvature. If we assume a slightly more general field variation we have

$$B_z = B_o \{1 + A_1(r-r_o)/\rho + A_2(r-r_o)^2/\rho^2\}.$$

The orbit tracing program has been modified to allow non-linear fields and includes second order interactions.

Field non-linearities cause the betatron oscillations to become asymmetric and dependent on amplitude. Severe non-linearity will cause the oscillation to become unstable.

¹²⁰ R.S. Larson, H.A. Woods, IEEE Trans. on Nucl. Sci. NS-12 (3) 862 (1965).

¹²¹ A.J. Sherwood, IEEE Trans. on Nucl. Sci. NS-12 (3) 925 (1965).

A beam oscillating about the central orbit will not remain sharp edged as described above but will smear into a uniform distribution about the central orbit with an increased radius. Correction is not possible if the beam has become smeared.

Non-linearities equivalent to a change in the field index of 2%/cm prohibit beam corrections and result in instabilities if the maximum excursion reaches $\sim 80\%$ of the beam tube radius. A value of 10%/cm restricts the useful aperture to less than the beam diameter. Only these two values have been examined.

3. Limitations

It is important that the limitations of this treatment be recognized.

The orbit calculations have all been done with the assumption that the magnetic fields change abruptly at the planes between magnet subunits. In practice the field changes smoothly along the track of any particle.

It has been shown¹²² that the effective boundary between a positive and negative gradient section is not only at an angle to the actual edge but is also not straight. This curvature represents a non-linearity in the field and may be troublesome.

Idealized RF cavities have been used. Transit time factors and RF defocusing effects have only been crudely approximated.

Space-charge calculations have been based on a very crude model which may be adequate for stages -2 and -3 but is questionable for stage -1¹²³.

Tolerance calculations have been done from a simplified viewpoint. A more exact calculation using a mesh of all possible values of input parameters may reveal unexpected limitations.

Types of errors which will arise may have been completely overlooked. About 40 types have been investigated but there is no guarantee that all important ones have been considered.

¹²² R.S. Lord, private communication (1965).

¹²³ T.D. Newton, FSD/ING-53 (1966).

APPENDIX VI.4

BEAM-CAVITY INTERACTIONS

1. Theoretical Studies

We consider first the equilibrium fields excited in a SOC cavity by the passage through it of rigid bunches of protons centred on the equilibrium orbit, that is, of the fields which exist after the passage of a large number of such pulses. From these fields we calculate the transverse momentum and displacement and the shifts in kinetic energy and in phase imparted to a proton of the bunch in passing through the cavity, that is, the "deflections" of a proton due to fields excited by the beam.

For an exactly defined cavity these deflections are not meaningful since the deviations of an actual cavity from its specified form are of such size that the higher modes, in terms of which the calculation is done, are significantly different from those of the exactly specified cavity. We therefore calculate, instead, the distribution of deflections for a statistical ensemble of cavities, defined by the expected deviations of an actual cavity from the ideal form.

The calculations suggest that in a very high percentage of actual cavities the deflections resulting from the modes which can be excited by proton bunches symmetrical with respect to the median plane of the cavity are negligible. If, then, the deflections due to an actual cavity are found to be not negligible it is highly probable that a minor adjustment of the cavity form (leaving the frequency of the wanted mode unchanged) will produce negligible deflections.

We next consider the effect of modes which cannot be excited by a properly located charge pulse but can be by a deflected pulse. The excitation of such modes may grow with the passage of successive pulses through the cavity. A simple theory is used to find upper bounds to the excitation of these modes. This upper bound is completely negligible in the case of non-resonant modes, but may not be so for modes resonant to a harmonic of the wanted mode. Further calculations are needed, taking into account all cavities and the focusing system, which has so far been ignored.

Because the diameter of a beam tube (about 5 cm) is much less than the wave length (600 cm) of the 50 MHz RF, frequencies below the 85th harmonic of the fundamental are not propagated through the beam tube. We thus assume that there is no electro-magnetic coupling between cavities. We also ignore all other openings in the cavity wall, the cavity been bounded by a closed surface of (for the time being) perfectly

conducting material. Such a cavity has a discrete, infinite set of natural modes of electro-magnetic oscillation.

Consider a single pulse passing through the cavity, entering and leaving through the perfectly conducting walls. Before it arrives there is no field and after it leaves the field can be described by a vector potential $\underline{A}(\underline{r}, t)$. Following Condon¹²⁴ we expand this in terms of the vector potentials $\underline{A}_\alpha(\underline{r})$ of the natural modes of the cavity

$$\underline{A}(\underline{r}, t) = \sum_{\alpha} \underline{A}_{\alpha}(\underline{r}) q_{\alpha}(t) \quad (1)$$

with amplitudes $q_{\alpha}(t)$ satisfying

$$\ddot{q}_{\alpha}(t) + \omega_{\alpha}^2 q_{\alpha}(t) = (1/\epsilon) \int \underline{J}(\underline{r}, t) \cdot \underline{A}_{\alpha}(\underline{r}) d\underline{r} \quad (2)$$

in which ω_{α} is the frequency of the α -mode, ϵ the electric inductive capacity of empty space and $\underline{J}(\underline{r}, t)$ the current density due to passage of the pulse through the cavity. We assume the pulse is rigid and moves uniformly through the cavity. Thus in calculating the fields induced by the pulse we assume the fields have no effect on the pulse. We are also ignoring the effect of the applied field on the pulse. Then the right side of (2) is a known function of t so that $q_{\alpha}(t)$ is given by integration of an elementary inhomogeneous differential equation. The right side of (2) is zero after (and before) the pulse has passed; q_{α} then oscillates sinusoidally with frequency ω_{α} and amplitude which is non-zero except in special cases.

We now specialise to a rectangular parallelepiped cavity. The integrations have been performed to obtain the q_{α} for the case of a pulse moving parallel to one edge of the cavity. (The q_{α} 's have also been calculated by the Green's function method¹²⁵). The charge density in the pulse is assumed uniform in directions perpendicular to its motion and to vary as one loop of a sine curve in the direction of motion.

The current density vector $\underline{J}$ in the case treated is everywhere parallel to the y -axis. Since the electric field of a natural mode is proportional to the vector $\underline{A}_{\alpha}$, if the electric field of a mode is everywhere perpendicular to the y -axis that mode is not excited. If the

¹²⁴ E. U. Condon, Rev. Mod. Phys. 14, 341 (1962).

¹²⁵ K. B. Winterbon, A. E. C. L. reports FSD/ING-16 (1965) and FSD/ING-48 (1966).

y-axis is the propagation direction, this means that TE modes are not excited. The label α represents the triplet of integers n_1, n_2, n_3 . Then the excited modes may be written:

$$\text{TM}_{n_1 n_2 n_3}$$

The integers n_1, n_2, n_3 , correspond to the x, y, z, directions. Let the z-axis be vertical. If the pulse moves in a plane mid-way between the upper and lower bounding planes, then the amplitude is zero unless n_3 is odd. For TM modes with n_3 odd the amplitudes q_α are non-zero, except for special values of x . These modes generally produce transverse forces on a particle, even when the beam is in its unperturbed position.

The pulse is, of course, one of a succession of uniformly spaced pulses. Because Maxwell's equations are linear the total fields induced by all earlier pulses can be obtained by addition, with a suitable adjustment of the origin of time. Consider next the fact that the cavity is really not made of perfectly conducting material. Each mode has a finite quality factor, Q_α . If the Q_α 's are large enough, the only important effect is to insert a factor $\exp(-\omega_\alpha t / 2Q_\alpha)$ in each term of the expansion (1). Now the sum over earlier pulses yields a finite result. Each amplitude is modified by a factor of the form $\Gamma_\alpha e^{i\psi_\alpha}$. Elementary formulae for Γ_α and ψ_α are easily obtained but all we need do here is to note that Γ_α displays a resonance behaviour if ω_α is nearly equal to an integral multiple of the fundamental frequency, - i.e. if $\omega_\alpha \simeq n\omega_0$. The value of Γ_α at a resonance is approximately $Q_\alpha / (\pi n)$; the full width at half the peak height is approximately $\sqrt{3} \omega_\alpha / Q_\alpha$. The electric field strength in a resonant mode can be dangerously high. For a typical 50 MHz SOC cavity and a 65 ma beam we calculate field strength on the order of 5×10^6 volts/metre for a low-n resonance, compared to 5×10^2 volts/metre for single-pulse excitation.

Having seen how to calculate the induced fields, at least in principle, we consider their effect on the motion of a proton. The changes in momentum are readily calculated to the first order; the approximations involved are the same as those used in the usual calculation of the transit-time factor. From the change in transverse momentum we obtain an angular deviation - $\delta_x = \Delta P_x / P$. The change in longitudinal momentum gives rise to a shift in kinetic energy, ΔT . A further integration produces a transverse displacement, Δx , and a phase shift $\Delta \phi$. These four changes in the motion we call the deflections. Analytic expressions for each of the four deflections resulting from any TM mode have been obtained. Because the effects of rapidly varying fields tend to cancel, the series for the deflections converge more rapidly than those for field components.

We ought now to be able to calculate, apart from convergence difficulties, the deflections corresponding to the equilibrium amplitudes of the induced modes of oscillation. Calculations for the nominal set of cavity dimensions would not be very meaningful. Because of errors in construction, the cavities will not have the desired size and shape. The frequency shifts corresponding to the expected errors in dimensions are large compared to the widths of resonances. The best that one can hope to obtain is some sort of probability information for cavities with dimensions nearly equal to the nominal values. We attempt to obtain this information by a Monte Carlo calculation. A 50 MHz cavity with dimensions $a = 7.72$ m, $d = 3.26$ m, $b = 1.60$ is assumed. Calculations were performed for the ensemble of cavities formed by choosing each dimension randomly in the tolerance range about the nominal value - $\pm 1/8$ in for a , $\pm 1/16$ in for b and d . For such a cavity the fundamental frequency is not quite at 50 MHz. To bring it back to 50 MHz we tune it with a plunger at one end. The frequency shifts for the fundamental and for the other modes considered were calculated by Slater's perturbation theory¹²⁶. The shift in the frequencies of the other modes has the desirable effect of destroying the harmonic relationship, a property of rectangular cavities, between the fundamental and certain higher modes. The cavity was assumed to be excited by 29 turns of a 65 mA beam. The spacings were obtained from a SOC-parameter optimization procedure³¹; the inner turn was 45 cm from the inner end, the outer 192 cm from the outer end. The input proton energy was 300 MeV; the output energy 1000 MeV. The pulse length was assumed to be $\beta\lambda/4$ at all times; its diameter was 1 cm. All modes with frequencies less than or equal to the 15th harmonic, except the fundamental, were included; there were 1408 of them. For each cavity of the ensemble the total deflections for all 1408 modes were calculated. Then probability distributions were constructed for each deflection.

In Fig. 51 the distributions of the two transverse deflections are shown for a proton in the inner turn which was initially half way between the centre of the pulse and the front end. The two longitudinal deflections are shown in Fig. 52. In every case the mean value of the deflection is insignificantly different from zero. Each of the distributions illustrated has two peaks, one on each side of zero. For other test particles the distribution sometimes appears to have only one central peak, but in these cases the total widths are very much smaller. The small vertical bars accompanied by percentages indicate that the deflections for these percentages of the total number of cavities lie beyond the bars.

The important feature of all these distributions is that their widths are extremely narrow. According to Chidley* a typical third-stage SOC can tolerate deviations chosen randomly in the range - 0.07 to +0.07 milliradians in every cavity. We believe that the other deflections are even less critical.

¹²⁶ J.C. Slater, Rev. Mod. Phys. 18, 441 (1946).

* See Appendix VI.3, Section 2.

FIG. VI. 51 - Distribution of Deflections Due to Higher TM-Modes

FIG. VI. 52 - Distribution of Deflections Due to Higher TM-Modes

To discover how rapidly the sum over modes converges, we also calculate the distributions for the 1416 modes lying between the 15th and the 19th harmonics. The widths are found to be roughly three orders of magnitude smaller than those in Figs. 51 and 52. This is not as good an indication of rapid convergence as it seems at first sight, because most of the width in the figures comes from the single mode TM_{303} . The doubly peaked nature of the distribution is also a result of this fact. The calculations suggest that in a very high percentage of the cavities that one might construct the deflections resulting from the TM modes considered will be negligible. However, more calculations will be needed before we can be sure.

Consider next the modes which are not excited by a perfectly placed beam. If the beam is moved slightly out of the horizontal plane of symmetry, the TM modes with n_z even will begin to be excited. Though the amplitudes of excitation are small for small deflections, the effects can grow as the beam passes through the accelerator. The excitation left behind in a cavity by one pulse can cause the next pulse to receive a greater deflection; this greater deflection means more excitation, and so on. Thus the fields in the cavities are in a sense coupled together by means of the beam. We call the modes for which this is possible secondary modes, to distinguish them from the modes considered earlier, which may be termed primary modes. The excitation of primary modes is less sensitive to the position and orientation of the beam.

If the beam is inclined at an angle to the y-axis, TE modes will be excited. These are secondary modes, since the excitation grows as the inclination is increased. However, the presence of TE excitation in a cavity does not lead to an increase in the inclination of a particle passing through it. A theorem of Panofsky and Wenzel⁹⁴ says that the change in transverse momentum is zero if the electromagnetic field can be derived from a vector potential. The condition is obeyed by the part of the excitation resulting from pulses which have already passed through the cavity, and this is by far the largest part of the excitation.

We give a simple theory which may be used in finding upper bounds for the growth of the excitation of secondary modes. The focusing forces will be ignored. Consider a SOC with N cavities and M orbit turns. Let the deflection in the r th beam position before the n th cavity be $\xi_{r,n}$, and let a field strength parameter for the n th cavity be F_n . We assume that

$$\xi_{r,n+1} = \xi_{r,n} + C_r F_n; \quad (3)$$

the coefficient C_r is an average for the r th turn. Next assume the F_n is a linear function of the deflections in all the turns at the n th cavity -

$$F_n = \sum_{s=1}^M G_s \xi_{s,n} \quad (4)$$

the coefficient G_s is an average for the s th turn. Combining (3) and (4) one gets a linear relationship between the deflections at the $(n+1)$ th cavity and those at the n th cavity. There is a slight complication of the notation between the N th and 1st cavity. The deflection $\xi_{1,1}$ is to be regarded as given, and $\xi_{M+1,1}$ is to be calculated. Consider the matrix B , defined by

$$B_{rs} = C_r G_s$$

Since

$$B^2 = \text{Tr}(B) B,$$

one can show that

$$\xi_{M+1,1} / \xi_{1,1} = 1 + \frac{\alpha \sum_{r=1}^M \sum_{s=1}^M G_r C_s}{1 - \alpha \sum_{r=2}^M \sum_{s=1}^{r-1} G_r C_s}, \quad (5)$$

with

$$\alpha = \frac{(1 + \text{Tr } B)^N - 1}{\text{Tr } B}$$

From (5) we can obtain an upper bound on the growth for the case in which all the products $G_r C_s$ are small. Replace G_r by an upper bound G , and C_s by an upper bound C . Then (5) yields

$$\xi_{M+1,1} / \xi_{1,1} < 1 + NM^2 G C. \quad (6)$$

This formula has a reasonable appearance. The growth factor for the passage through one cavity is $1 + G C$; there are NM passages through cavities, and the beam excites each cavity M times.

We apply (6) to the case of the growth of the displacement of the beam from the horizontal plane of symmetry through the excitation of TM modes with n_3 even. The second term on the right of (6) can be shown to be less than $0.7 \times 10^{-2} \Gamma_a \omega_0 / \omega_a$, for the 50 MHz SOC.

Thus for non-resonant modes, for which $\Gamma_a \sim 1$, the effect is completely negligible. For a mode exactly resonant at the n th harmonic we have $\Gamma_a \simeq Q_a / (\pi n)$. The upper bound is then much larger than unity, at least for the lower harmonics. To make further progress it is probable that a Monte Carlo calculation is necessary, taking into account all cavities and the focusing system.

There is another line of argument which suggests that the effects of the secondary modes should not be much greater than those of the primary modes. The excitation is really a non-linear function of deflection. The maximum values of the secondary excitations for the worst possible values of the deflections are of the same order of magnitude as the excitations of the primary modes. Thus the electromagnetic forces resulting from the secondary excitations should not be appreciably greater than those resulting from the primary excitations.

2. Electron Analogue Beam Loading Experiment

The calculations discussed in the preceeding section are being checked experimentally.

Ideally one would like, to investigate beam loading, to have a full size SOC cavity and a proton beam with the same microstructure as a SOC beam.

We have chosen a more modest approach. First, since electron beams are easier to produce than proton beams we shall use electrons. This means, incidentally, that RF power levels are considerably reduced. Second, since the 50 MHz SOC cavity is an enormous structure we have elected to have cavities of a size manageable in the laboratory, to scale the frequency to 400 MHz.

Basically the experimental program involves sending a pulsed electron beam through a 400 MHz model of a rectangular SOC cavity and studying the effect of the beam on the electromagnetic fields in the cavity and also the effect of the fields on the beam. Figure VI.53 is a schematic of the setup.

To simulate accelerator microstructure the electron pulses must have a width of less than 20% of the oscillation period of the cavity field, i.e. 0.5 ns in this case.

The magnitude of the field in the cavity is established by the requirement that the change in velocity of the electron in the analogue should be the same as for protons in passing through an SOC cavity. The scaling relation derived from this requirement is

FIG. VI. 53 Schematic of Electron Analogue Beam Loading Experiment.

$$E_e = (\lambda_p m_e / \lambda_e m_p) E_p$$

where, λ_p , E_p are the wavelength and magnitude of the accelerating field in the SOC and λ_e , E_e the same in the electron analogue case. m_e/m_p is the ratio of the electron to proton mass.

Equality of the ratio of the energy extracted from the cavity by each pulse to the total stored energy for the SOC cavity and the analogue determines the magnitude of the electron beam current, i.e., which is given by

$$i_e = (m_e / m_p) i_p,$$

where i_p is the proton beam current in the SOC.

A summary of the important parameters for the electron analogue beam loading experiment are shown in Table VI.11 along with the corresponding SOC values for comparison.

The first and most obvious measurement that can be made with the electron analogue apparatus is the energy gain of the electrons on passing through the cavity. This can be done as a function of beam current, thus providing the first evidence of where beam loading is significant.

Simultaneous measurement of the phase of the RF field in the cavity may also be useful in interpreting the results.

The experiment will also provide a direct check on the theoretical treatment of beam loading. For example, Winterbon has calculated the various excitations expected in a cavity resonant at 400 Mc/s in the TM_{010} mode traversed axially by an electron beam with characteristics shown in Table VI.11¹²⁷.

In Table VI.12 the degree of excitation, relative to the fundamental, of ten higher order modes is indicated as

$$\log(E_{\text{fundamental}}/E_{\text{mode}}).$$

Although the power levels of these higher modes is 70 db - 107 db below the fundamental power level one should nevertheless be able to detect them with a good spectrum analyzer.

¹²⁷ K.B. Winterbon, Private Communication.

TABLE VI. 11

COMPARISON OF EABLE PARAMETERS WITH
THOSE OF A 300 MeV - 1000 MeV SOC

	SOC	Analogue expt.
<u>Beam</u>		
Particle	proton	electron
Current (ave.)	65 mA	35.6 μ A
Diameter	1 cm	1.3 mm
Pulse Length	3.2 ns	0.5 ns
Energy	150 MeV	80 keV
<u>Cavity</u>		
Gap	1.73 m	21.4 cm
Height	3.18 m	39.8 cm
Length	8.93 m	111.5 cm
E _{max}	0.84 MV/m	3.68 kV/m
Resonant Frequency	50 MHz	400 MHz
Q	92146	32573
Power Loss in Cavity Walls	131 kW	50 mW

TABLE VI. 12

EXCITATION ENERGIES OF HIGHER ORDER MODES IN A
CYLINDRICAL CAVITY, RELATIVE TO FUNDAMENTAL WHEN
A PULSED ELECTRON BEAM PASSES THROUGH AXIALLY

$\log(E_{\text{fundamental}}/E_{\text{mode}})$	Frequency (MHz)
0	400.00
7.09	1601.37
8.37	807.75
9.29	3597.29
9.50	2411.76
9.82	2010.40
10.20	1155.63
10.31	918.17
10.60	2083.08
10.76	4783.58
10.79	1677.16

APPENDIX VI.5

EFFECTS OF SPACE AND IMAGE CHARGES

The SOC of this proposal is, by present standards, a high current machine. It is therefore necessary to consider what difficulties may arise from the large current.

The protons travel in bunches, each of which contains about 10^{10} protons. The separation between bunches is about 3 times the length of a bunch. At 10 MeV in the low energy stage a bunch can be about 22 cm long and 2.4 cm in diameter.

The protons repel one another by mutual electromagnetic interaction (the space charge effect) and induce charges and currents on the surface of the conducting beam tube which also modify the electromagnetic fields through which the proton beam moves (the image charge effect). One calculates both these effects together, i.e. one seeks to determine the electromagnetic fields set up during the passage of a bunch through a beam tube and the effect of these fields on the structure of a bunch. There are interactions between bunches, but these are greatly reduced by the screening provided by the beam tube so that the dominant effect is that of one bunch on itself. This is most significant at low energies.

The self-field of a bunch, and the distribution of protons within the bunch, are obtained as a self-consistent solution of Maxwell's equations and the collisionless Boltzmann equation. The basic method is described by Sessler¹²⁸ as the "second approach". A calculation made by Morton¹²⁹ is similar in principle and purpose but we have made fewer approximations and have included a consideration of the distribution of protons in transverse position and momentum. The latter can have a very significant effect.

The self-consistent calculation cannot be carried out for a real machine design. We used a model, - a single bunch of charge travelling through a very long uniform cylindrical beam tube and subject to continuous, cylindrically symmetrical, effective transverse and longitudinal focusing forces. These effective focusing forces represent the time average of those provided by the machine design. The appropriate transverse focusing force is most easily obtained from the betatron oscillation frequencies determined by the orbit tracing described above in

¹²⁸ A.M. Sessler, Proceedings of the V International Conference on High Energy Accelerators, (Frascati, 1965) also available as UCRL-16440, (Oct. 4, 1965).

¹²⁹ P.L. Morton, Rev. Sci. Instr. 36, 1826 (1965).

Appendix VI. 3. Longitudinal focusing in the machine is provided by the sinusoidal variation in time of the cavity voltages and the effective longitudinal force can be directly calculated from the appropriate machine parameters.

It is obvious that this model does not allow for passage through cavities. Results of the calculations described in this subsection apply only to the drift tube sections of the orbit. The interactions between bunch and cavity are discussed in Appendix VI. 4.

The effects of high current can be most simply expressed in terms of the admittance (see Appendix VI. 3) of the SOC which must be matched by the emittance of the beam provided by the injector or previous SOC stage. The effect of large currents is to reduce the admittance and thus to require a better quality of beam from the previous accelerator.

Complete numerical results are not yet available*. However from presently available solutions it can be estimated that both the transverse and longitudinal admittances of the 10-50 MeV stage will be reduced to about 50% of the zero current values at a current of 65 mA. Thus the injected beam must be of high quality to avoid spill.

However the spill, if any, will occur in the first few orbits of the initial stage. The admittance of the stage is defined by the characteristics of the first orbit which passes through the low voltages across the inner ends of the cavities. At the position of maximum voltages near the middle of the first stage (about 30 MeV) the phase focusing is greatly increased and spill should not occur. The cavity voltages are again low at the 50 MeV end of the first stage but at this energy the effects considered here are not so serious.

Also there do not appear to be significant effects of this kind in the second and third stages of the design presented in this proposal.

In summary, there is no evidence that space and image charge effects will prevent the operation of SOC at currents up to 65 mA. Beam spill at energies above 30 MeV is not indicated by these calculations.

We know that currents of the order required can be accelerated to 50 MeV. Measurements²² on the CERN 50 MeV proton linear accelerator (linac) have shown that 130 mA can be accelerated from 10 to 50 MeV with less than 10% beam spill. The actual spill is not estimated. At these low energies space and image charge effects should be similar in SOC and linac. However a linac can be constructed with larger radial focusing forces and will have more uniform longitudinal focusing.

* Reference 123 will contain a full description of the method of calculation and detailed numerical results.

APPENDIX VI.6

SOC SIDE YOKE MAGNETS

1. Magnet Design

The end yoke type of magnet as described in section VI.E3 is the reference design for each of the SOC stages. Consideration is, however, being given to an alternative design herein described as the side yoke magnet. This magnet offers a considerable decrease in size and weight, requiring only 1/3 as much yoke steel. The basic difference between the two designs are illustrated in figure VI.54. The flux path of the side yoke (or "picture frame") is directed sideways instead of radially, as in the end yoke magnet. The more direct flux return path of the side yoke magnet results in the large weight difference of the two designs. Coils, pole stems and pole tips are common to both magnets.

A computer program was prepared to optimize the SOC designs of side yoke magnet¹³⁰. A mathematical model of the magnetic and electric circuits was prepared in terms of magnet geometry and materials. Performance requirements and machine constraints were developed. Output equations were generated for ampere-turns required and components of capital and operating costs. The above information was placed in the computer program and magnet parameters were varied to minimize total magnet cost. Important parameters were found to be the ratio of pole height to coil width, yoke flux density and coil current density.

General assembly sketches of the 3rd stage SOC magnet are shown in figure VI.55. One disadvantage of the side yoke design is that the side yokes make the assembly wider than the reference design thus reducing the magnet-to-cavity wall clearance. This affects the cavity wall construction and the assembly procedure somewhat but should not involve any great cost penalty. Figure VI.56 illustrates a general assembly of magnet and RF cavity walls. The side-yoke-to-cavity clearance does not allow the use of continuous wide structural support members on the cavity walls but a cantilever support structure is possible. The use of tie rods, if necessary, between cavity walls would reduce the amount of structural steel and not interfere with the magnet assembly. The reduction, compared to the reference design, in cavity-to-magnet clearance may be acceptable with the smaller distance from the top of the yoke to the beam tube.

¹³⁰ R.A. Pollock, G-20 Programme for Picture Frame Magnets in an SOC, FSD/ING-35, (February, 1966).

Typical
End-Yoke
SOC Magnet
3rd stage

Side Yoke
SOC Magnet
[equivalent to
End-Yoke above]

FIG. VI. 54 Comparable End-yoke and Side-yoke magnets
3 Stage SOC Side Elevation View.

FIG. VI. 55 Stage 3 SOC Side-yoke Magnet.

FIG. VI. 56 Side-yoke Magnet and Cavity Assembly.

Side yoke magnets offer an advantage during construction, in that a pole assembly can be adjusted, aligned or shimmed by removal of an individual upper yoke, while with the end yoke design, removal of a complete upper yoke is required.

2. SOC Assembly

A logical assembly sequence for the SOC would consist of each magnet being shop assembled on a levelled, concrete or steel pedestal (see figure VI.56), which would provide structural rigidity.

Pole tips and beam tubes would be aligned and all possible magnet shimming and flux measurements completed before installation in the SOC. The RF cavities must be moved horizontally into position beside each magnet and the most logical sequence would be to install progressively magnets and cavities rather than to install all of the magnets first. If it were considered necessary to install all magnets first sufficient clearance between the room walls and the magnets would have to be provided to allow radial insertion of the cavities between the magnets.

3. Cost Comparison

Table VI.13 is a cost comparison of the two designs as applied to the three stages of the SOC. It indicates the side yoke design to be 3.416 million dollars cheaper for the complete magnet system of the 3 stage SOC.

The cost assumed for the yoke steel was 32¢ per pound for both magnet designs.

However, it seems likely that the larger yoke pieces of the reference design would cost less per pound than the side yokes¹³¹ so that the cost differential of \$3.416 million shown in Table VI.13 is probably the maximum that could be realized. As indicated, the coils, pole tips, power supplies and required power are considered common to both designs.

¹³¹ Private communication, Workshops, Estimating and Planning Branch, (March 9, 1966).

TABLE VI. 13

COST COMPARISON OF END YOKE AND SIDE YOKE
MAGNETS FOR THE THREE STAGES OF SOC

Item	End Yoke Cost \$ M	Side Yoke Cost \$ M
Yoke steel (SAE 1010) for 3 stages of SOC apply 32¢/lb. as finished yoke cost	5.124 (8,007 tons at 32¢ /lb.)	1.708 (2,669 tons at 32¢ /lb.)
Remainder of magnet system common to both designs which include:	3.513	3.513
<ul style="list-style-type: none"> - copper coils - pole tip assemblies - magnet power supply - magnet power for 5 years 		
Total Cost of Magnet System	<u>8.637</u>	<u>5.221</u>
Cost Differential between the two magnet systems		\$ 3.416 M

APPENDIX VI. 7

THEORY OF CAVITY LOOPS AND TUNING DEVICES

These are considered together since the design equations are similar for each. Various simplifying assumptions are implicit in the development of the expressions and some factors are neglected, such as the contribution of higher order modes to the reactance of the coupling loop. We will consider (a) coupling loop (b) capacitively terminated loop for fast tuning, and (c) slow tuning by cylindrical post.

1. Cavity Fields

Consider the cavity in the coordinate system below:

For the TE_{101} mode the cavity fields are:

$$E_y = E_0 \sin(\pi x/d) \sin(\pi z/a) \cos \omega t,$$

$$H_x = (\lambda E_0 / 2a\eta) \sin(\pi x/d) \cos(\pi z/a) \sin \omega t,$$

$$H_z = -(\lambda E_0 / 2d\eta) \cos(\pi x/d) \sin(\pi z/a) \sin \omega t.$$

We are concerned with either (a) a loop whose plane is normal to the magnetic field at $(a/2, b/2)$ or at $(d/2, b/2)$ or (b) a cylindrical metal post at $(d/2, b/2)$ whose axis lies along z' and which penetrates a distance Δl into the cavity from $z' = a$ towards $z' = 0$.

1.1 Coupling Loop Area

For a loop of area S normal to a field H we have

$$\text{Loop Voltage } V_L = -j\omega\mu HS.$$

Substituting for H and simplifying, if S_{ab} is area of loop at $(a/2, b/2)$ and S_{db} is area of loop at $(d/2, b/2)$ we get

$$S_{ab} = bdV_L / \pi V_C \quad S_{db} = baV_L / \pi V_C$$

where V_L is the loop voltage (peak),

V_C is the cavity voltage (peak).

1.2 Capacitively Closed Loop

Consider a loop of area S whose normal is at an angle θ to the H field

The voltage induced in the loop is given by $V_L = -j\omega\mu HS \cos \theta$. We will consider here only H_x and assume that θ is zero. The loop is designed to be resonant far from the cavity fundamental mode resonance.

Let

- ω_0 be resonant radian frequency of loop
- ω be resonant radian frequency of cavity
- L be inductance of loop
- C be capacitance (assumed lumped)

For far off resonance in a high Q circuit R is negligible and the loop current is given by

$$I = V_L / j\omega L (1 - \omega_o^2 / \omega^2),$$

whence, neglecting ohmic losses the capacitor voltage V' is given by $I/j\omega C$ and is

$$V' = V_L / (1 - \omega^2 / \omega_o^2).$$

The stored energy in the loop circuit which perturbs the cavity fields is given by $\Delta E = \Delta E_H \sim \Delta E_{V'}$, which after manipulation reduces to

$$\Delta E = \frac{1}{2} C V_L V_L^* / [1 - \omega^2 / \omega_o^2]$$

Hence the perturbing energy is changed from that for a capacitor or straight loop by the factor $[1 - \omega^2 / \omega_o^2]^{-1}$.

For a loop located at $(d/2, b/2)$ we have

$$H_x = \lambda E_o / 2a\eta$$

whence as before

$$V_L = (\pi S / ab) V_C, \quad V_C = \text{cavity voltage.}$$

Energy stored in the loop is

$$\Delta E = \frac{1}{2} C (\pi S / a)^2 E_o^2$$

The frequency change due to perturbation is given by

$$\delta \omega / \omega = \Delta E / 2E$$

where E is the stored energy in the cavity and is given by $E_o^2 abd / 8\eta C$ whence

$$\delta \omega / \omega = 2\pi^2 S^2 C / \epsilon a^3 b d.$$

Putting in the correction factor we get

$$\delta \omega / \omega = (2\pi^2 S^2 C / \epsilon a^3 b d) (1 - \omega^2 / \omega_o^2)^{-1}$$

We wish to achieve $\delta \omega / \omega = 0.0001$ whence

$$S^2 = 4.3634 \times 10^{-17} (a^3 b d / C) / (1 - \omega^2 / \omega_o^2).$$

1.3 Post Tuner

Consider a cylindrical metal post centred at $(d/2, b/2)$, of radius R and penetrating a distance Δl in the direction $z' = a$ to $z' = 0$.

Putting the field equation for H_x into cylindrical coordinates and assuming that Δl is so short that the $\frac{\Delta}{E}$ field components can be neglected, we get

$$H_x \Big|_{z=a} = -j(\lambda E_o / 2a\eta) \cos(kr \cos \theta) \Big|_{k=\pi/d}.$$

The incremental energy represented by the plunger volume is given by

$$\begin{aligned} \Delta E &= \frac{1}{2} \mu \int_{\Delta V} H \cdot H^* dv \\ &= \frac{1}{8} (\mu^2 \lambda^2 E_o^2 / a^2 \eta^2) \int_{\Delta V} \cos^2(kr \cos \theta) dV. \end{aligned}$$

Carrying out the integration and substituting in

$$\delta \omega / \omega = \Delta E / 2E \text{ we get for a post of radius } R$$

$$\delta \omega / \omega = -(\pi R^2 \lambda^2 \Delta l / 4a^3 b d) \{1 + J_1(2kR) / kR\}.$$

CHAPTER VII

TARGETS AND EXPERIMENTAL FACILITIES

A.	THERMAL NEUTRON FACILITY	VII. 1
1.	Introduction (J.S. Fraser, J.C.D. Milton)	1
1.1	Outline Description of the System	1
1.2	Outline Description of Thermal Neutron Experimental and Irradiation Facilities	3
2.	Performance (J.S. Fraser, J.C.D. Milton, S.A. Kushneriuk, R.L. Clarke, J. Walker)	7
2.1	Monte Carlo Calculations of Neutron Yield	8
2.2	Measurements of Neutron Yield	11
2.3	Flux Perturbation Effects	17
2.4	The Beryllium Multiplier	20
2.5	Target and Moderator Geometry	21
2.6	Moderator Theory	22
3.	Liquid Metal System (B.C. Stonehill, J.P. Toronchuk, B. Cox, T.A. Eastwood)	44
3.1	Description	44
3.2	Target Flow Configuration	49
3.3	Materials	49
3.4	Flow and Temperatures	58
3.5	Thermal Stresses	59
3.6	Heat Exchanger	69
3.7	Pumps	72
3.8	Vaned Heads	74
3.9	Valves	75
3.10	Purification	76
3.11	Vacuum System	77
3.12	Target Tube Fabrication	79
3.13	Instrumentation	82
3.14	Activation and Spallation Products	83
4.	D ₂ O Moderator System (B.C. Stonehill, J.P. Toronchuk and A.W. Boyd)	87
4.1	General	87
4.2	Moderator Tank	87
4.3	Beryllium Multiplier	89
4.4	D ₂ O Flow	90
4.5	Gas Production	90

5.	Experimental and Irradiation Facilities (B. C. Stonehill and J. P. Toronchuk)	94
5.1	Experimental Beams	94
5.2	Cobalt Production Facility	96
5.3	Isotope Production Facilities	97
6.	Shielding (B. C. Stonehill and Q. Walker)	100
6.1	General	100
6.2	Source Strength	100
6.3	Permissible Doses	100
6.4	Shield Materials	102
6.5	Main Shield	102
6.6	Beam Tubes and Gates	107
6.7	Shield Cooling	108
6.8	Proton Beam Transport Shielding	112
6.9	Inert Gas System	113
7.	Layout (B. C. Stonehill and J. P. Toronchuk)	114
7.1	General	114
7.2	Neutron Beams	118
7.3	Liquid Metal System	118
7.4	D ₂ O System	121
7.5	Top Deck	121
8.	Operation (B. C. Stonehill and J. P. Toronchuk)	124
8.1	Liquid Metal System	124
8.2	Cooling Systems	127
8.3	Moderator System	127
8.4	Cobalt System	127
B.	RESONANCE NEUTRON FACILITY (G. A. Bartholomew, L. Katz, K. G. McNeill)	128
1.	Introduction	128
2.	Characteristics of the System	130
3.	Evaluation of Performance	133
3.1	Flux Available at Doppler Width	133
3.2	Comparison with other Resonance-Neutron Facilities	135
4.	Effect of Change of Accelerator Frequency	139
5.	General Design of Time-of-Flight Facility	139
6.	Future Extension of Resonance-Neutron Facilities	140
6.1	Storage-Ring	140
6.2	Polarized Neutrons	140

C. MESON FACILITIES (R.L. Clarke, B.C. Stonehill)	142
1. General	142
2. Yields	143
3. Choice of Beam-1 or Beam-2 Targets	147
4. Technical Problems Beam-1 Target	148
4.1 Heat Dissipation	148
4.2 Target Life	148
4.3 Shielding of Targets	149
4.4 Effect on the Emittance of the Beam	150
5. Technical Problems of Beam-2 Targets	151
6. Polarized Protons	151
D. FAST NEUTRON FACILITIES (R.L. Clarke)	152
1. General Description	152
2. Production of Fast Neutrons	152
2.1 Unpolarized Neutrons	152
2.2 Polarized Neutrons	154
3. Targets	154
E. BEAM DUMP AND IRRADIATION FACILITY (I.M. Thorson, R.L. Clarke, J.S. Fraser)	156
F. NUCLEAR POWER TECHNOLOGY FACILITY (C.H. Millar)	157

VII. TARGETS AND EXPERIMENTAL FACILITIES

The primary target of the accelerator beam will generate an intense flux of thermal neutrons in a D_2O moderator. At the same time secondary beams of mesons, protons and neutrons will be produced by thin targets placed in the main beam. Other beams of full energy protons will be produced by the lateral deflection of micropulses selected from the main beam and from the 50 and 400 MeV beams at the outputs of the first and second SOC stages.

A. THERMAL NEUTRON FACILITY

1. Introduction1.1 Outline Description of the System

The principal parameters of the reference design of the thermal neutron facility are summarized in Table VII.A.1.

TABLE VII.A.1

ING THERMAL NEUTRON FACILITY

Beam Tube Maximum Flux (perturbed)	$10^{16} \text{ n cm}^{-2} \text{ s}^{-1}$
Source Strength	10^{19} n s^{-1}
Target Material	Pb-Bi eutectic, Zr tube, Nb liner
Target Dimensions	20 cm dia x 60 cm effective length
Moderator	D_2O
Moderator Tank	120 cm radius
Shield	Iron, heavy concrete
Shield thickness (midplane)	450 cm (iron)
Proton Beam	65 mA, 1 GeV, CW
Beam Power	65 MW
Target Power	38 MW
Moderator Power	16 MW
Shield Power	11 MW

The choice of particle to be accelerated to produce a high yield of neutrons in a target is confined to protons and deuterons. For particles heavier than the deuteron the high rate of energy loss by ionization in a thick target reduces the efficiency of the conversion of beam energy to

nuclear excitation. Although a deuteron has a higher specific ionization than a proton of the same energy, it is a loosely bound particle that is easily dissociated into a neutron and a proton with an approximately equal division of energy between them. D. West¹ has shown that the yield of neutrons from 650 MeV deuterons bombarding a lead target is 6% greater than for protons of the same energy. Extrapolation of his yield curves for both deuterons and protons indicates that the yield from deuterons would be about 9% higher at 1 GeV. This advantage is offset by several disadvantages in the acceleration of deuterons. Lee-Whiting² has shown that for 1 GeV deuterons the final stage SOC above would cost 3% more than one for 1 GeV protons. Although the detailed cost minimization has not been done for a complete deuteron accelerator it seems likely that a small penalty would exist for deuterons. However, the higher magnetic rigidity for deuterons would significantly increase the cost of the beam transport system over that for protons. In the low energy end of the accelerator the activation by spilled beam would be very much worse than with protons. In the higher energy section, and in the beam transport system the activation by lost particles would be slightly worse for deuterons than for protons. At the present time the preference clearly lies with protons as the choice of particle for the ING system.

The requirement of a high yield of neutrons from spallation reactions restricts the choice of target to a few heavy elements. Uranium and thorium have the following two disadvantages:

- the high fission cross sections (about 1 barn) result in a large production of heat in the target for each useful neutron emitted, and
- their thermal neutron absorption cross-sections (2.4 and 7.4 barns, respectively) would cause an undesirable flux depression near the target.

The heaviest elements that have neither of these drawbacks are lead and bismuth. Both of these materials have relatively low melting points and we may minimize the heat transfer problem by using a liquid metal target which can act as the heat transfer medium between the source (proton beam) and the sink (heat exchanger). The binary eutectic of lead-bismuth permits an even lower operating temperature than for either constituent used separately.

¹ D. West (AERE, Harwell) private communication (March, 1966).

² G.E. Lee-Whiting, SOC Parameters by Cost Minimization, report FSD/ING-10 (1965), released as AECL-2267.

Any window separating the liquid metal target from the vacuum of the beam transport system would be subjected to very severe radiation damage and corrosion so a windowless design has been used. The proton beam enters the Pb-Bi target vertically downwards along the axis of a column of the liquid metal, the upper part of which has a hollow core at a pressure of 10^{-6} Torr. The stability of the core is maintained by the angular motion imparted to the liquid metal as it enters the target tube through a manifold with tilted vanes.

Of the 65 MW carried by the beam, about 38 MW is deposited in the target and the remainder is divided between the binding energy of the neutrons released from the target and the energy of the radiations from the target. Most of the energy of the beam is dissipated in a 5 litre portion of the target volume, the peak power density rising to perhaps 15 MW/l. The liquid metal is circulated through a heat exchanger with a 38 MW capacity.

The target is surrounded by a moderator of D_2O to provide a very high flux of thermal neutrons. The useful volume of the high flux region is increased by a cylindrical blanket or 'multiplier' of beryllium. The fast neutron source strength is approximately doubled and thus doubles the radius at which a flux of 10^{16} n cm $^{-2}$ s $^{-1}$ can be provided for the beam tubes.

1.2 Outline Description of Thermal Neutron Experimental and Irradiation Facilities

The experimental and irradiation facilities are listed in Table VII.A.2 and shown in Fig. VII.1.

The facilities are planned to give access to the highest flux with the highest beam quality. To provide this in a flexible manner, but without causing large flux perturbations, tubes of 10 cm diameter were adopted as standard, with the addition of a single 20 cm through-tube.

There are seven horizontal beam tubes, placed as follows:

- Five tubes lie in one plane and are tangential to the target. Four of these terminate at a radius of 45 cm from the centre of the target, 12 cm from the outer surface of the beryllium blanket. The fifth terminates at a radius of 86 cm.
- 20 cm below the five-tube plane is a radial tube and 20 cm above it is the through-tube on a tangent 45 cm from the target centre.
- At the inner ends of four of the tangential tubes are 10 cm vertical access tubes and at the centre of the through-tube is a 20 cm vertical tube. These vertical tubes can be used as

FIG. VII. 1 Section through the moderator tank at the beam tube level.

additional irradiation facilities if necessary but they are provided primarily for servicing equipment, for mechanical support and for cooling targets or moderators without obstructing the neutron beams. Since beam tubes that are not in use will probably be flooded, the vertical tubes will be useful for circulating cooling water. It is planned that a vertical tube not in use can be flooded separately from its horizontal partner.

TABLE VII.A.2

THERMAL NEUTRON EXPERIMENTAL AND IRRADIATION FACILITIES

Beam Tube Number	Facility	Diam cm	Quantity	Max Thermal Flux unperturbed $\text{cm}^{-2} \text{s}^{-1}$	Westcott r approx.
2, 4, 5	Horizontal tangential "L-tube"	10	1	10^{16}	0.026
3	Horizontal tangential "L-tube"	10	1	5×10^{15}	0.003
1	Horizontal tangential stub	10	1	10^{16}	0.026
7	Horizontal radial stub	10	1	10^{16}	0.026
6-6A	Horizontal tangential "T-tube"	20	1	10^{16}	0.026
	Pneumatic rabbits	10	2	10^{16}	0.026
	Vertical irradiation thimbles	15	2	$\sim 5 \times 10^{15}$	0.003
	Vertical irradiation thimbles	15	3	$\sim 1 \times 10^{15}$	---
	Hydraulic capsule facilities	4	45	$\leq 10^{15}$	---
	Inner Cobalt blanket 3/8" thick		1	$\leq 10^{15}$	---
	Outer Cobalt blanket 3/4" thick		1	$\leq 10^{15}$	---

The 20 cm through tube is intended for 'unusual' experiments, see subsection V.A. 1.4.4 for an example. It may also be useful for experiments in which beams of charged particles bombard a thermal neutron 'gas target' at the mid-point of the tube.

High beam quality is essential for many experiments. Here quality denotes the ratio of neutrons in the energy range of interest to those outside it. Usually this means the ratio of thermal to fast, that is epithermal or MeV-range, neutrons. For this reason most of the tubes are tangential and end on a circle not less than 12 cm from the surface of the beryllium blanket. The 12 cm value is the same as that chosen for HFBR; it is felt to be reasonable for ING but has in no sense been optimized to allow for the different flux distribution and other conditions in ING. The quality of the beams emerging from the tubes is discussed further in subsection VII.A 2.6.3, but accurate estimates still remain to be made. In particular no attempt has been made to account for the effect of the beryllium blanket. We will make here two very crude estimates of the beam quality, realizing that the inclusion of the beryllium blanket would give a more favorable result.

The background in many thermal neutron experiments results from the interactions between neutrons with energies of one MeV and greater and the experimental equipment. Therefore we compare the ratio of thermal to fast (greater than 1 MeV) neutrons for ING and HFBR. The first estimate is obtained by comparing the fluxes at the input end of the tube. From Fig. VII.9 we obtain 30:1 for ING and from Kouts³ we obtain 100:1 for HFBR. Thus the ING quality is three times poorer than HFBR. The fluxes quoted above include the uncollided neutrons and these are relatively more numerous in ING. An independent estimate of the quality may be obtained by calculating for ING and HFBR the numbers of neutrons from the source that collide in an annular region 10 cm wide centred on the target and extending across the inner faces of the beam tubes. In this case, ING is found to be 3.2 times poorer than HFBR. The agreement is probably fortuitously close but indicates that the factor of three is not far wrong. Measurements made for HFBR indicate that, with the beam tube configuration used there, the quality of a tangential tube is about 30 times better than a radial tube³. Assuming that a radial tube in HFBR is similar to an NRU beam tube, the ING quality should then be about 10 times better than NRU. In case the Be blanket does not improve the quality to a point near that of HFBR, the ING quality can be improved considerably, for a very small loss in thermal flux merely by terminating the tubes at a point slightly farther out from the 12 cm point now adopted (see Fig. VII.1). For

³ H. Kouts, Reactor Sci. and Tech. (J. Nuclear Energy A and B) 17, 153 (1963).

those experiments that require a large fast flux, one 10 cm radial tube has been provided; for those that require a much better quality, one 10 cm tangential tube located 86 cm from the target centre has been provided. This latter tube will be highly desirable for those experiments (e.g. neutron lifetime experiments) that require a low epithermal content in the beam.

From Eqn. VII.4, it can be seen that for experiments using the full 10 cm aperture, the thermal neutron beam at the outer face of the biological shield is $\sim 10^{13} \text{ n s}^{-1}$. Some experiments may be able to use a higher flux, or others may require special filters, or collimators that cannot be installed in a small diameter tube. To anticipate such requirements a 4' x 4' x 4' portion of the outer edge of the shield has been made removable. The flux at the closest point thus made available is 60% higher than at the outer face. Of course additional shielding would have to be installed to protect personnel in the immediate neighborhood.

The building surrounding the thermal neutron facility (see Fig. VII.47) is designed to give the maximum unobstructed floor space to each beam. It is probable that each experiment will require a considerable amount of shielding and accordingly, close to the target, the floor loading is 8000 lbs/ft². Because beam catchers required to stop the very high energy neutrons emanating from the tube may be very massive, it is proposed to put them outside the building, if possible. This may improve traffic circulation in the building.

The irradiation facilities in the highest flux consist of two 10 cm diam vertical tubes, centered 12 cm from the Be blanket. It is anticipated that both these tubes would be equipped with rabbits to provide rapid access to about 6 positions in the tube. The problem of cooling the sample will probably limit the amount of absorbing material which can be placed at these locations. Five larger irradiation tubes, whose use is discussed in Chapter XII, are located in regions of lower flux. Facilities for ⁶⁰Co production include a blanket of cobalt pellets in a fluidized bed inside the outer wall of the moderator tank. Most of the thermal neutron leakage from the moderator will be absorbed in the cobalt.

2. Performance

The flux of thermal neutrons produced by the proton bombardment of a heavy-element target has been calculated in two major steps. The first step is a calculation of a neutron yield by a Monte-Carlo method that gives detailed predictions of the neutron source strength, energy and angular distributions as a function of proton beam energy, for various target materials and sizes. The calculation also estimates the heat deposition in the target as a function of the same variables. The second step, which utilizes the results of the first step, is a multi-group diffusion theory calculation to obtain the neutron fluxes in the moderator surrounding

the target. The yield calculations have been checked by direct measurement⁴.

2.1 Monte Carlo Calculations of Neutron Yield

The neutron yield is calculated by a Monte Carlo method that treats in turn the generation of cascades of high energy nucleons and evaporated neutrons until all of the energy of the incident proton has been carried out of the target volume by the neutrons or deposited in the target as heat by ionization. The running of between 400 and 1000 case histories is adequate to give the required statistical estimates of the yields, spectra and angular distributions.

Some of the results of a calculation for a 10 cm diam Bi target are shown in Fig. VII.2⁵. The points in the upper part of the figure give the calculated source strength along the axis of the target. The points in the lower part of the figure show the distribution of heat produced by ionization. In both parts of the figure the solid lines are exponential distributions with the mean free path characteristic of inelastic collisions of high energy protons in bismuth.

The neutron yield per proton and the heat deposited per neutron are shown in Fig. VII.3 for U and Pb targets 10 cm diam and 60 cm long. At a proton energy of 1 GeV the ratio of the neutron yields is

$$Y_U/Y_{Pb} = 36.9/20.8 = 1.77$$

but the ratio of the heat per neutron is

$$H_U/H_{Pb} = 50.1/25.7 = 1.95.$$

The increase in the heat per neutron is due to fast neutron fission. This means that for a neutron source strength of about 10^{19} s^{-1} a U target would produce a target power of 80 MW as compared with a power of 41 MW for a Pb target. A similar calculation for a Bi target of the same dimensions shows that a neutron source strength of 10^{19} s^{-1} would be accompanied by a target power dissipation of about 39 MW. Thus the Pb-Bi eutectic fluid (45 wt % Pb, 55 wt % Bi) has a much smaller heat removal problem than the uranium. A target of uranium metal would have the additional disadvantage

⁴ J.S. Fraser, R.E. Green, J.W. Hilborn, J.C.D. Milton and W.A. Gibson, E.E. Gross, A. Zucker (ORNL), Phys in Canada 21 (2) 17 (1965).

⁵ J.C.D. Milton and J.S. Fraser, A Monte Carlo Calculation of Neutron Production in Heavy Element Targets in the Range 0.3-1 BeV, report AECL-2259 (1965).

FIG. VII. 2 Total neutron production and heat deposition along the axis of a 10 cm diam. Bi target.

FIG. VII. 3 Heat production per neutron produced and neutron yield vs incident proton energy.

of requiring a very high heat transfer rate between the solid and a coolant fluid interface.

2.2 Measurements of Neutron Yield

The calculations have been substantially verified in an extensive series of measurements carried out at the BNL Cosmotron in collaboration with a group of physicists from ORNL⁴. A variety of target materials and shapes and a range of proton energies from 0.5 to 1.5 GeV were used.

Six different targets were studied: cylinders of Sn, Pb and depleted U 10.2 cm diam by 61 cm long, a cylinder of Pb 20.4 cm diam by 61 cm long, a cone of Pb 61 cm long with a diameter varying from 10.2 cm to 20.4 cm and a rectangular prism of Be 10.2 cm by 10.2 cm by 91.6 cm long. The targets were mounted in a large cylindrical tank of H₂O (1.83 m diam by 1.83 m high) which was located in an external beam of the Cosmotron. The absolute neutron density distributions in the water surrounding the targets were measured with up to 55 Cu or Au foils mounted on a lucite frame. The foils were counted on an automatic counting system which had been calibrated previously against a 4π β - γ coincidence system. As a further check on the system a standardized neutron source was measured in the Chalk River Pool Test Reactor tank using the same foil array and counting system. The source strength thus determined was within 2% of the value determined at the National Research Council.

In one series of experiments with the 10.2 cm diam Pb target the lucite foil holder was replaced by a self-powered vanadium β -current detector⁶ similar to that used for in-reactor flux measurements. The vanadium wires were arranged in grooves on a lucite plate with the spacing varying proportionally with radial distance from the target axis so that the current induced in the wire by the β -activity of the vanadium was proportional to the average neutron flux in the H₂O and hence to the neutron source strength.

In all runs the integrated proton current into the targets was measured by the irradiation of polyethylene foils placed at the entrance of the beam into the water tank. The ¹¹C activity produced in the foils by the ¹²C(p, pn)¹¹C reaction was measured in a calibrated counter at BNL.

A summary of the neutron yields per incident proton is given in Table VII.A.3.

⁶ J. W. Hilborn, *Nucleonics* 22 (2), 69 (1964).

TABLE VII.A.3

NEUTRON YIELD PER INCIDENT PROTON

Target	Proton Energy, GeV.			
	<u>0.47</u>	<u>0.72</u>	<u>0.96</u>	<u>1.47</u>
Be 10.2 cm x 10.2 cm x 91.6 cm	1.38	1.94	2.90	3.43
Sn 10.2 cm diam x 61 cm	4.72	8.20	11.45	15.87
Pb 10.2 cm diam x 61 cm	7.96	11.76	16.64	26.40
Pb 20.4 cm diam x 61 cm	8.67	13.94	20.29	31.47
U 10.2 cm diam x 61 cm (depleted)	18.50	29.06	40.48	56.75

These results are plotted in Figs. VII.4 and VII.5. The Monte Carlo calculation for a 10.2 cm diam by 61 cm Pb target is shown in Fig. VII.6 together with the Au foil activation measurement and the β -current integrator measurement. The integrator results are systematically higher than the foil activation results. This discrepancy is caused by the response of the detector to fission γ rays that were not taken into account when the vanadium wire was calibrated in the Chalk River Pool Test Reactor. The calculated and observed yields for the 20.4 cm diam target are plotted in Fig. VII.7.

The results obtained by the foil activation method are believed to be accurate to within $\pm 5\%$. For the Pb targets the calculated yields for the 10.2 cm diam by 61 cm cylinder are about 13% higher than the observed yields and for the 20.4 cm diam by 61 cm cylinder are 9% higher than the observed yields. In calculating the beam current required to produce a flux of 10^{16} n cm⁻² s⁻¹ in a moderator around the target, the observed neutron yields were used. The neutron source strength produced by the bombardment of a 20.4 cm diam x 61 cm long target of Pb by 65 mA of 1 GeV protons is $20.29 \times 65 \times 6.28 \times 10^{15} = 8.29 \times 10^{18}$ n s⁻¹.

The measurements of thermal neutron flux that were made in an H₂O moderator around a Pb target bombarded by 1 GeV protons indicate that the effective length of the neutron source is about 30 cm. Diffusion theory (Section A.2.6 below) then predicts that the required flux at the entrance to an experimental beam tube in the absence of perturbations would be produced by a proton beam of 41 ± 2 mA at 1 GeV.

FIG. VII. 4 Measured neutron yield vs proton energy for various targets.

FIG. VII. 5 Measured neutron yield vs atomic mass number of the target for various proton energies.

FIG. VII. 6 Comparison of calculated and measured neutron yields for a 10.2 cm diam x 61 cm long Pb target.

FIG. VII. 7 Comparison of calculated and measured neutron yields for a 20.4 cm diam x 61 cm long Pb target.

The calculated neutron yield for this target is 22.2 neutrons per incident proton, 9.4% higher than the observed yield. In estimating the energy deposition rate in the target it was assumed that the energy carried off by each neutron was as calculated but the energy left behind as heat was taken to be 9.4% higher than given by the calculation.

The moderator absorbs the kinetic energy of the evaporation component of the neutrons and an estimated 75% of the energy of the cascade component. The remainder is absorbed in the shield. The thermal neutron leakage from the moderator results in the heating of the shield through the absorption of the neutron capture γ rays.

2.3 Flux Perturbation Effects

The above estimate of beam current does not allow for several flux perturbation effects which are difficult to calculate. A series of experiments was therefore carried out to determine the flux depressions caused by the following structural components:

- the tube enclosing the liquid metal target
- a gas coolant annulus that will be placed between the target and
- the inner wall of the moderator vessel,
- the experimental neutron beam tubes which introduce voids into the moderator and,
- the isotope irradiation facilities that are to be placed at an intermediate radius in the moderator.

The experiments⁷ used a simulated thermal neutron facility consisting of a Ra-Be neutron source placed at the center of a Pb cylinder 61 cm long. Diameters of 10.2 cm and 20.4 cm were used. This assembly was placed in a tank 153 cm diam by 153 cm deep, containing H₂O or D₂O. A later series of measurements⁸ was made with the assembly in the ZEEP reactor vessel. Thermal neutron flux distributions were obtained with a small BF₃ proportional counter or by Au and Mn foil activation. The flux perturbations were then found by measurements with and without the various structural components added to the assembly.

⁷ J. Walker, Some Neutron Measurements with Simulated ING Targets, FSD/ING-57 (unpublished).

⁸ J.S. Fraser, Flux Perturbation Effects of Beam Tubes with a Simulated Target, report FSD/ING-58 (unpublished).

- a) The target tube was simulated by a stainless steel cylindrical shell 0.16 cm thick, placed over the Pb cylinder. The observed flux depression was 13%. Taking into account the relative absorption cross-section of stainless steel and the average cross-section of the materials in the proposed target tube, a flux depression of 4.4% was calculated.
- b) A gas coolant annulus (effectively a void in the D_2O) around the target was found to depress the flux by about 5%.
- c) As in a) above, the inner wall of the moderator tank was estimated to depress the flux by 0.9%.
- d) Various symmetrical arrays of up to six 10.2 cm diam tubes were used to test the effect of beam tubes. They were placed tangentially at a distance of 12 cm from the surface of the 20.4 cm target. These measurements are summarized in Table VII.A.4. The "unperturbed" flux refers to the measured flux at the end of a flooded beam tube.

TABLE VII.A.4

BEAM TUBE FLUX DEPRESSIONS

Unperturbed Flux	1.00
One Beam Tube Empty	0.90
Two Beam Tubes Empty	0.88
Three Beam Tubes Empty	0.87
Six Beam Tubes Empty	0.80

The use of the beryllium multiplier increases the spacing between beam tubes. It is estimated that, with the beryllium in place, the flux perturbation of six beam tubes would be roughly equivalent to the perturbation of three tubes without the beryllium.

- e) A typical isotope irradiation facility was simulated by a cylindrical shell of Cd 15.3 cm diam by 122 cm long by 0.038 cm thick. This was placed at distances between 60 and 90 cm from the source for flux measurements on beam tubes on the near and far sides of the target. In the 60 cm position (which corresponds approximately to the proposed position in the ING moderator) the flux depression on the nearest beam tube entrance was 5%.

It is estimated that the average flux depression at the end of one beam tube due to the combined effects of the other beam tubes and irradiation facilities will be approximately 35%. For some beam tube positions the perturbation would be reduced to about 25% if the vertical arms of the L tubes were filled with D_2O .

In the calculation of the beam current of 41 mA required to produce the desired flux a Pb target was assumed. The proposed target of a Pb-Bi eutectic would have a smaller absorption of thermal neutrons. The average thermal neutron absorption cross-section for the eutectic is 0.077 barns as compared with 0.17 for Pb alone. This factor gives an increase over the earlier estimate of about 8% in the flux per unit of beam current.

Another factor that is not included in the diffusion theory calculation is the multiple production of neutrons by the $D(n, 2n)p$ reactions that are produced in the D_2O moderator by the high energy neutrons from the target. A crude estimate of the increased flux from this source is 5%.

Table VII. A. 5 contains a summary of the above flux perturbation factors.

TABLE VII. A. 5

SUMMARY OF FLUX PERTURBATION FACTORS
OMITTED FROM DIFFUSION THEORY CALCULATION

1	Pb-Bi Eutectic vs. Pb	+ 8%
2	$D(n, 2n)p$ Reactions	+ 5%
3	Zr-Ni Target Tube	- 4.4%
4	Gas Coolant Void	- 5%
5	Moderator Tank Wall	- 0.9%
6 a	Average Perturbation of Beam and Irradiation Tubes	- 35%
	Net	- 32%
6 b	Average Perturbation with vertical arms of L-tubes flooded	- 25%
	Net	- 22%

With these estimates of the flux perturbations the required beam current at 1 GeV proton energy then becomes $41/0.68 = 60$ mA. The proposed beam current of 65 mA therefore allows for a contingency of 8%.

If the beam tube perturbation were to be reduced from 35% to 25% by operating with the vertical arms of the L-shaped beam tubes filled with D_2O the required current would be $41/0.78 = 53$ mA (18% less than the proposed beam current).

2.4 The Beryllium Multiplier

A preliminary theoretical investigation of the performance of a beryllium annulus surrounding the target has been reported by R. L. Clarke⁹. A multiplication of the neutron source strength would be produced by the ${}^9\text{Be}(n, 2n){}^8\text{Be}$ reaction. The cross-section for this reaction is known only from the threshold at 2.4 MeV up to neutron energies of 14 MeV. The cascade component of the neutron spectrum from the target extends up to several hundred MeV, the average energy being about 100 MeV. The calculation is, therefore, necessarily based on a crude model of the reaction mechanism from which the cross-section above 14 MeV is estimated. Bearing these limitations in mind, however, the significant result of the calculation is that for annulus thicknesses up to 50 cm the thermal flux at its outer boundary is increased by the presence of the beryllium. The greatest increase, 20%, is found for a blanket thickness of 20 cm.

Although this estimate may be uncertain to a large degree, a more general conclusion is justified, namely, that a Be multiplier would increase the useful volume in which a large thermal neutron flux exists. For a given number of experimental beam tube and isotope irradiation facilities, the increased separation brought about by the expansion of the high flux volume would reduce the flux depressions caused by these components.

Other advantages that would accrue from the use of Be are

- reduction of the fast (~ 4 MeV) to thermal neutron ratio at the experimental beam tubes,
- reduction of the contamination of the thermal neutron beams by the scattering in of the cascade neutrons,
- reduction of the hydrolysis of the D_2O by the high flux of fast neutrons near the target and,
- an increase of the total number of neutrons available for isotope production.

The use of Be in a very high flux of fast neutrons poses severe engineering problems. The end product of the ${}^9\text{Be}(n, 2n){}^8\text{Be}$ reaction is unstable against the breakup into two He nuclei and the agglomeration of this He into gas bubbles at the grain boundaries can produce a great stress in the material.

⁹ R. L. Clarke, Neutron Multiplication by a Beryllium Blanket, report FSD/ING-2 (1965).

The limited experience gained at other laboratories on the behavior of Be in fast neutron fluxes indicates that it would be unwise to use it as a structural material. Provision would have to be made to remove the Be for replacement several times per year.

2.5 Target and Moderator Geometry

From the data given above, the chosen target is 20 cm in diameter by 60 cm long, and is centred in the moderator tank which is to have a radius of 120 cm.

Since the target material is a liquid Pb-Bi eutectic, circulated through a heat exchanger for cooling, it is necessary to provide an inlet pipe to carry cool Pb-Bi to the target and an exit pipe to carry the heated Pb-Bi away. Consideration of the possible locations for these pipes¹⁰ shows that the preferred arrangement is to have them co-axial with the proton beam. Any arrangement in which these pipes cross the proton beam at an angle, for instance the case in which they are at right angles to the beam, results in a Pb-Bi filled pipe passing through a high flux region of the moderator. This both depresses the flux and occupies space which could be better used for experimental or irradiation facilities. Minimum flux depression, a uniform flux pattern, and minimum interference with other components is therefore obtained with the co-axial arrangement. Details of this design are given below in the section on the Liquid Metal System (VII.A.3).

The target provides a thermal neutron flux pattern which approximates that produced by a point source. An acceptable moderator geometry would therefore be that of a sphere of 120 cm radius. Such a geometry, however, would seriously complicate the problems of manufacture, particularly as regards the installation of experimental and irradiation facilities. For such installations, the most attractive geometry is that of a cylinder 120 cm in radius and 240 cm high. The only disadvantage of the cylinder is that its greater volume increases the heavy water inventory, the volume of the cylinder being 1.5 times that of the sphere, and this increased inventory is offset by the increased space for irradiation facilities. A compromise geometry would be that of a tank having a cylindrical centre section and conical ends. The chosen moderator tank configuration is a cylinder with one conical end. This reduces the D₂O inventory, where practical, but retains a simple geometry and room for the many desired installations.

¹⁰ J.S. Fraser, The Intense Neutron Generator Target, proc. AECL Symp. on The Generation of Intense Neutron Fluxes (Chalk River, 1965); report AECL-2177 (1965).

The entire target-moderator assembly could be arranged so that the proton beam enters the assembly either vertically or horizontally. Since the beam from the accelerator approaches the target horizontally, the horizontal arrangement has the minor advantage of not requiring a turning magnet to change the beam direction to the vertical. The vertical arrangement, however, has the advantage of allowing experimental beams to be distributed around the full circumference of the target in a horizontal plane. In addition, if the beam passes vertically downwards through the target, the ground beneath the target forms a safe and reliable beam stop. Finally, a windowless target can be used in the vertical case, as described later in the section on the Liquid Metal System, whereas the horizontal case requires a window to prevent liquid Pb-Bi from entering the evacuated proton beam tube. The cooling of such a window is a formidable problem. As a result, the vertical target arrangement is adopted.

2.6 Moderator Theory

2.6.1 Outline of the Multigroup Diffusion Theory Calculations

Our main concern to date has been with the calculation of the neutron flux in an unperturbed moderator surrounding the proton bombarded target and we present here some results of the calculations. The calculations are performed numerically on the basis of first collision and multigroup diffusion theories as outlined in FSD/ING-5¹¹. The target is taken to be a right cylinder of length h symmetrically embedded in a D_2O moderating blanket of length H , outer radius R , as illustrated in Fig. VII.8. The target length was generally taken to be comparable with the range of primary proton in the target material (~ 40 cm in Bi, Pb; 25 cm in U for a 800 MeV proton) and the source neutrons resulting from the proton interaction in the target were assumed to be uniformly spread throughout the target. These dimensions do not conform to the reference design but supplementary data are given so that the flux distributions for various designs may be obtained by interpolation.

¹¹ S.A. Kushneriuk, et al., Neutron Fluxes in a Moderator Surrounding Targets Bombarded by High Energy Protons. FSD/ING-5 (1964).

FIG. VII. 8 Idealized target-moderator assembly.

The neutron flux is calculated by a computer code that makes a fairly detailed account of the neutron flux in the moderator that results from the low energy ($\lesssim 20$ MeV) source neutrons leaving the target. We take the result of the Monte Carlo calculation (section VII.A.2), on the bombardment of a 10 cm diameter Bi target by 1000 MeV protons, as typical of the energy spectrum of the source neutrons leaving the target. The spectrum is

$$S(E) = 19.04 \times \frac{2}{\sqrt{\pi}} \frac{E^{1/2}}{(3.2)^{3/2}} \exp(-E/3.2) + 2.19 [0.00685 \exp(-E/18) + 0.00776 \exp(-E/113)]$$

VII.1

where E is in MeV and the normalization is such that $\int_0^\infty S(E) dE = 21.23$, the yield of neutrons per proton. The first term in $S(E)$ is the "evaporation" spectrum with a yield of 19.04 n's per proton with an average energy of 4.81 MeV. The last two terms are the "cascade" neutrons, 2.19 per proton with an average energy of 103.5 MeV. The breakup of the source spectrum into energy groups is given in Table VII.A.6. It is evident that about 92% of the source neutrons have energies less than 20 MeV and, as mentioned, the contribution by these neutrons to the neutron flux in the moderator is taken into account quite precisely. For neutrons of higher energy the transport processes are complicated because of the emission of other high energy particles (neutrons, protons, alphas, mesons, etc.) in

the nuclear interactions and so far we have made only approximate calculations of the neutron flux produced by the high energy component of the neutron source. Since only about 8% of the source neutrons have these higher energies the approximate treatment given this component does not result in any serious errors in estimating the low energy neutron flux. However, a more precise and detailed treatment of this component is essential for purposes of determining accurately where the energy carried off by these neutrons is deposited and also the extent of shielding required.

TABLE VII.A.6

ENERGY SPECTRUM OF THE SOURCE NEUTRONS

Bi Target 10 cm diam x 40 cm long

Energy Range ($E_1 \leq E \leq E_2$)	Fraction of neutrons in group	Fraction of neutrons with $E < E_2$	Fraction of energy carried by neutrons with $E < E_2$
< 1 MeV	0.100	0.100	0.0030
1-2 MeV	0.136	0.236	0.0180
2-3.2 MeV	0.152	0.388	0.0448
3.2-4 MeV	0.089	0.477	0.0668
4-6.6 MeV	0.207	0.684	0.139
6.6-8 MeV	0.071	0.755	0.174
8-10 MeV	0.065	0.820	0.214
10-13 MeV	0.054	0.874	0.258
13-20 MeV	0.041	0.915	0.303
20-36 MeV	0.0174	0.9324	0.335
36-108 MeV	0.0327	0.9651	0.480
108-216 MeV	0.0215	0.9866	0.702
216-432 MeV	0.0114	0.9980	0.942
432-864 MeV	0.0019	1.000	0.997

In the last column of Table VII.A.6 we have listed the fraction of the neutron kinetic energy carried by neutrons with energies less than E_2 , the upper limit in the column 1 entry. It is evident that only 30% of the energy is taken up by the 92% of the source neutrons with energies less than 20 MeV, and that 30% of the energy is borne by the 1.3% high energy source neutrons with energies greater than 216 MeV. The corresponding figures for the reference design target do not differ greatly from these.

In Table VII.A.7 we list some of the group-average neutron cross-sections† we have used for neutron interactions in D_2O in the

0 < E < 20 MeV energy range.[†] Elastic collisions dominate though (n, α) (n, 2n), (n, n'), (n, p) and (n, d) interactions are all significant at the higher energies. In the tables σ_T is the total cross-section. The reactions (n, α), (n, p) and (n, d) in oxygen result in neutron losses. Actually, in the energy range indicated, these losses are slightly overcompensated for by the production of neutrons via the (n, 2n) reactions with the oxygen and deuterium. Information on the nuclear interactions for neutrons (and other particles) with energies > 20 MeV was obtained from the data of Hughes and Schwartz¹² and the Monte Carlo calculations of Bertini¹⁵.

TABLE VII. A. 7

D₂O CROSS-SECTIONS FOR NEUTRONS (IN BARNS)

Energy Range	Oxygen Cross-Sections						Deuterium Cross-Sections	
	σ_T	$\sigma(n, \alpha)$	$\sigma(n, n')$	$\sigma(n, p)$	$\sigma(n, d)$	$\sigma(n, 2n)$	σ_T	$\sigma(n, 2n)$
<1.0 MeV	3.8						3.4	
1-2 MeV	2.5						2.85	
2-3.2 MeV	1.2						2.45	
3.2-4 MeV	3.0	.003					2.1	.008
4-4.46 MeV	↓	.10					↓	.025
4.46-5 MeV		.06						.035
5-5.2 MeV	1.5	.17					1.75	.041
5.2-6.3 MeV		.04						.06
6.3-6.6 MeV	↑	.10					↑	.07
6.6-8 MeV	1.2	.07	.17				1.4	.09
8-10 MeV	1.15	.07	.34				1.15	.12
10-13 MeV	1.5	.15	.45	.039	.011		.93	.155
13-20 MeV	1.56	.29	.50	.036	.015	.0005	.77	.175

[†] These cross-sections were derived from data contained in:

- ¹² D. J. Hughes and R. B. Schwartz, Neutron Cross Sections, BNL-325, Second Edition, (1958).
- ¹³ J. R. Stehn, Neutron Cross Sections, BNL-325, Second Edition, Supplement (2) (1964).
- ¹⁴ G. D. Joanou and H. Fenech, Reactor Sci. and Tech. (J. Nuclear Energy Parts A and B) **17**, 425 (1963).
- ¹⁵ H. W. Bertini, Phys. Rev. **131**, 1801 (1963) and private communication (1964).

2.6.2 Discussion of the Results

We present here some results of the calculations, with emphasis on the low energy neutron fluxes. We wish to indicate principally the magnitude and spatial distribution of the fluxes, the dependence of the flux on the target material, on size and source disposition in the target, and on the moderator size. The energy spectrum of the neutron flux is also discussed.

In so far as the energy spectrum of the flux is concerned, the most detailed calculation has been carried out for a Pb-Bi target 10 cm diameter, 40 cm long, embedded in a D₂O moderator 118 cm thick, 240 cm long, and these results are presented. The fluxes are normalized to a total source strength of 10^{19} source n's/sec. In figure VII.9 the radial distribution of the neutron flux in the moderator mid-plane is plotted for various indicated neutron groups. We see that for the higher energy neutron groups the flux tends to be concentrated near the target. For neutrons with energies greater than 2 MeV the main component of the flux, particularly near the target, is the "uncollided" flux, i.e. the flux of source neutrons coming directly out of the target without collision. Farther from the target the "collision" flux becomes important. Our estimate of this flux becomes rather uncertain at the higher energies because we have made only approximate calculations of the contributions to this flux produced by the source neutrons with energies >20 MeV. Note the change of scale in the abscissa at 20 cm.

In figures VII.10 to VII.12 the energy spectrum of the neutron flux at all energies is given at a location where it is most accurately known, i.e. at the target half-height position on the target surface. (Note that the energy interval dE for plotting the ordinate is eV in Fig. VII.10, keV in Fig. VII.11 and MeV in Fig. VII.12.) The thermal flux is approximately a Maxwellian with an effective temperature of 313 °K. In the epithermal energy regions the spectrum is approximately of the $1/E$ type. At the higher energies the flux is mainly the uncollided flux and the flux spectrum is therefore similar to the source neutron spectrum. As we move away from the target surface into the moderator the flux of high energy neutrons decreases relative to the thermal neutron flux as illustrated qualitatively in Fig. VII.9.

Figure VII.13 indicates the manner in which the thermal neutron flux at the target mid-position depends on the target length. The normalization is 10 source n's per sec per cm length of target and the source neutrons are assumed to be uniformly distributed throughout the target. The flux is almost linearly proportional to the target length for lengths up to about 60 cm indicating that, in systems in which the target and moderator are weakly thermal neutron absorbing and the system is large (i.e. the D₂O moderator is thick), the thermal neutron flux in the system mid-plane is not very sensitive to the exact disposition of the source

FIG. VII. 9 Radial distribution of the neutrons flux for a 10 cm diam., 40 cm long Pb-Bi target Source Strength 10^{19} neutrons/sec.

FIG. VII. 10 Neutron flux spectrum at the target surface. See Fig. VII. 9 for target specifications.

FIG. VII. 11 Neutron flux spectrum at the target surface. See Fig. VII. 9 for target specifications.

FIG. VII. 12 Neutron flux spectrum at the target surface. See Fig. VII. 9 for specifications.

FIG. VII. 13 Mid-plane thermal neutron flux as a function of target length. Target diameter = 4 cm, source strength 10 neutrons/cm of lengths of target. D₂O moderator thickness = 118 cm.

neutrons in the target. By the same token the argument would apply to targets of larger diameter.

In figure VII.14 we plot the radial distribution of the thermal neutron flux for Bi and ^{238}U (i.e. depleted uranium) targets for different thicknesses of moderator. The total source strength for both targets is 330 n's s^{-1} . The large depression of the neutron flux with a uranium target is mainly caused by thermal neutron capture by the uranium.

In figure VII.15 we show more explicitly how the thermal neutron flux at a position 12 cm away from the target face in the system mid-plane depends on the moderator thickness surrounding the target. A moderator thickness of about 120 cm seems desirable. The flux however does not increase very much beyond a thickness of about 90 cm and it therefore follows that any large neutron absorbing facility located in the periphery of the moderating blanket beyond 90 cm from the target will not decrease the neutron flux near the target by much.

In figure VII.16 the flux at the target surface and in the system mid-plane at 12.5 cm from the target surface are plotted as a function of the target radius for Bi and Pb targets. The difference in the fluxes for the two targets is caused by the differences in thermal neutron absorption in the targets. Figure VII.17 illustrates the effects which neutron absorbing sheaths of iron surrounding the target produce on the neutron flux 12 cm from the target. These curves are useful in estimating the perturbing effect of the target tube.

It is of interest to use the results given in figures VII.16 and VII.17 to relate the thermal flux depressions to the strength of the thermal neutron absorption in the target and in the sheath.

The Bi and Pb targets and the sheaths are considered to be relatively weak neutron absorbers (i.e. self-shielding corrections are small).

From the Bi and Pb results one sees that for a weakly capturing target, 30 cm long, for each cm^2 of absorption per unit length of target, the flux depressions are (a) 22% at the target surface and 7.7% at 12.5 cm from the target, for a 5 cm target radius (b) 12% at the target surface and 4.4% at 12.5 cm from the target, for a 10 cm target radius.

From the iron sheath results one sees that for each cm^2 of absorption per unit length of sheath, the flux depressions are (a) 30% at the sheath surface and 16% at 12 cm from the sheath, for a 5 cm radius target (b) 20% at the sheath surface and 14% at 12 cm from the sheath, for a 10 cm radius target. One may use the above or similarly derived results to assess the effect of other weakly absorbing sheaths or of "poisons" in the target on the neutron flux in the moderator. The 0.15 in. (0.38 mm) thick

FIG. VII. 14 Mid-plane thermal neutron flux profiles for Bi and U targets in D₂O moderators of various thicknesses. The targets are 16 cm diam x 33 cm long. The source strength is 10 neutrons per cm of length.

FIG. VII. 15 Mid-plane thermal neutron flux 12 cm from the target surface. Target length is 33 cm and source strength is 10 neutrons per cm of length.

FIG. VII. 16 Effect of target radius on the thermal neutron flux. The source is 10^{19} neutrons/sec in a target 30 cm long.

FIG. VII. 17 Effect of neutron absorbing tube around the target. The target is a 60 cm long cylinder of Bi with a source strength of 600 neutrons/s

Zircaloy-2 target tube of the reference design (Section VII. A. 3.3) is equivalent in absorption to an iron tube 0.013 mm thick. One might conclude from the results given above that a neutron absorber located at the target surface gives rise to a larger flux depression than when the absorber is uniformly distributed throughout the target. This is not so (the flux depressions should be comparable). The reason that the iron sheath gives rise to a larger flux depression is that the sheath is assumed to extend to the full 240 cm length of the moderator whereas in the Bi and Pb results presented in figure VII.16 the absorption is only over the 30 cm of the target length.

Figure VII.18 contains further flux distribution plots, this time for 12 cm radius Bi and Pb targets surrounded by 118 cm of D₂O. The flux ϕ_1 comprises those neutrons which have had one or more collisions in the moderator and whose energy is >1.46 eV. ϕ_F is the first-collision distribution. Figure VII.19 shows the Westcott¹⁶ r value pertaining to the distributions plotted in figure VII.18. In terms of our epithermal group flux ϕ_2 (0.127 to 1.46 eV) and the thermal flux ϕ_{th} , r_w is

$$r_w \approx (0.41 \phi_2 / \phi_{th}) [1 + 0.41 \sqrt{16/5\pi} \phi_2 / \phi_{th}]. \quad \text{VII.2}$$

It is essentially a measure of the ratio of the density of neutrons with energies >0.127 eV to the total neutron density.

2.6.3 Characteristics of the Neutron Beams Emerging from the ING Beam Tubes

In the following we make a few qualitative and quantitative remarks concerning the intensities and energy distribution of the unfiltered, uncollimated neutrons emerging from the beam tubes in the ING facility. We consider "tangential" and "radial" beam tube configurations as illustrated schematically in figure VII.20. The tubes are located in a plane perpendicular to the target axis and the characteristics discussed are for neutrons emerging at position P (i.e. P_A , P_B) of the tube. We assume to begin with that the beam tube does not perturb the moderator flux and later indicate what the perturbing effects of the tube will be. We define thermal, epithermal, intermediate, fast and very fast neutrons to be neutrons with energies $\approx 5kT$ for thermal, $5kT \lesssim E \lesssim 1.5$ eV for epithermal, 1.5 eV $\lesssim E \lesssim 1$ MeV for intermediate, 1 MeV $\lesssim E \lesssim 20$ MeV for fast and $\gtrsim 20$ MeV for very fast. We recall that the neutron spectrum extends to about 1 GeV, the energy of the bombarding proton.

16 C.H. Westcott, et al, Effective Cross Sections and Cadmium Ratios for the Neutron Spectra of Thermal Reactors, proc 2nd UN Intl. Conf. Peaceful Uses Atomic Energy, 16,70 (1958).

FIG. VII. 18 Mid-plane flux distributions for Pb and Bi targets, 24 cm diam. 30 cm long. Source strength 10^{19} neutrons/s

ϕ_F = flux of first collision neutrons

ϕ_1 = " " neutrons with energies > 1.46 eV

ϕ = " " " in range 0.127 eV $< E < 1.46$ eV

Thermal group has $E < 0.127$ eV.

FIG. VII. 19 Westcott¹⁶ r values for the targets of Fig. VII. 18.

FIG. VII. 20 Schematic diagram illustrating radial and tangential beam tubes.

It is found¹¹ that for the thermal, epithermal and intermediate energy neutron fluxes the main contribution to the emergent flux is from the tube end, this contribution for a narrow tube being

$$\phi_{\text{End}}(P) \approx \frac{\bar{\phi}}{4} \frac{a^2}{L^2} \quad \text{VII. 3}$$

in which $\bar{\phi}$ is the neutron flux at the tube end in the moderator averaged over the cross sectional area of the tube end, a is the tube radius, L the tube length. The total emergent flux, including the contribution from neutrons which cross the curved surface of the tube, is obtained by increasing the estimate (VII. 3) for the tube end by about 30% for thermal neutrons, 10% for the epithermal and intermediate neutrons.

For narrow tubes $\bar{\phi}$ in (VII. 3) is nearly equal to the flux at the point where the tube axis intersects the moderator. Call this flux $\phi(b)$ where b is the distance from this point of intersection to the target axis (see figure VII. 20). Then the intensity of the flux of thermal, epithermal and intermediate energy neutrons at the point P for the tangential tube, the unperturbed case, is given by

$$\begin{aligned} \phi_{\text{th}}(P) &\approx \frac{1.3}{4} \phi_{\text{th}}(b) \frac{a^2}{L^2} \\ \phi_2(P) &\approx \frac{1.1}{4} \phi_2(b) \frac{a^2}{L^2} \\ \phi_{\text{IN}}(P) &\approx \frac{1.1}{4} \phi_{\text{IN}}(b) \frac{a^2}{L^2} \end{aligned} \quad \text{VII. 4}$$

It is evident that at the lower energies the relative strengths of the various emergent neutrons is similar to the relative strength of these neutrons at the entry tube end in the moderator. In the radial configuration the intensity of the thermal groups is expected to increase by about ~10%, ~20% for the epithermal groups and ~30% for the intermediate group. The emergent neutron flux may be characterized by a Westcott "r" value. From the definition of r_w (see 2. 6. 2) it is evident that in the tangential configuration, in the unperturbed case the r_w value for the emergent neutron beam is slightly lower (by about 15%) than the appropriate r_w value at radius b in the moderator. The r_w value in the radial tube is comparable with the r_w value at radius b in the moderator.

$\phi(P, E) \Delta E$, the strength of lower energy neutrons in a narrow energy band about an energy E , may be obtained by resolving the thermal, epithermal and intermediate energy groups into energy spectra. The thermal group may be represented quite well by a Maxwellian spectrum with an effective temperature T so that

$$\phi_{th}(E, b) \approx \phi_{th}(b) \frac{E}{(kT)^2} \exp(-E/kT)$$

with $kT \approx 0.027$ and thus in a tangential tube

$$\phi_{th}(E, P) \approx \frac{1.3}{4} \phi_{th}(E, b) \frac{a^2}{L^2} \quad \text{VII.5}$$

The epithermal groups ϕ_2 for which $5kT \lesssim E \lesssim 1.46 \text{ eV}$ is fairly well resolved by

$$\phi_2(E, b) \approx 0.41 \phi_2(b)/E$$

and then

$$\phi_2(E, P) \approx \frac{1.1}{4} \phi_2(E, b) \frac{a^2}{L^2} \quad \text{VII.6}$$

A rough guide to the intermediate neutron spectrum may be provided by taking $\phi_{IN}(b)$ to be the $\phi_1(b)$ plotted in figure VII.18 and writing

$$\phi_{IN}(E, b) \approx 0.066 \phi_1(b)/E.$$

Note that for $E \gtrsim 5kT$ the "thermal" flux (VII.5) may contribute appreciably to the flux in the epithermal energy region, i.e. the flux (VII.6) overlaps the flux (VII.5).

The intensities of the fast and very fast neutrons emerging from the tangential tube are not readily available. For neutrons in the energy range $1 \text{ MeV} \lesssim E < 8 \text{ MeV}$ these intensities could be derived reasonably well from the type of fluxes presented in figure VII.9 by subtracting the "uncollided" flux component. However, as already mentioned in section 1, our treatment of source neutrons with energies greater than 20 MeV is only approximate. Hence, an estimate of the intensity of fast and very fast neutrons in the beam would require a detailed examination of the

contribution of the source neutrons to the collision fluxes at energies greater than about 8 MeV.

We finally indicate the perturbing effect of the beam tube itself on the intensity of the emergent neutron flux. The tube creates a void in the moderator which in the particular case of the ING assembly permits unhindered transport of neutrons from the high flux region near the centre of the moderator to a less favourable region in the moderator periphery. The peak flux is thus depressed while the flux in the peripheral regions may be somewhat enhanced. The tube material also absorbs neutrons and contributes to an overall flux depression. Of the two configurations, the radial tube is expected to cause the largest perturbation since it is most favourably oriented to cause unhindered neutron leakage, particularly of the fast neutrons.

An early and approximate calculation of the flux depression was made for nine, 7.6 cm diameter tubes located at a distance of 15 cm from a 4 cm diameter target. The tube walls were assumed to be 0.63 cm Al. The calculated depression factor of the flux at the tube end was 0.55. A large part of this depression was caused by the overall effect of thermal neutron absorption by these relatively thickwalled tubes. The effects of individual tubes were not calculated at this stage.

Recent measurements by Walker⁷ and Fraser⁸ indicate that the depression effect of a single tube (in their case a 10.2 cm diameter tube with a 0.16 cm Al wall) is relatively small, being about 10 % at the tube end. (see Section VII. A. 2.3).

It is expected that the beam tubes will increase the emerging flux of the fast and very fast neutrons and will decrease the flux of thermal and epithermal neutrons. The depression in the thermal flux leaving the tube will be somewhat less than the flux depression measured (or calculated) at the tube end in the moderator because of two compensating factors, (a) the neutron currents in the moderator surrounding the tube caused by the presence of the tube itself and (b) the enhancement of the flux near the tube in the peripheral regions of the moderator.

As mentioned in section VII. A 2.3, the beam tubes introduce a considerable geometric complication in the calculation of the neutron fluxes in the moderator. Conkie¹⁷ has recently been developing an iterative procedure, using the calculated (or measured) unperturbed flux as a starting point, for estimating the effect of the tubes on the flux in the moderator. He has applied his procedure to the analysis of the measurements made by Walker⁷ on the single tube and appears to get a satisfactory reproduction of the thermal neutron flux distribution along the tube surface and the tube end at the first iteration. The analysis is being continued.

¹⁷ W. R. Conkie, (Queen's University, Kingston, Ontario), private communication (1966).

3. Liquid Metal System

3.1 Description

The liquid metal system is shown schematically in Fig. VII.21 and basic data is given in Table VII.A.8. The cooled liquid metal from the heat exchanger flows up a pipe outside the main target shielding and then almost horizontally through the shielding to the vaned head. This vaned head discharges the liquid downwards as a thick film attached to the pipe wall. The vanes in the head impart a whirl to this annular flow and the resulting centrifugal forces are essential to keeping the flow attached to the wall. The cylindrical space down the centre of this flow is evacuated and the proton beam passes through it, as shown in Fig. VII.22. The top of the target is formed by the liquid metal surface at the elevation where the flow changes from a film on the wall to a fully flooded pipe. The target surface can be adjusted to the correct elevation by adding Pb-Bi to, or draining Pb-Bi from, the liquid metal system.

The interactions between the proton beam and the target result in a high intensity neutron flux, and also produce heat which appears directly in the target material. For a 65 mA beam of 1 GeV protons, 38 MW of heat will be generated and 95% of this heat will appear in the first 60 cm of target length. This causes a relatively rapid rise in target temperature. The heated liquid metal passes down the target tube and flows to the pumps. From the pumps the Pb-Bi flows to the heat exchanger, where it is cooled to target inlet temperature before being returned to the target.

The material used in the liquid metal system - the pumps, piping and heat exchanger - must resist corrosion by liquid Pb-Bi at the appropriate temperatures and pressures. However, for the section of pipe which passes through the moderator and contains the target there is an additional requirement. This pipe must absorb as few neutrons as possible and must be highly resistant to radiation damage. It is called the Target Tube and is dealt with as a separate problem.

The liquid metal system includes a dump tank, heaters, a level control tank, an inert gas system, an intermediate cooling system, a vacuum system and a variety of instrumentation and controls. The dump tank will contain the complete charge of Pb-Bi when the system is drained, and will also serve as a melt tank. Heaters will be provided for the dump tank, capable of melting the entire charge, and trace heating will be required for all components and piping. Inert gas will be provided as a blanket over the Pb-Bi in the dump tank and in the pumps. An intermediate cooling system is preferred so as to allow cooling of the Pb-Bi without danger of its freezing in the heat exchanger with consequent loss of target flow. In section IX D.1.10 a direct heat exchanger is adopted for heat recovery. This question requires further study.

VII.A

FIG. VII. 21 Schematic of liquid metal system.

TABLE VII. A. 8

LEAD-BISMUTH SYSTEM DATAPrimary System

Liquid metal	Pb-Bi eutectic
Freezing point	125°C
Flow	4560 lb s ⁻¹ = 2680 IGPM
Pb-Bi inventory	115000 lb
Target surface pressure	Vacuum
Pump inlet pressure	102 psia
Pump outlet pressure	330 psia
Heat exch. inlet pressure	325 psia
Heat exch. outlet pressure	267 psia
Heat exch. inlet temperature	450°C
Heat exch. outlet temperature	325°C
Pump efficiency	Assume 72%
Pump H. P.	600
Target tube ID	8 in
Target tube wall thickness	0.15 in Zr-2, 0.01 in Ni liner
Pb-Bi velocity in target	20 ft s ⁻¹
System piping ID	10.19 in (10 in. Sch 40)
Pb-Bi velocity in pipe	12 3/4 ft s ⁻¹

Pb-Bi To Intermediate Coolant Exchanger

Exchanger capacity	38 MW
Exchanger type	Tube in shell single pass, counter flow.
Liquid flowing in pipes	Pb-Bi
Liquid flowing in shell	NaK
Tube size	1 1/4 in
Tube pitch	1 9/16 in
Number of tubes	124
Shell ID	20 in.
Effective tube length	14.1 ft.
Max tube stress	12300 psi
Tube side press. loss	57 1/2 psi
Shell side press. loss	12 psi
Pb-Bi velocity	10 ft s ⁻¹
NaK velocity	15 ft s ⁻¹
Pb-Bi heat trans. coeff.	3740 BTU hr ⁻¹ ft ⁻² °F ⁻¹
NaK heat trans. coeff.	4340 BTU hr ⁻¹ ft ⁻² °F ⁻¹

TABLE VII. A. 8 (Cont' d)

Intermediate Coolant System

Intermediate Coolant	NaK
Freezing point	-11° C
Flow	678 lb s ⁻¹ = 5010 IGPM
NaK inventory	2800 lb.
System design pressure	325 psia
System operating pressure	Fixed by required pump inlet pressure
NaK vapor press. at 450° C	10 mm Hg.
NaK max temp.	344° C (650° F)
NaK min temp.	206° C (403° F)
NaK system flow losses	3 x Pb-Bi exchanger loss
Pump efficiency	Assume 70%
Pump H. P.	180

FIG. VII. 22 Schematic Diagram of Pb-Bi Flow through thermal neutron target.

3.2 Target Flow Configuration

The arrangement shown in Figs. VII.21 and VII.22, with the Pb-Bi inlet flow in an annulus around the beam and with the outlet flow continuing along the beam axis, meets the requirement that the flow be co-axial with the beam.

Three other flow configurations, as shown in Fig. VII.23, would also meet this requirement. Configuration (a), however, requires a window which cannot be satisfactorily cooled. Configuration (b) avoids the necessity of a window by replacing it with a stable cavitation zone. This is theoretically possible, but it is difficult to achieve a stable cavity in practice. In addition, it requires high Pb-Bi velocities to maintain cavitation and thus poses a problem of avoiding cavitation damage to the target and beam tube. Configuration (c) would be practical if Pb-Bi velocities could be kept low enough to provide a stable liquid surface, with no significant jet rising from the top of the inlet pipe. For this design, the velocities could be kept low enough only by using an unacceptably high Pb-Bi exit temperature or an unacceptably large diameter target.

Of the four possibilities considered, then, that of Fig. VII.22 is clearly the first choice and it is adopted for the reference design.

3.3 Materials

3.3.1 General System Materials

Materials which resist corrosion by liquid Pb-Bi include most ceramics, fused quartz, graphite, and the metals iron, niobium, tantalum, molybdenum and tungsten. Steels containing nickel, or appreciable amounts of chromium, are seriously attacked by Pb-Bi and are not acceptable.

Steels containing 2 1/4% Cr, 1% Mo, and 1 1/4% Cr, 1/2% Mo, (i. e. ASTM A335, Grades P22 and P11) have been used successfully for Bi and Pb-Bi loops to 1050° F, but corrosion increases to an unacceptable rate if the Cr content is increased to 5% or more^{18, 19, 20, 21}.

¹⁸ C. J. Klamut, et al, Material and Fuel Technology for an LMFR, proc. 2nd UN Intl. Conf. Peaceful Uses Atomic Energy (Geneva) 7, 173 (1958).

¹⁹ A. J. Romano, et al, The Investigation of Container Materials for Bi and Pb Alloys. Part 1. Thermal Convection Loops, report BNL-811, (1963).

²⁰ B. R. T. Frost, Liquid Metal Fuel Technology, proc. 2nd UN Intl. Conf. Peaceful Uses Atomic Energy (Geneva) 7, 139 (1958).

²¹ Y. Imai, et al, Corrosion and Erosion of Ferritic Steels by Liquid Bismuth, proc. IAEA Intl. Conf. Corrosion of Reactor Materials (Salzburg) 2, 51 (1962).

FIG. VII. 23 Schematic diagram of three early target concepts.

A more exact demonstration of the increase in corrosion rate with Cr content is illustrated²¹, see Fig. VII.24. At the same time corrosion is reduced by an increase in carbon content of the steel²¹, see Fig. VII.25.

In accordance with these results the specification, ASTM A 335 Grade P11, has been chosen for the general system piping, heat exchanger, and pumps. ASTM A 387 Grade C, firebox quality, is the equivalent specification for plate, and this will be used where plate occurs. Welding rod must be of an equivalent specification since the use of a higher Cr rod produces preferential corrosion at the welds^{18, 19}.

Some components, such as pump impellers, the vanes of the vaned head and possibly valves, if they are later demonstrated to be feasible, will be subject to erosion and/or cavitation damage. The cavitation can be minimized by good designs of the flow systems and erosion-resistant materials will be essential. Generally speaking, a high strength, hard material resists erosion best, as illustrated by the results of the cavitation test²¹ shown in Fig. VII.26. Materials for these components will therefore be hardenable, low-alloy sheets of high carbon or hard cast iron, free of Ni and with low Cr. The final choice of material will depend upon stress and fatigue analysis of the component.

The system will include some small components, notably diaphragms or bellows for instruments, which will be best made of Nb, Ta, or Mo. These items will require relatively high strength, good fatigue resistance, and exemplary resistance to corrosion because they will be very thin. Molybdenum, in particular, is preferred for these applications because it is essentially insoluble in Pb-Bi.

3.3.2 Target Tube Materials

The target tube is a special problem in that it must not only resist corrosion by liquid Pb-Bi and have adequate structural strength at the operating temperature, but must also resist radiation damage and have a low thermal neutron absorption cross-section.

Studies of the neutron production in the target indicate that one can tolerate only very small amounts of structural materials which have a thermal neutron capture cross-section greater than 1 barn. The possible metals with low cross-sections are Be, Mg, Al, Zr and Nb. Aluminum and magnesium will have inadequate structural strength at the upper temperature 450° C, and their corrosion resistance is inadequate above 300° C. Zirconium has too high a solubility in Pb-Bi to be considered without a protective coating¹⁹. Niobium has a solubility comparable with that of iron in bismuth, though its solubility in Pb-Bi eutectic is at present undetermined, and its thermal neutron cross-

DATA FOR 165 HRS. AT 700°C NO Zr ADDED

DATA FOR 165 HRS. 700 ppm Zr ADDED

FIG. VII. 24 Effect of chromium on corrosion of steel in Pb-Bi.

DATA FOR Fe - 2% Cr - C ALLOYS

DATA FOR Fe - 10% Cr - C ALLOYS

FIG. VII. 25 Effect of carbon on corrosion of steel in Pb-Bi (in 165 hrs with 700 ppm Zr added).

DATA FOR Fe - C AND Fe - Cr ALLOYS

DATA FOR CARBURIZED STEEL

FIG. VII. 26 Weight loss vs hardness for steels tested for erosion by the oscillation method for 1 hr.

section is too large to consider its use as the sole structural component of the target tube.

The remaining metal, beryllium, has good resistance to Pb-Bi at temperatures up to 500° C and would offer an advantage over the other materials by reason of the neutron multiplication obtained from its (n, 2n) reaction. However, its poor mechanical properties, particularly thermal shock resistance²² and stress rupture²³, and the serious effect on these properties²³ of the helium produced in the (n, α) reaction, make it unsuitable as the main structural component of the target tube, although it can probably be incorporated as a free-standing blanket if there is a suitable method for replacing it.

Non-metallic materials (e.g. Graphite, Al_2O_3 , SiC, SiO_2 , ZrO_2) which might be used for the target tubes, or as cladding for a Zircaloy-2 tube²⁶, suffer from problems of brittleness, particularly when hydrogen and helium are produced^{24, 25} (see Table VII.A.9). They have poor thermal shock resistance and may possibly suffer serious neutron damage. Whilst a satisfactory non-metallic target tube (or tube coating) may be developed, this is considered to be part of the development potential of the system, and from the feasibility standpoint only metallic materials will be considered.

The important parameters of these materials, in addition to thermal neutron cross-section and solubility in Pb-Bi, are the rates of helium and hydrogen production from (n, p) and (n, α) reactions^{24, 25} and the rate of transmutation to a foreign product. These properties are listed in Table VII.A.9. In addition, properties such as thermal conductivity and thermal expansion are important in the stressing of the target tube.

With the exception of its solubility in Pb-Bi, the other properties of zirconium and existing experience in its fabrication make it the obvious choice for the main structural member. Thus, the chosen solution to the problem of the target tube is a tube of Zircaloy-2 clad on the inside with a corrosion-resistant liner. The possible liner materials,

²² E.E. Baldwin and R.F. Koenig, Mechanical Properties of Beryllium report KAPL-1049 (1954).

²³ Proc. Intl. Conf. Metallurgy of Beryllium, Institute of Metals (London, 1961).

²⁴ H. Alter and C.E. Weber, J. Nuclear Materials 16, 68 (1965).

²⁵ I.M. Thorson, private communication, (April, 1966).

²⁶ The Composition of Zircaloy-2 by wt. is as follows: Zr, 98.04%; Sn, 1.5%; Fe, 0.13%; Cr, 0.1%; Ni, 0.05%; N, $\leq 0.01\%$; O, 0.17%.

TABLE VII.A.9

PROPERTIES OF POSSIBLE TARGET TUBE MATERIALS

Property		Be	C	Mg	Al	Si	Fe	Zr	Nb	Mo
Strength at 450°C		good	adequate	poor	poor	--	good	adequate	good	good
Ductility (unirradiated)		poor	poor	good	good	--	good	good	good	adequate
Solubility in Pb-Bi wt ppm	300°C	not detectable	low	~ 1000*	~ 200*	--	0.3	10	<1*	not detectable
	450°C	<0.1*	low	~ 5000*	~ 1000*	<1.0*	~ 1.0	55	2-3*	not detectable
Hydrogen Production wt ppm / yr	neutrons < 20 MeV ²⁴	--	0.0052	32	72	86	44	3.5	12	7.5
	neutrons > 20 MeV ²⁵	500?	485	485	485	485	250	200	200	200
Helium Production wt ppm/yr	neutrons < 20 MeV ²⁴	8700	99	305	61	60	18.5	4.8	1.0	20
	neutrons > 20 MeV ²⁵	2400	2000	600	600	600	100	40	40	40
Thermal neutron cap- ture cross-section barns		0.010	0.0037	0.069	0.23	0.16	2.62	0.185 (0.22 for Zr-2)	1.16	2.70
Transmu- tation	Principal Products	He (¹⁰ Be)	¹³ C	Al	Si	P	Mn (Co)	Nb (Mo)	⁹⁵ Nb	Tc (Ru)
	atom %/yr	2.5	0	0.09	7	0.1	5	0.4	0	4.2

* Estimated from BNL data for bismuth (BNL-9107)

with the smallest solubility in Pb-Bi, are Be and Mo, Nb, Ta and W being almost as good. Tantalum and tungsten can be discarded immediately because of their high cross-section. Beryllium is not acceptable as a coating because of damage by the helium produced in it. Molybdenum will suffer from transmutation to technetium, and embrittlement by hydrogen and helium could be serious since the metal is relatively impermeable to hydrogen and forms no stable hydride at these temperatures²⁷. As for thermal expansion, the respective coefficients in inches per inch per degree C are 6.5×10^{-6} for Zircaloy-2, 7.2×10^{-6} for Nb, and 4.9×10^{-6} for Mo. Hoop stresses caused by differential thermal expansion would therefore be -4900 psi (compression) for Nb and +27800 psi (tension) for Mo, assuming that all the strain is taken by the liner and that the tube is fabricated at 15°C and operated at 450°C. If the tube is fabricated at higher temperatures these stresses will be reduced. Conversely, for fabrication at temperatures above 450°C the operating stresses could be reversed. Both Nb and Mo stresses are acceptable, and within the allowable limits for the material at 450°C, but the Mo liner would result in much higher stresses in the liner-to-tube bond. Any liner could of course be designed and installed so as to undergo a room-temperature prestress that would reduce the operating stress. However, such a procedure is undesirable, and Nb remains the most attractive liner.

The chosen combination therefore is a Zircaloy-2 tube clad with Nb. Niobium has a very high permeability to hydrogen and is not likely to be embrittled by it. It might even act as a valve to permit hydrogen to diffuse out of the zirconium and into the Pb-Bi if the hydrogen activity in the eutectic could be maintained below the partial pressure of hydrogen in zirconium at 450°C. A pressure of 10^{-4} mmHg should maintain the hydrogen concentration in the zirconium below 100 ppm²⁸ provided that no oxide barrier forms at the Nb/ eutectic interface and that no diffusion barrier exists at the Zr/ Nb interface.

Thus, at the present calculated rate of hydrogen production, embrittlement does not appear to be a problem in the selected target tube combination. Helium embrittlement may be serious, however, if the helium is able to migrate to grain boundaries at 450°C. There is no direct experimental evidence to use to judge the probability of such a migration but analogies with beryllium suggest that migration will not occur. Radiation damage should not be a serious problem in the hot part of the tube, but will definitely build up in the cooler region above the

²⁷ R. W. Webb, Permeation of Hydrogen Through Metals, report NAA-SR-10462 (1965).

²⁸ C. E. Ells and A. D. McQuillan, J. Inst. Metals 85, 89 (1965).

point of impact of the proton beam where the temperature will be 325°C. The problem would get progressively worse if this temperature were to be reduced and although an increase in this temperature would improve the situation, it cannot be permitted if it involves an increase in the upper temperature.

The restriction on the upper temperature arises from the significant solubility of niobium in Pb-Bi at 450°C. Estimates place it at 2-3 ppm, and, although this may be reduced by zirconium and/or magnesium additions to the eutectic there is no current evidence that the quantity of these additives that is soluble in Pb-Bi at 450°C will have a significant effect. A differential solubility of 1-2 ppm is quite sufficient to give significant long term corrosion of the niobium. Until measurements of this corrosion rate are available from pumped loops it will not be possible to verify that a 0.025 cm cladding of niobium will be sufficient to ensure the desired life of at least 6-12 months.

3.4 Flow and Temperatures

From the thermal stress analysis of the target tube, given in a following section it is evident that ΔT , the allowable temperature rise in the liquid metal circuit, is limited by the transient thermal stresses. A ΔT of 125°C will give transient thermal stresses in the Zircaloy target tube of about 4500 psi, when the proton beam is interrupted. This stress is acceptable, and 125°C is therefore adopted as the design ΔT .

A 65 mA beam will give a heat production, in the target, of 38 Mw, or 36000 BTU/s⁻¹. Then, for the chosen ΔT of 125°C, or 225°F, the required Pb-Bi flow may be calculated as:

$$W = (36000) \frac{1}{225} \frac{1}{.035} = 4560 \text{ lbs s}^{-1},$$

where the heat capacity of Pb-Bi is 0.035 BTU/lb⁻¹ °F⁻¹ ²⁹

At an average density¹⁴ of 10.25 gm cm⁻³ (640 lbs/ft⁻³), this is a volume flow of 7.15 cfs, or 2680 IGPM of Pb-Bi.

For the reasons noted in the previous section on materials, a maximum Pb-Bi temperature around 450°C is desirable. The minimum Pb-Bi temperature is then 325°C. This is a good choice for the additional reasons that corrosion rates increase rapidly at temperatures above 500°C (as illustrated in Fig. VII.24 for instance),

²⁹ S. J. Stachura and G. Burnet, The Lead-Bismuth Eutectic, report 15-316 (1961).

allowable working stresses in Zircaloy-2 are acceptable at this temperature, and it provides an excellent margin of safety over the eutectic freezing point of 125°C (257°F). Some variations in temperature must be expected around the loop, particularly in the heat exchanger where temperature variations from tube to tube will be inevitable, and it is essential that plugging by freezing be avoided. In addition, the 325°C minimum is high enough to allow the installation of a cold trap purification system. This system will cool a part of the flow to a lower temperature, in order to precipitate dissolved contaminants out of the Pb-Bi in a disposable cooler.

3.5 Thermal Stresses³⁰

During operation of the liquid Pb-Bi circuit, radial and axial temperature gradients in the circuit piping can occur. With reference to Fig. VII.27, an axial temperature gradient in the Pb-Bi occurs between points A and B and is caused by heat from the proton beam interaction with the liquid target. A radial temperature gradient in the piping can be expected if the proton beam is suddenly stopped. In this case, heating of the Pb-Bi no longer takes place and cooler liquid will be circulated beyond point A. Thus liquid at temperature A will come in contact with the inner wall of the pipe which is at a temperature between A and B and will cause a radial temperature gradient. The Pb-Bi enters the target tube, above A, at 325°C and is heated to 450°C by the time it reaches point B.

Figure VII.27 shows a cross-section of the piping at the target tube, consisting of the target tube itself, a gas layer and the tank inner wall. Zircaloy-2 has been selected for both tubes, with the target tube having a thin layer of niobium to prevent attack of the zirconium by liquid Pb-Bi.

The radial temperature gradient in the piping, when the temperature of the fluid at one wall is changed, was estimated by the method of Ref. 31, using a computer program. Temperature gradients through the tube wall, at various time intervals after proton beam shut-off, and for an initial temperature difference of 125°C (225°F) are shown in Fig. VII.28. The calculations are for a 9 inch diameter target tube, although the reference design tube is 8 inches. The results will be very little affected by this change.

³⁰ J. Toronchuk, Thermal Stresses in Piping for Liquid Metal in the ING Thermal Neutron Target, report FSD/ ING-39 (1966).

³¹ E.R. Eckert, Heat and Mass Transfer, (with Appendix of property values by R.M. Drake), p.80, McGraw-Hill (1959).

FIG. VII. 27 Schematic diagram of target tube.

VII. 28 Plot of temperature difference against radius for a Zr wall thickness of 0.15" and an initial temperature difference of 225 F degs at time zero.

The highest axial temperature gradient in the piping will occur between points A and B. Taking this temperature gradient as linear from A to B, no stress will occur³².

The radial temperature distribution will, however, result in radial, axial and tangential stresses³³. Figs. VII.29 and VII.30 illustrate the results of a computer solution to the equations for these stresses, in a Zr-2 tube, for the temperature distribution of Fig. VII.28. They show radial and tangential stresses - axial stresses are very nearly identical to tangential stresses. All stresses vary with time, and the maximum stress occurs at the inner surface of the tube, where tangential stress is a maximum, at a time which may be determined from the plot of stress vs time. Such a plot is presented in Fig. VII.31. Here the above calculations have been repeated for a number of values of temperature difference ($T_B - T_A$) and intermediate curves may be interpolated. The maximum stress for a 125°C (225°F) temperature difference is about 4500 psi in the Zr-2 target tube.

A similar analysis for the 1/4 inch (0.634 cm) wall steel pipe of the Pb-Bi system yields the data illustrated in Fig. VII.32. Here the maximum transient thermal stress is 16500 psi for a temperature difference of 125°C (225°F).

In addition to the thermal stresses, additional stresses can be produced in the system by mechanical loads such as internal pressure and by thermal expansion of the piping system.

Because of the thin wall of the target tube there is a possibility that stresses other than thermal can be very high. By proper support of the target tube these stresses can be reduced so that the largest stress will be due to thermal transients and other stresses will be minimal.

Results of thermal stress-fatigue tests are available³⁴ for Zircaloy-2 and such results are reproduced in Fig. VII.33. This shows that a plastic strain of approximately 1400×10^{-6} in per in per cycle gave a fatigue life of 10,000 cycles. However, the data are not sufficient to give reliable constants for the equation that is used to predict fatigue life³⁴ and hence the target tube stresses, as calculated above, have been kept well below the yield stresses shown in Fig. VII.34³⁴. This design will provide a fatigue life greater than 10,000 cycles.

³² P.P. Bijlaard and R.J. Dohrmann, J. Eng. for Ind. 83, 467 (1961).

³³ S. Timoshenko and J.N. Goodier, Theory of Elasticity, p. 413, McGraw-Hill (1951).

³⁴ K.E. Horton and R.S. Stewart, Thermal-Stress-Fatigue Behavior of Zirconium and Zirconium Alloys, report ATL-A-127 (1961).

FIG. VII. 29 Plot of tangential stress vs radius (for a Zr. tube of 0.15" wall thickness, and initial temperature difference of 225 F degs).

FIG. VII. 30 Plot of radial stress vs radius (for a Zr tube of 0.15" wall thickness and initial temperature difference of 225 F degs).

FIG. VII. 31 Plot of tangential stress against time at inner radius of a 0.15" thick Zr tube.

FIG. VII. 32 Plot of tangential stress against time at inner radius of a 0.25" thick steel tube.

FIG. VII. 33 Plastic strain per cycle versus cycles to failure for zircaloy-2 strain-cycled in air.

FIG. VII. 34 Yield strength versus temperature for zircaloy-2 short-time tensile-tested in air.

Data for life and thermal stress of low alloy steels are also available³⁵ and a similar check of the life of the steel piping of the system has been made. Since the yield strength of (ASTM A-335 Grade P11) is 21,700 psi at operating temperature and the stress is only 16,500 psi, thermal fatigue will not limit the life of the system. Mechanical stress-fatigue data is available for Nb³⁶ but thermal stress-fatigue data is not available. To obtain an estimate of the life of the Nb, the method that was used for steel³⁵ can also be applied to Nb, using the mechanical stress data available. In this way it is estimated that the Nb liner will also stand more than 10,000 thermal cycles.

A shear stress will exist in the bond between the Zircaloy -2 target tube and Nb liner and an estimate of its magnitude can be obtained from the values of maximum stresses calculated above. This gives a value of shear stress of about 2600 psi which is low enough.

3.6 Heat Exchanger

The reference design heat exchanger for the Pb-Bi circuit is a single pass, counter-flow, tube-in-shell exchanger. The heat is transferred to an intermediate fluid, rather than directly to the river water and this use of an intermediate fluid solves three problems; it prevents the escape of active material to river water in case of a tube failure, it prevents the river water from boiling, and it avoids the freezing of the Pb-Bi by a cold coolant if the proton beam is interrupted. The first two of these problems could be solved by embedding separate, parallel, pipes for water and Pb-Bi in blocks of metal of high thermal conductivity or by use of a complex exchanger as shown in Fig. VII.35. However, the problem of preventing freezing of the Pb-Bi can be conveniently and safely handled only by the use of a coolant whose minimum temperature is above the Pb-Bi freezing point.

The intermediate fluid could be pressurized water, and a preliminary tube-in-shell design shows that this would give a practical exchanger. The water must be pressurized, to avoid boiling, to at least 500 psi and a 1000 psi H₂O system would be preferable in order to allow higher water temperatures, and hence a lower ΔT from Pb-Bi to water and lower thermal stresses in the heat exchanger tubes. However, the system is undesirable because a leak in a tube joint would allow water to enter the Pb-Bi mixture. Again, a complex exchanger could be used, and the Pb-Bi being the lower pressure fluid would be located in the shell. However, such an exchanger would be larger than a simple exchanger

³⁵ B. F. Langer, The Welding J. 37, (9) (1958).

³⁶ F. T. Sisco and E. Epremian (editors), Columbium and Tantalum, Wiley, New York (1963).

FIG. VII. 35 Simplified cross section of complex exchanger.

because of the increased thermal resistance of the double tube arrangement, would have twice as many joints which might leak, and would be very much more expensive.

Since this will be the first major Pb-Bi system to be put into operation anywhere, and since all available data are experimental rather than operational, all components associated with the Pb-Bi circuit must be kept as simple as possible to ensure reliability and to minimize maintenance problems. On these grounds, a complex exchanger is rejected for the Pb-Bi end of the intermediate cooling system. A complex exchanger is acceptable at the other end, where heat is transferred from the intermediate coolant to cooling water, since this exchanger will not be active and can be readily accessible for maintenance. The intermediate coolant must be at a lower pressure than the Pb-Bi and it must not react with Pb-Bi if it is to be used in a simple exchanger in the Pb-Bi circuit.

An intermediate liquid metal system with NaK or an organic coolant is therefore more attractive and its adoption is recommended. This intermediate circuit would normally operate at atmospheric pressure, compared to the Pb-Bi pressure of 310 psig at exchanger inlet and 250 psig at exchanger exit. A leak in the exchanger would therefore allow Pb-Bi to escape into the intermediate system. This would make the intermediate circuit active and would be a nuisance, but it would involve no danger of a burst Pb-Bi system. In the event that circulation stopped, and the intermediate coolant rose to the 450°C of the Pb-Bi system, the pressure in the intermediate system would remain atmospheric for a NaK coolant, because its vapor pressure is only 10 mm Hg at 450°C. For an organic coolant the pressure would rise to about 125 psig but this would still be lower than in the Pb-Bi system.

The intermediate system would, however, be designed for a pressure of 310 psig on the Pb-Bi side, in order to avoid damage in the event of a leak from one system to the other in the heat exchanger.

Taking NaK as an example, the Pb-Bi to NaK exchanger consists of 114 tubes, 1-1/4 inch diameter on a 1-9/16 inch pitch, in a 19 inch ID shell. The Pb-Bi flows through the tubes, the NaK through the shell. The effective length of the exchanger is 14.1 ft. and it will be manufactured in a U shape in order to avoid stresses caused by unequal expansions of tubes and shell. Stresses produced by the thermal gradient across the tubes from Pb-Bi to NaK will be a maximum of 12,300 psi. This is below the normal design value of 14,400 psi given for ASTM A335 Grade P11 or P22 in the 'Unfired Pressure Vessel Code' for 850°F (455°C). The tubes will normally operate at 50°F to 100°F below this maximum of 850°F, but hotter spots, approaching 850°F, must be expected.

Although this exchanger is entirely feasible, equally satisfactory designs could be made, involving different numbers and sizes of tubes, exchanger lengths and fluid velocities. This study therefore proves feasibility but the design is not unique, and a design of similar performance but somewhat different geometry could be acceptable.

3.7 Pumps

Pumps for the Pb-Bi system will be centrifugal. The total power requirements are 550 H. P., assuming a pump efficiency of 70%. This efficiency may be optimistic but the power required will not make a significant change in power requirements for the target.

The Pb-Bi pumps will be vertical, with a canned motor and a relatively long shaft from motor to impeller, generally as illustrated in Fig. VII.36. The liquid metal will be allowed to rise up inside the pump body to a point about halfway between motor and impeller. The level will be maintained at this point by the pressure of an inert gas above the liquid, the gas pressure being regulated by a liquid level controller. The motor will be mounted in conventional anti-friction bearings and the lower end of the shaft will be supported radially by a sleeve bearing in the liquid metal. The pump illustrated, and another of this general configuration, each capable of 360 USGPM and a 55 ft. head, have been run in a Bi loop at BNL³⁷. Although they did have some troubles and were run for only 1700 hours, the results indicate that the pumps necessary for the Pb-Bi circuit are quite feasible.

The intermediate coolant will be circulated with centrifugal pumps whether it is NaK or an organic coolant. In either case, a body of operating experience is available and no feasibility problem will arise. For the case of NaK, for a pump 70% efficient, 165 H. P. will be required. The intermediate cooling system will not be active and can be maintained in a normal way. A standby pump can be provided to avoid a shut-down in the event of a pump failure. In the event of a leak of Pb-Bi into the intermediate system, the leak can be detected by γ radiation monitors and a shut-down and subsequent dump of the Pb-Bi can minimize contamination.

Maintenance of the primary liquid metal pumps will be more difficult as no satisfactory valve is now available for Pb-Bi service. However, a standby pump can be provided, isolated from the rest of the system by "freeze-valves". A pump failure will then involve a delay while plugs of Pb-Bi are thawed from one set of lines and frozen into those leading to the pump that has failed. A freeze-valve operation

³⁷ K. C. Hoffman, et al., Liquid Metal Fuel Reactor: Four-Inch Utility Test Loop, report BNL-619 (1960).

FIG. VII 36 Typical liquid metal pump.

of this kind should take less than 30 minutes, and operation can then be resumed while the damaged pump is repaired. Since the pumps will be radio-active their maintenance will require the use of a suitable hot cell. Freeze valves are not the most desirable solution, because the low temperatures may encourage deposits in the adjacent piping, and a program to develop a satisfactory valve should be undertaken prior to the final design.

3.8 Vaned Head

The vaned head is a solution to the problem of providing a window between the proton beam and the Pb-Bi target. The beam is transported through a beam tube which is evacuated to 10^{-6} torr and it is necessary to avoid a flow of Pb-Bi, or its vapor, back up this tube. The use of a window to separate the beam transport system from the liquid metal target would create heat removal and radiation damage problems that are probably insuperable.

The low vapor pressure of the Pb-Bi eutectic makes the present alternative possible. The arrangement is essentially a vortex and the hole down its centre is terminated at a chosen level by fixing the volume of liquid in the system. In an ideal system, a given volume of liquid in the circuit would produce a given level of the target surface since the circuit volume is fixed and the fluid is incompressible. In practice, however, the circuit piping is slightly elastic, and is subject to thermal expansion, and a change in flow rate can change the thickness of the film on the wall above the target surface. As a result, a level control system is required, and the target surface level will be adjusted by adding or subtracting liquid, using a level control tank provided for the purpose.

Hydraulic tests show that a satisfactory vortex can be established by flow through a vaned head or by radial inflow, with swirl, over a circular weir. The weir is slightly simpler, but much larger in diameter than the vaned head. The vaned head affords better access, for experimental holes and rods, to the top of the moderator tank and has been adopted as the reference design.

Although the beam tube is evacuated to 10^{-6} torr, this pressure may not be attainable in the evacuated space down the centre of the vortex. The Pb-Bi film flowing down the wall of the target tube is at a temperature of 325°C , giving a Pb vapor pressure of 4.5×10^{-9} torr and a Bi vapor pressure of 10^{-8} torr. The target surface, however, will be at a higher temperature. If it is at the average fully heated value of 450°C , the Pb vapor pressure will be 3×10^{-6} torr and the Bi vapor pressure 8×10^{-6} torr. Since the Bi vapor pressure is greater than that for Pb, the vapor will always be rich in Bi. The temperature of the target surface is not accurately predictable.

The rate of heat generation in the target by the beam will be a maximum at the surface but the temperature will rise to a maximum a few centimeters below the surface. Turbulence will bring some of the heated liquid to the surface from below and the scale and intensity of this turbulence cannot be accurately calculated, or readily determined by test. However, the high vertical velocity of the liquid metal will carry hot material away from the surface rapidly, and the flowing film on the wall will act as an ejector to pump vapor back into the liquid, in addition to being cold enough to condense vapor from a hot target surface. Since the mean free path of a heavy molecule, such as Hg, Po or Bi, is over 180 cm at 10^{-6} torr, and the diameter of the space inside the film is about 17.8 cm, collisions between vapor particles and the cold film will occur and the effectiveness of the film in recapturing vapor will be good. Considering Pb and Bi vapor, therefore, it is reasonable to anticipate a vapor pressure of about 10^{-5} torr at the target surface and to expect that the flowing film will reduce this to a lower value, 10^{-6} torr or less, at the vaned head.

There are, however, spallation products with a higher vapor pressure than the Pb-Bi, and the removal of these vapors will be the problem that will limit the attainable target vacuum. Spallation product vapors and gases are discussed later, in connection with the vacuum system.

3.9 Valves

No satisfactory valve is available for use in a flow of Pb-Bi. The outstanding problem is that of a seal with an adequately long life. For complete sealing, a welded-in bellows seal must be used and in past loops these bellows have failed from corrosion, erosion, or fatigue, or from a combination of all three. The fatigue problem arises from the turbulent flow of the liquid metal through the irregularly shaped valve body. Satisfactory valve bodies and seats have been demonstrated³⁷.

There has been no serious program undertaken, to date, to develop a satisfactory bellows, and it is anticipated that such a program would result in success. The few bellows used in past loops have been made from whatever was available (even if the material was known to be of doubtful corrosion resistance) or from low-chromium steel, fabricated by relatively short-cut methods. A program to develop reasonably stressed bellows made of low-Cr steel, or of the more promising materials such as molybdenum, and to provide these bellows with protection against buffeting by the flowing metal, would have every hope of success. Such a program will be undertaken prior to final design of the Pb-Bi circuit, since acceptable valves would simplify the maintenance problems.

In the meantime, the Pb-Bi system has been designed to use only one valve - a dump valve - between the dump tank and the system.

This valve is to be installed with the bellows on the dump tank side of the valve. The bellows will thus be immersed in Pb-Bi when there is flow through the pipe, i. e. during fill or dump. With the system filled, the valve will be closed, to trap the desired amount of Pb-Bi in the system, and the mixture in the pipe below the valve will be allowed to drain back into the dump tank, thus leaving the bellows exposed only to an evacuated space. After dump, the Pb-Bi will all be in the dump tank and the bellows will again be free of liquid metal. The bellows exposure to liquid metal will therefore be only a small fraction of the time that the target is in operation and bellows life should be satisfactory even if the bellows are not improved over past models.

3.10 Purification

As noted earlier, it is intended to incorporate a cold trap in the Pb-Bi circuit to remove dissolved contaminants in the liquid metal and thus to prevent or reduce deposits in the cold leg of the system. The component that will be the most liable to plugging will be the heat exchanger. In addition to the tendency of deposits to form on the cooled surfaces in the system, the exchanger suffers from having smaller diameter tubing and the fact that it offers alternative flow paths. A small tube is more easily plugged than a large one, and a deposit in one tube will increase its resistance, with the result that its Pb-Bi flow is reduced, its average temperature is reduced, and the deposition is accelerated.

Evidence available to date, from work by previous experimentors, indicates that a satisfactory life can be obtained for the system by keeping it clean, by excluding oxygen, and by building it from materials that have good resistance to corrosion. A number of experimental thermal convection loops have been run for periods of more than a year^{19, 38} without plugging, and a number of other thermal loops have been run for shorter periods of time but with rates of corrosion and deposition low enough to have allowed the loop to run a year.^{18, 19, 37, 38} A thermal loop plugs more readily than a pumped loop because the low velocities in the thermal loop result in a localized, low-density plug, which can stop the flow with a small total deposited mass. Pumped loops^{20, 37, 38} develop much more dense plugs, the density often approaching that of the pipe wall, distributed over a greater length of pipe. The pumped loop therefore accepts a relatively large total mass of deposited material before plugging. It is, however, unlikely that a large operational system can be run as cleanly as a small experimental loop. In addition, the processes of corrosion and deposition are not fully understood, and there is considerable scatter in the 'life-to-plugging' times of loops which should have had comparable lives. As a result, it must be considered possible that

³⁸ R. Cygan, Circulation of Lead-Bismuth Eutectic at Intermediate Temperatures, report NAA-SR-253 (1953);
Lead-Bismuth Eutectic Thermal Convection Loop, report NAA-SR-1060 (1954);
Lead-Bismuth Pump Loop, report NAA-SR-MEMO-622 (1953).

the Pb-Bi heat exchanger may have to be replaced after a year of operation. After the first year, when methods of operation and clean-up have been developed by experience, the exchanger lifetime may be expected to increase. Given a reasonably inexpensive exchanger, and design for safe and convenient replacement, this situation is acceptable.

It is reasonable to believe, moreover, that a major increase in 'life-to-plugging' can be achieved by protecting the hot leg piping with a suitable coating to resist corrosion by Pb-Bi (as discussed earlier under materials) and/ or by the use of a clean-up circuit, including a disposable cold trap to catch contaminants. The use of a cold trap is supported by evidence from a thermal convection loop³⁸ in which a cold trap was employed.

Deposition occurs mainly at the point of minimum film temperature in the Pb-Bi,³⁹ rather than at minimum bulk temperature. This should allow the use of a cold trap that is much smaller than the heat exchanger so that although the Pb-Bi is exposed to a wall colder than any part of the heat exchanger the bulk temperature of the Pb-Bi is reduced by only a fraction of the required ΔT for the system. Development work is required to provide design criteria for this device.

In addition to the cold trap, which is in operation when the system is in operation, a removable cooling coil will be provided in the dump tank. This coil will be used for a periodic clean-up operation in which the Pb-Bi will be held in the tank at an elevated temperature while the coil is maintained at a temperature just above the freezing point of the eutectic so as to encourage deposition on the coil. This clean-up, if carried too far, could actually accelerate corrosion of the system by reducing the percentage of dissolved materials in the Pb-Bi below the concentrations necessary to just-avoid deposition in the heat exchanger. It is desirable to operate, for instance, with just under 2 ppm of Fe in the Pb-Bi entering the target, because this is the saturation value at 325°C and should thus reduce the corrosion of Fe in the hot leg without depositing out in the cold leg. The cooling coil in the tank is therefore to be used to clean-up after a serious excess of some material has entered the Pb-Bi - for instance an excess of Zr due to failure of the Nb target tube liner. Sampling stations will be provided in the circulating system, and in the dump tank, to allow monitoring of the condition of the Pb-Bi.

3.11 Vacuum System

At start-up, the vacuum system will have to deal with any gases which may be dissolved in the Pb-Bi, in addition to the normal

³⁹ J.R. Weeks and C.J. Klamut, Nuclear Sci. and Eng. 8, 133 (1960).

outgassing of the system pipework. After this initial outgassing, the major load on the vacuum system will come from the spallation products produced in the target.

The spallation products will consist mainly of heavy elements, close to Pb and Bi, and some very light elements. Of the heavy elements, isotopes of Pb and Bi, Hg, Po, Au and Tl, only the Hg will make a significant contribution to the vacuum problem. About 13 Kg of Hg will be produced per year and, at 325°C, 10^{-4} torr, this will amount to 730 litres/sec of Hg vapor. At 325°C and 10^{-5} torr, the volume is increased to 7300 litres/sec.

The light elements are not so exactly determined. However, a 1.0 mA beam will produce 2×10^{23} protons, deuterons and tritons per year. Assuming that all of these are converted into atoms of light gases, a 65 mA beam will produce 240 litres/sec of such gases at 325°C and 10^{-4} torr, or 2400 litres/sec at 325°C and 10^{-5} torr.

The total gas and vapor production from spallation products is therefore about 970 litres/sec at 10^{-4} torr, the majority of this material being active. The Hg vapor, about 75% of the total, can be removed best by simply condensing it in a cold trap. This will greatly reduce pump contamination and will recover the Hg in a readily disposable form. A cold trap temperature of -39°C will freeze the Hg, while -25°C is required to give a vapor pressure of 10^{-5} torr. A cold trap which freezes the Hg will therefore be used since it will cost little or no more than a trap which achieves only an acceptable vapor pressure.

At the temperatures and pressures of the upper target tube, it appears certain that Po will vaporize and will be removed as a vapor along with the Hg. It is not now possible to predict the form in which the Po will appear, i.e. whether or not it will form a compound with some other spallation product, and hence its vapor pressure and its equilibrium concentration in the Pb-Bi is not known. Equilibrium will be reached, however, and after this time the cold trap will collect approximately 500 gms of Po per year, along with the Hg.

The remaining gas will be dealt with by a vacuum unit, which will exhaust approximately 1 1/3 litres of active gas per day, at atmospheric temperature and pressure. The composition, activity and method of disposal of this gas remain to be determined, but since only a small quantity of active material is involved its disposal will be feasible.

The possibility of removing these light gases, or the Hg, from the Pb-Bi by chemical means is not discarded, although it does not currently appear to be practical. The reference design therefore assumes that the above noted volumes will appear at the cold trap and vacuum pump.

Under these circumstances, the vacuum attainable is limited by the gas volume and the cross-sectional area available for the gases to pass up through the space in the perforated whirlpool and through the vaned head. At a vacuum of 10^{-4} torr, the gas volume passing through this space is acceptable, but 10^{-5} torr may not be attainable.

3.12 Target Tube Fabrication

The components used in the construction of the target tube are shown in Fig. VII.37. Here the Nb lined section of Zircaloy-2 tube is shown as being 8 ft. long. This is a minimum length, just sufficient to pass through the moderator tank. In the event that it finally proves both practical and economical to fabricate greater lengths of Nb-lined Zircaloy-2 tube, then a lined tube can be made long enough to extend from an inlet coupling on the vaned head to the exit coupling in the tunnel beneath the target shielding. It would not require the joints, item B of Fig. VII.37, but it would have to extend through the lower shielding (16-1/2 ft), through the moderator (8 ft), and up to the bottom of the vaned head (8-1/2 ft), for a total length of 33 ft. Such a tube appears difficult, and expensive at the present time and the reference design is therefore that of Fig. VII.37.

Construction begins with item B, the steel to Zircaloy-2 joint. A tapered joint is necessary here to accommodate the different coefficients of thermal expansion of the two components and there is no existing example of a joint of this type, using these two materials. Almost identical joints have been made using other materials and a successful one was developed by Battelle⁴⁰, using explosive bonding to join Zircaloy to stainless steel. The thermal expansion coefficients for stainless steel and Zircaloy are more widely separated than those for low alloy steel and Zircaloy. Similar joints have been achieved by the Nuclear Metals Div., of Textron⁴¹, using a method of co-extrusion. Successful co-extruded joints have been made between stainless steel and aluminum, stainless steel and Zircaloy-2 and stainless steel and niobium. A third method of joining two dissimilar metals, and one that has been used for such joints as stainless steel to aluminum, is the friction welding procedure now used by Caterpillar⁴². No joint of the desired geometry is reported, but the method produces excellent bonds. Since these successful joint fabrication processes exist, it is considered that joint B is feasible. Development will, however, be necessary to adapt the existing methods and parameters to yield a satisfactory joint for the target materials.

⁴⁰ S. J. Paprocki and S. W. Porembka (editors), Joining Zircaloy-Stainless Steel and SAP Alloys by Friction, Rolling and Explosive Techniques, report BMI-1594 (1962).

⁴¹ W. B. Tuffin, *Mats. in Design Eng.* 63, (2), 27 (1966).

⁴² T. L. Oberle, et al., *Eng. Digest* 12, (3), 23 (1966).

FIG. VII. 37 Target tube construction.

The two joints B, which will each be about 1 ft., long, are attached to the tube C by means of a Zircaloy-to-Zircaloy butt weld. The Nb liner, D, is then bonded in place. Finally, the lined section of tube is attached to the two steel pipe sections, A, by means of a steel-to-steel butt weld.

The Nb liner must be bonded to the Zircaloy tube over its entire area to ensure good heat transfer from liner to tube, to avoid high stresses due to large temperature differences, and to avoid wrinkling of the liner. A continuous bond will also be necessary to permit hydrogen mobility. There are several possible methods of obtaining this bond, the most attractive being brazing, electric resistance welding, and diffusion bonding.

A test program of brazing shows that an excellent brazed joint can be obtained by vapor-depositing a film of Be on either the Zr-2 or the Nb, clamping the two materials together, and induction heating in a vacuum. A 0.0003 inch film of Be has also given good results. In this procedure, which works equally well with the Be on either the Nb or Zr-2, the Be combines with Zr to form a brazing alloy. Brazed flat specimens have withstood repeated cycles of heating to 200°C and quenching in water. Tubular test specimens of Nb lined Zr-2 have yet to be tested for resistance to thermal cycling, but all indications are that the method will prove satisfactory.

Resistance welding tests have been carried out in which Nb has been spot welded to Zr-2 using a stitch-welding technique, the spots being overlapped to provide a bond over 100% of the area. A complete and satisfactory bond has been obtained, and a test specimen has withstood repeated heating to 200°C and quenching in water. As in the case of brazing, tubular test specimens will be made and subjected to thermal cycling.

The diffusion bonding approach has not been developed as far as the brazing and spot-welding methods, but tests are proceeding to determine the limits of temperature, time, and clamping pressure necessary to provide a good diffusion bond. This approach is well worth carrying through the initial stages since, if pressures and temperatures prove to be moderate, it offers a simple and possibly inexpensive fabrication method. In addition, it avoids the presence of an extra element (necessary in the braze) and offers a less complex alloy at the interface.

As a back-up to the Nb lined tube, other coatings have also been considered. These include a flame-sprayed Nb coating and a ZrO₂ coating. Although such coatings are normally classed as brittle, it must be acknowledged that any material used for the target tube will have a very low ductility after a brief period of operation, and the design must

allow for this condition. Flame-sprayed coatings are normally expected to be porous but a disc which had been flame-sprayed with a nominal 0.005 inch layer of Nb survived for 500 hrs. in 450°C Pb-Bi with no visible damage. The disc was rotated at a speed which provided a disc-to-liquid relative velocity of 15 ft/sec. A coating of this type remains undesirable because of the difficulty of inspection to discover a flaw in the coating.

A highly promising alternative is the ZrO₂ coating. This is obtained by growing the coating on the parent Zr-2 material simply by heating in air. A specific surface preparation is necessary, and the process has been developed to a reliable and repeatable technique by the Mechanical Equipment Division at Chalk River. Since the zirconia coating is actually composed of the parent material, the bond between coating and base is the best obtainable. A disc with an 0.003 inch ZrO₂ coating has run for 500 hrs. without discernable damage, and a Zr-2 tube similarly coated with ZrO₂ has completed 1000 cycles in a thermal cycle rig in Pb-Bi without damage. In the thermal cycle rig, a tubular test specimen is heated to 450°C in an inert gas atmosphere and then quenched by a flow of Pb-Bi at 325°C. This coating has not yet been checked for erosion or cavitation damage - it may 'spall' off under turbulent flow of Pb-Bi - however present indications are that it will prove to be satisfactory. It therefore forms an excellent back-up to the main program, and may prove to be an equally satisfactory choice.

3.13 Instrumentation

A large number of temperature measurements will be required around the system to check trace heating and to provide a picture of system operation. During running only target inlet and outlet temperatures and heat exchanger inlet and outlet temperatures will be important. Thermocouples, generally attached to the outside of pipes or buried in pipe walls, will be quite satisfactory and no problem is anticipated here.

Pb-Bi and intermediate coolant flows will have to be checked initially and monitored during running. Venturi flow-meters are to be used here, rather than orifices, because they allow smoother flow.

Pressure measurements will be necessary at a number of points in the Pb-Bi circuit including the venturi, the pump and target and heat exchanger inlets and outlets. These instruments can be made reliable but their designs will require careful attention to avoid either excessive buffeting by the liquid stream or corrosion and deposition in a cooler, stagnant pocket. A test and development program will be carried out on pressure sensors, but it is currently considered that a gas pressure balanced-diaphragm instrument will be best. Non-standard diaphragms

of low alloy steel or Mo will have to be tested to ensure that these instruments will perform satisfactorily.

Level controls will be required for the pumps (and for the level control tank, if this is not incorporated in the pumps) and for the target surface. Electric resistance probes are probably the best choice for the pumps, but details remain to be decided and several possibilities exist. Control of the target level is more difficult. It is proposed to set this level fairly closely by filling the system carefully with a predetermined amount of Pb-Bi and then to obtain final (and running) adjustment by means of a collimated fast neutron flux monitor. The beam will be turned on at low power to check the initial setting and then raised to full power as the level is verified. The flux monitor will provide an error signal and the level will be adjusted by changes in the level in the pumps and/or the level control tank. The pump-level control will therefore be initially guided by a preset average level and then, when the flux monitor is activated, will become a live control which will vary the level in the pump as requested - though not beyond a preset limit. Other possibilities for target level control exist, for instance measurement of pressure at a point below the target surface to determine head, and these possibilities will be followed up to see if one of them is more desirable than the reference design.

3.14 Activation and Spallation Products

Prolonged exposure of the Pb-Bi target to the proton beam will result in a variety of spallation products, both stable and unstable. These will contribute to the activity of the Pb-Bi system, and the more abundant products may become a significant chemical impurity.

The most prominent spallation products will be isotopes of the elements immediately below Pb in the periodic table. The large number of stable isotopes of Hg results in a relatively large yield of Hg. In addition, many light particles, particularly H and He isotopes, will be produced. As noted under the discussion of the vacuum system, the Hg and light gases form the major load on this system. Capture of thermal neutrons by ^{209}Bi produces ^{210}Po . This Po will also be removed by the vacuum system, thus limiting its concentration in the Pb-Bi system to some value less than the equilibrium value. However, the operational limit for Po is unknown and it is thus necessary to consider the activity of the Pb-Bi system under the assumption that Po concentration does reach equilibrium.

The yields of various contaminants have been estimated on the basis of yields calculated, by the Monte Carlo method, by Bertini⁴³

⁴³ H. Bertini, private communication (1964).

at ORNL. After one year of bombardment by a 65 mA beam of 1 GeV protons, the following yields are expected:

TABLE VII.A.10

CHEMICAL CONTAMINANTS PRODUCED IN THE TARGET

Element	Weight Produced Per Year g	Weight ppm in 48000 Kg Pb-Bi
H	12.2	0.25
He	0.82	0.02
Au	505	10.5
Hg	14000	292.
Tl	3130	65.
Po	950 (saturation level 520)	10

In addition, the yields of some products of possible biological significance have been estimated. These figures are very approximate since they are based on thin target cross-sections at 660 MeV^{44,45,46}. The results of this calculation are tabulated below:

TABLE VII.A.11

SOME RADIOACTIVE CONTAMINANTS PRODUCED IN THE TARGET

Product	ING Target g/yr.	ING Target curies/yr.
28 yr- ⁹⁰ Sr	79	1.1 x 10 ⁴
1.3 yr- ¹⁰⁹ Cd	61	1.2 x 10 ⁵
2.1 yr- ¹³⁴ Cs	3.7	4.0 x 10 ³
7.2 yr- ¹³³ Ba	3.7	1.4 x 10 ³
18 yr- ¹⁴⁵ Pm	6.4	8.8 x 10 ²

⁴⁴ A. P. Vinogradov, et al., Radiochemical Investigation of the Spallation of Copper and Bismuth Nuclei with High-Energy Particles, AEC-tr-2435 (part 2) 85 (1955); (NSA 10: 4105).

⁴⁵ A. N. Murin, et al., Spallation and Fission Reactions of Complex Nuclei, AEC-tr-2435 (part 2) 101 (1955); (NSA 10: 4106).

⁴⁶ A. V. Kaliamin, et al., Soviet J. Atomic Energy 4, 267 (1958).

For comparison with the above figures, the yield of ^{90}Sr from a 10 MW fission reactor in one year is about equal to that tabulated for the target. Thermal neutron fission does not produce ^{145}Pm , but the yield of 2.7 yr ^{147}Pm from a 10 MW-yr irradiation of ^{235}U is about 10 times the target yield. The methods and precautions needed to handle these active, medium-weight, isotopes have been developed by experience with fission reactor fuels, but care must be taken to incorporate these precautions in maintenance procedures.

A calculation has been made⁴⁷ of the activation of a variety of materials, using a 6 months irradiation time and a decay period of 100 hours. The result of this calculation is a set of values of a factor C. To obtain the field in R/hour from one gram of material, the value of C (for that material) is multiplied by the proton flux/cm² sec and by the appropriate solid angle factor. The values of C obtained in this calculation are approximate because the published cross-sections for high energy protons are not always complete, and there are cases of disagreement in data from two different sources. The results can be improved as better basic data becomes available. In the meantime, this calculation forms our best estimate of activation and is adequate for the purposes of the current study.

Applying the value of C for Bi to the liquid metal activated by the proton beam in the target, a field may be obtained for the Pb-Bi of the target circuit. The resulting field, for one gram of Bi at one meter, is 26 mR/hr. Considering a 10 inch diameter pipe filled with Pb-Bi of this activity, the 1/e attenuation value for Pb is about 1/2 inch. The γ radiation will therefore come from the outer 1 inch of Pb-Bi around a 180° arc of the pipe. Taking this section of the pipe as a line source, gives a field of 4.24×10^3 R/hr at one meter.

Where the Pb-Bi piping passes through an occupied area, this field should be attenuated by a factor of 7.1×10^5 , to reduce the field to 6 mR/hr⁴⁸. Since the γ 's produced by the active material in the liquid metal will generally have energies below 1 Mev, one inch of lead will provide an attenuation of one order of magnitude and the shielding required will be about 6 inches of lead, or its equivalent. The α 's emitted by contaminants such as Po will be a hazard in spilled Pb-Bi but will not require shielding. To contain such active materials in case of a leak in the liquid metal piping, an airtight duct must surround the piping in all occupied areas.

⁴⁷ R. H. J. Bower and G. T. Ewan, Activation of Materials by High Energy Protons, report FSD/ING-25 (1965).

⁴⁸ W. J. Henderson and A. C. Whittier, Handbook of Shielding and Heat Production Calculations for the NRU Reactor, report CRR-578 (1955) released as AECL-403.

Similar calculations may be made for the materials of the target core, again using appropriate values of C . In such calculations one must estimate the applicable flux and the effective mass of material being activated.

Considering the target tube, it may be assumed that the source strength is 10^{19} ns^{-1} and that 75% of these neutrons pass out through the walls of a 25 cm long section of the 20 cm diameter target tube. The average flux is therefore $4.8 \times 10^{15} \text{ n cm}^{-2} \text{ s}^{-1}$ of which 10%, or $5 \times 10^{14} \text{ n cm}^{-2} \text{ s}^{-1}$, have an energy high enough for the use of the factor C . For Zr, $C = 1.3 \times 10^{-9}$ and, considering the target tube as a line source with no self-shielding, a field of $1.08 \times 10^5 \text{ R/hr}$ at one meter is obtained. This is for fast neutron flux only.

The target tube is also exposed to a flux of 10^{16} thermal $\text{n's cm}^{-2} \text{ s}^{-1}$. This flux will result in an activity per g of tube that yields 170 R/hr at one meter. Converting this value to that for the tube as a line source, with no self-shielding, gives a field of $3.6 \times 10^6 \text{ R/hr}$ at one meter. This is more than an order of magnitude above the field obtained for activation by fast neutrons. The γ 's produced will be less than 1 MeV - almost entirely about 3/4 MeV from ^{95}Zr and ^{95}Nb - so that 1 inch of lead will provide an order-of-magnitude attenuation. A flask for handling this tube should provide an attenuation of 6×10^8 , so that a flask wall of 9 inches of lead should be adequate.

Since the central tube of the moderator tank and the Be blanket will be handled in the same way as the target tube, these components can also be considered here. The Zr-2 moderator tube will have an activity equal to that of the target tube since it is exposed to the same thermal neutron flux. The radiation from the Be will, however, be much less since it forms comparatively little activity under either the fast or thermal neutron flux.

As a result of these activity calculations, it is concluded that the flask necessary for handling components of the target core will pose no difficulties or unusual problems. The wall thickness required is moderate and the flasks can be comparable to, or lighter than, the fuel handling flask for NRX.

4. D₂O Moderator System

4.1 General

In general the D₂O system is very similar to the moderator system for a heavy water moderated reactor.

4.2 Moderator Tank

As noted previously, in Section VII.A.2.6, the required moderator thickness is 120 cm and the tank geometry is a modified vertical cylinder, see Fig. VII.38. The radius to the outside of the D₂O is 120 cm and any item such as the tank wall, or a layer of cobalt inside the tank wall, must lie outside this radius. The tank height at its centre-line, is 240 cm. The height at the wall is less, because of the conical top that has been adopted to reduce the D₂O inventory. The reduction in D₂O volume achieved by the cone angle adopted here is not great, and the design is far from optimum. However, the tank is a robust and simple and a very large number of commercial irradiation facilities can be installed.

The target tube must pass through the centre of the moderator, and it is not practical to allow D₂O to touch the very hot target tube. Hence the moderator tank must be provided with a central tube with an inside diameter slightly greater than the outside diameter of the target tube. This central tube must have a low cross-section to minimize the depression of the thermal neutron flux.

Because of the high fast neutron flux, the central tube has the same problems of hydrogen production as the target tube, and it is discussed in the section on materials above. Like the target tube, this central tube must be easily replaceable, because its service life may be comparatively short. To be readily removable, the connections between the central tube and the outer shell of the moderator tank must be made at a point outside the shielding, or at a point which is near the outside of the shielding and readily accessible. Extensions are provided, to both the top and the bottom of the moderator tank, out through the shielding at the bottom and most of the way through the shielding at the top. A readily removable plug in the shielding gives access to the necessary flanges at the top. The extension through the shielding at the bottom is dictated by a desire to have this connection accessible in the service tunnel beneath the shielding. At the top, the extension is long enough to place the top flanged connection far enough from the target to avoid serious activation of the flange materials. At the same time, some shielding must be left above the vaned head of the Pb-Bi system. The elevation of this assembly is therefore a compromise, and is chosen so that the activation of the material by neutrons from the target is about equal to the activity of the Pb-Bi.

FIG. VII. 38 Detailed schematic of thermal neutron target system.

The outside wall of the tank is of 1 1/2 inch stainless steel. This will provide excellent durability and adequate structural stiffness to minimize dimensional changes which might result in stresses and misalignments in experimental tubes and in the moderator central tube.

As noted above, the central tube is of Zircaloy for at least the 240 cm of the moderator tank height. Above and below the tank proper, inside the tank extensions, the tube can be of stainless steel and it is so shown in Fig. VII.38. This is an arbitrary choice and the final tube can be made entirely of Zircaloy if it is economical to do so. However, the tube wall thickness is minimized for the 240 cm section in the tank to minimize flux depression. With a pressurized moderator, this tube would be subjected to an exterior pressure and it is corrugated to provide extra resistance to collapse. An all-Zircaloy tube would require an increased wall thickness through the tank extensions to avoid corrugations in these regions. The steel tube shown does have the major advantages of providing shielding and of reducing the streaming of neutrons through the shielding along the target axis.

The joint at the top of the tank, between tank extension and central tube, is not restricted in shape, but the one at the bottom must allow the central tube to be removed vertically upwards. The joint adopted is a welded-in bellows. This must be cut for removal of the tube, but it is readily accessible, it offers a reliable joint, it meets the requirement for vertical withdrawal, and it provides for the differential thermal expansion of the central tube and the tank. Both upper and lower joints will be provided with D₂O-leak detection.

4.3 Beryllium Multiplier

A layer of Be, 20 cm thick, is placed around the liquid metal target to increase the available flux by its (n, 2n) reaction. As discussed under materials in Sec. VII. A. 3 the Be will suffer damage in the existing neutron flux, mainly by He production. The Be layer must therefore be arranged to permit periodic replacement. The location shown in Fig. VII. 38 has been chosen to allow such replacement, to allow cooling with the existing moderator flow, and to avoid interference with any other component if the Be distorts or cracks.

The shape adopted is that of a cylinder with a 9 3/8 inch ID - to provide clearance around the moderator central tube - a 25 inch OD and a 30 inch height. The 850 lb. cylinder of Be is inserted, and removed, through the upper moderator tank extension. The space between the moderator central tube and the outer wall of the tank extension is filled with a removable, annular, steel shield. The D₂O flow leaves the moderator tank at the top, passing over the Be and through slots in this shield to provide cooling. The Be cylinder is supported by a Zircaloy structure from the removable shield, and is removed with the shield.

4.4 D₂O Flow

With a 65 mA beam, approximately 13 MW of heat will be produced in the moderator and about 3 MW of heat will be produced in the Be. To remove this 16 MW of heat with a D₂O temperature rise of 40° F, a minimum flow of 2300 IGPM would be needed. A 3000 IGPM flow has been adopted for this design. The moderator tank illustrated will contain 18000 lbs of D₂O, about 1630 gallons. Thus the circulation time is 30 secs. This high rate of replacement will help to reduce the amount of radiolytic gases present in the tank. The D₂O moderator circuit is shown schematically in Fig. VII. 39.

A separate D₂O flow of 1100 IGPM will be provided for the cobalt, as noted below in Sec. VII. A. 5.2. For the arrangement in which two cobalt annuli are provided, plus the H₂O reflector, a multiple cooling flow will be required. The inner cobalt annulus will require the cooling flow noted above. The second, or outer, cobalt annulus will normally require about an order of magnitude less cooling. Provision will have to be made, however, to divert the inner annulus cooling flow to the outer annulus in the case where the inner annulus does not contain cobalt, because the main heating load would then occur in the outer annulus.

With a full load of cobalt, heating in the tank wall will be predominantly caused by cascade neutrons. With the cobalt all out, the tank wall will receive the full thermal neutron heating load as well. As a result, the tank wall cooling flow will have to be designed for the no-cobalt case which, as noted under Shielding (Sec. VII.A.6), will require about 550 IGPM to each side of the wall, in this case to the external cooling jacket and to the internal reflector. As in the case of the outer jacket, the reflector will require baffling, or flow guidance, to provide coolant velocities that will result in satisfactory heat transfer rates. This tank wall cooling will always be by H₂O on the outside of the wall. Inside it will be H₂O if a reflector is adopted, and in use. Otherwise, the inside cooling will be by D₂O.

The main moderator D₂O flow enters the tank through an annular inlet at the bottom of the tank, around the central tube. Flow is upwards through the tank, around the Be multiplier, through the annular shielding insert in the upper tank extension, and out at the top of the extension. This provides a good cooling pattern, follows the normal convection direction, and will sweep out gas bubbles effectively. The conical top of the tank will also serve to direct gas bubbles towards the outlet.

4.5 Gas Production

A detailed calculation of gas production by radiolysis of the moderator depends upon a knowledge of the flux intensity throughout the moderator and of the energy spectrum at each point. In addition, the

FIG. VII. 39 Moderator circuit.

relationship used to calculate the net D_2 yield should be checked experimentally. Without a detailed calculation an approximate estimate of gas production may be made to provide data on the severity of the problem as follows:

The energy deposition rate in the D_2O is taken as 13 MW. The neutrons may be divided into the evaporation group (up to about 20 MeV) and the cascade group which extends up to the proton beam energy. The evaporation neutrons have 5.8 MW of the power and are practically all absorbed in the first 15 cm of moderator. The total γ -ray power from the target (440 kW) may be neglected. The fast neutrons deposit energy in the moderator at an average rate of 1.4 Wg^{-1} . The maximum is estimated to be 100 Wg^{-1} .

The maximum yield of hydrogen from the radiolysis of water has been obtained by using fission fragments, and is 1.8 molecules per 100 eV. If all the 13 MeV of fast neutrons absorbed by the D_2O formed hydrogen with this yield, and oxygen with half this yield, the total volume of gas would be 81 litres or $2.9 \text{ ft}^3 \text{ s}^{-1}$. The expected gas yields are much less.

The absorption of ionizing radiation in water results in the formation of hydrogen and hydroxyl radicals, and molecules of hydrogen and hydrogen peroxide. The yields of each of these depend upon the LET (linear energy transfer - the rate of energy loss along the particle track of the radiation). It appears that if the molecular yields exceed the radical yields then there is continuous decomposition of the water. If the radical yields are in excess then only small steady state concentrations of hydrogen and hydrogen peroxide are obtained, unless the products are continuously removed as in a boiling system. In a system with radiations of different LET the net yield of hydrogen can be taken as the total molecular hydrogen yield less the average of the two (hydrogen and hydroxyl) radical yields.

It is necessary to calculate the LET in deuterium and in oxygen for all the neutrons. Rough approximations may be made as follows:

For the evaporation neutrons, all the 5.8 MW of energy is absorbed. Most of this is by elastic scattering, ~13% by oxygen and the remainder by deuterium. All the oxygen ions at these and higher energies have LETs $> 20 \text{ eV per } \text{\AA}$ and can be considered to give net hydrogen yields of 1.6 molecules per 100 eV. The deuterium ions have LETs in the range $0.9 - 6 \text{ eV per } \text{\AA}$ and the net hydrogen yields range from -0.3 to $+0.9$. Assuming that the deuterium ions give equal amounts of molecular and radical products, then the decomposition will result only from the oxygen ions - a total of 0.75 MW with a yield of 1.6 molecules per 100 eV.

Above 20 MeV inelastic scattering becomes much more important and both the elastic and inelastic cross sections of oxygen increase relative to those of deuterium. It is assumed that:

- a) The remaining 7.2 MW ($= 13 - 5.8$) is absorbed from neutrons in the range 20 - 216 MeV
- b) The energy from these neutrons is absorbed by the D_2O as deuterium or oxygen ions
- c) The relative energy of each of these is proportional to the total cross sections of the deuterium and oxygen and to the energy transfer term $2A/(A+1)^2$.

On these bases, the ratio of oxygen ion energy to deuterium ion energy is 44 : 56. From oxygen ions then, we have 3.2 MW with a yield of 1.6. The LETs of the resulting deuterium ions range from 0.1 - 0.9 eV per Å and the net hydrogen yields from -0.3 to -1.2 molecules per 100 eV. Taking an average of -0.7, yields 4.0 MW of these deuterium ions.

Now, summing the products of the energies and net hydrogen yields gives:

$$1.6(0.75 + 3.2) - 0.7(4.0) = 3.52$$

It was found above, that an absorption of 13 MW with a yield of 1.8 gave a total of 81 litres s^{-1} . Thus the expected yield is $(3.52 \times 81)/(13 \times 1.8) = 12$ litres s^{-1} and this value is adopted for the reference design.

The gas production is thus $12 \times 60/28.35 = 25.5$ cfm, at 1 atmosphere pressure, compared with the 3000 IGPM = 480 cfm of D_2O . This would give an exit flow, from the moderator, of about 5.3% gas, by volume. The gas concentration in some locations, such as immediately beside the moderator central tube, would be higher than this. At such points of maximum gas production, the moderator density, and effectiveness, could be significantly reduced. The moderator will therefore be operated at 4 atmospheres (absolute) pressure to reduce the gas volume by a factor of 4. In addition, the D_2O flow is directed to carry gas directly from the point of production to the moderator exit. The gas production should therefore not be a problem in the moderator tank.

Continuous gas separation and recombination will be required in the D_2O circuit. To prevent gas buildup, the recombination unit will have to handle the gas at the same rate as it is produced. This involves a larger recombiner than those now in use on reactors, and the unit must be capable of handling abrupt changes in gas flow as the proton beam current is increased or cut off. Such a unit is feasible, but will require some development.

5. Experimental and Irradiation Facilities

5.1 Experimental Beams

A plan section through the moderator tank, showing the experimental beam tube arrangement, is shown in Figure VII.1. All tubes are of 10 cm ID, except tube 6-6A which is 20 cm diameter. With two exceptions, the tubes are all located in a horizontal plane at the elevation of the moderator mid-height, i. e. at the elevation of maximum thermal neutron flux. The through tube is located 20 cm above this plane, the radial tube 20 cm below. The elevation of the moderator tank is such that this places the experimental beams 8 feet above the experimental floor.

All tubes in the moderator will be of Zircaloy to minimize flux depression. As a further step in avoiding depression of the flux, it is desirable that any tube not in use be flooded with D_2O . The vertical tubes can be continuous, that is, a tube can extend up through the top of the tank and through the shielding. It is much more difficult to assemble the shielding so that the horizontal tubes can be continuous through the shielding, and it must be assumed that these tubes will terminate at the tank wall. Flooding with D_2O will therefore be accomplished by putting a special insert into the tube. This will consist of a solid shielding plug with a thin-walled, end-capped, Zircaloy tube on the end. The thin Zircaloy tube will fill that part of the beam tube which lies in the moderator tank and will be flooded with D_2O . This will allow either the vertical leg, or the horizontal leg, or both legs, of any tube to be flooded as desired.

Inserts consisting of a tube capped at both ends can be employed to allow a beam tube to be evacuated. Such an evacuated tube will have to provide an annular gap between the evacuated insert and the existing beam tube, so that the gap can be used for a cooling gas flow.

Rolled-in bellows, installed after assembly between the moderator tank and the inner shield and between the inner and outer shield, may allow flooding and evacuation without inserts. Where possible, these will be used. However, they are not considered to be desirable as the only means of flooding. The inserts form a reliable, and easily maintained, flooding device and are adopted as the basic design.

In addition to the beam tubes, one additional 10 cm vertical tube is provided, terminating 12 cm from the Be, for experimental use. This will normally contain an insert, in the form of a pneumatic capsule facility, for use in irradiation experiments. This is separate from the irradiation facilities provided for commercial isotope production. It will allow irradiation in a flux of 10^{16} thermal neutrons $cm^{-2} s^{-1}$. All available space inside this tube not occupied by the 1/2 inch pipe for the capsule, will be filled with D_2O to minimize flux depression.

SECTION D-D

LEGEND

- "L" TUBES FOR IRRADIATION
AT 10^{15} N/CM²/SEC.
- "I" TUBES FOR IRRADIATION
IN AN INTERMEDIATE FLUX.
- "R" RABBIT

LAYOUT OF HYDRAULIC TUBES

FIG. VII. 40 Layout of hydraulic tubes.

The experimental beams are carried from the main shield to the beam stops through steel pipes of 2 ft. and 3 ft. diameter. This arrangement ensures against the possibility of persons or objects moving inadvertently through the beam and, in addition, meets the requirement that it be possible to have experimental neutron beams pass through a controlled environment, such as a helium atmosphere or a vacuum. To install an experiment in any beam, a section of the protective beam ducting will be removed and the experiment set up in the space thus provided. If a controlled atmosphere is required between the experiment and a target, or from the target downstream to the beam stop, the experiment will have to be provided with suitable attachments or blanking plates so that the opened ends of the beam tubes can be sealed off or joined to the experimental apparatus. Inert gas and vacuum systems are provided in order to allow this controlled atmosphere to be attained.

5.2 Cobalt Production Facility

At the wall of the moderator tank a relatively high thermal neutron flux is available for production of ^{60}Co .

The simplest method of introducing cobalt for irradiation would be to provide for a series of rods located outside a radius of 120 cm, and to move the tank wall out to a larger radius. The unattractive features of such an arrangement are that the tank diameter is increased and the shielding around the tank is therefore pushed to a larger radius, thus increasing the overall outside diameter of the shielding. In addition, the neutron flux on one side of any given cobalt irradiation rod would be somewhat higher than that on the other because of the shadowing effect of the rod itself. Also, the rods cannot be spaced so closely together that they touch and, as a result, a significant portion of the available neutrons must escape between the rods and into the shielding.

The most attractive solution is therefore a thin layer of cobalt spread uniformly all over the inside of the moderator tank wall, and that arrangement has been adopted here. In practice, the circumference of the moderator tank has been divided up into six segments, one segment in between each pair of experimental beam tubes. In each segment, liners are then provided inside the wall of the moderator tank to hold a layer of cobalt between the liner and the outer wall of the tank. Also, the cobalt has been split into two layers, an inner layer $3/8$ inch thick and an outer layer approximately $3/4$ inch thick. The inner layer will provide high specific activity cobalt and the outer layer, which will see a neutron flux about one order of magnitude lower than the inner layer, will provide Co of a lower specific activity.

Pipes will be provided to the top and bottom of these layers, which will be sealed off from the heavy water in the moderator. Cobalt in the form of small cylindrical pellets will be transported through

the pipes and into or out of these layers by a flow of heavy water. The D_2O circuit for the cobalt is shown in Figure VII. 41. It will be separate from that of the moderator in order to allow cooling to be continued when circulation of the moderator itself is stopped. Since D_2O is used to cool the cobalt a moderate leakage between the cobalt cooling circuit and the moderator itself will be tolerable. Pellets in the form of 1/8 inch right circular cylinders, and pellets in the form of 1/4 inch right circular cylinders, are currently under consideration for use in these layers. Fluidized bed tests are under way to determine what problems will arise in fluidizing the pellets for transfer, and the possibilities of jamming of the pellets by bridging across the relatively narrow gap. The pellets will be nickel plated to prevent contamination of the D_2O by ^{60}Co .

An arrangement with the two layers of cobalt immediately inside the tank outer wall is the simplest and most inexpensive one. However, an increase in cobalt production can be effected by the introduction of a light water reflector, and a tank wall geometry incorporating such a reflector is shown in detail in Fig. VII. 38. Here the 1 1/2 inch stainless wall of the tank has been moved out radially about 3 inches in order to allow the inclusion of a 2 inch light water reflector. A space is provided between the inner containing wall of the H_2O and the outer containing wall of the D_2O in order to provide a dry space for leak detection.

This arrangement is not immediately attractive in that it provides an impossible place to repair D_2O or H_2O leaks. Also, even though they might be purged with a dry inert gas at all times, experience shows that such spaces encourage corrosion and the development of eventual leaks. Such an arrangement - with both H_2O and D_2O inside the main tank wall - would therefore normally be rejected, particularly since cobalt production is not the main purpose of the target.

In this case, however, suitable construction and provision for a future piping change may make the H_2O reflector acceptable. The plan would be to install the H_2O reflector, to use it until an unacceptable leak developed, and then to drain the H_2O and fill both the H_2O annulus and the leak detection space with D_2O . The advantages of the reflector would then be available for a significant length of time, and a leak would mean only that the reflector was lost, and not that repair was necessary. This assumes that the design is such as to maintain a wholly reliable outer tank wall and that piping suitable for D_2O is installed to the leak detection space during manufacture. The design is worthwhile if the benefits obtained from the reflector exceed the cost of the extra construction and later cost of D_2O . This choice is left for later consideration.

5.3 Isotope Production Facilities

The flux available from the target is attractive from the viewpoint of isotope production, and a number of facilities are provided for this purpose.

FIG. VII. 41 Cobalt irradiation circuit.

Immediately inside the Co annulus, a row of hydraulic capsule tubes, of 4 cm 8D, are arranged, as shown in Fig. VII. 40. These run vertically down the wall, and about 45 such tubes can be accommodated. They will be exposed to about the same flux as the inner layer of Co. When these tubes are all in use, they will significantly reduce the flux available at the Co, so their use will be an operational choice to be made on economic grounds. It is expected that a number of capsules will be loaded into each tube, to cover most of the height of the tank wall. When not in use, the tubes will be flooded with D_2O and will have a negligible effect on flux at the Co. Six hydraulic capsule tubes can be accommodated at the bottom of the moderator tank.

Five vertical tubes, or thimbles, are provided for irradiation of larger samples. These are of 15 cm diameter and are located as shown in Fig. VII. 40. Two of these tubes are located in a region of 5×10^{15} neutrons/cm² s flux and three at a larger radius and lower flux. If all these tubes are loaded simultaneously with large quantities of high cross-section material, the flux available at the experimental beam tubes will be reduced. Small quantities of material, or low cross-section material, will have less effect on flux and will be acceptable for irradiation at almost any time. When the maximum obtainable flux is needed for experimental purposes, these tubes may be flooded with D_2O to minimize flux depression. Any tube not in use will normally be flooded.

Two pneumatic capsule facilities, or 'rabbits', are provided in the 10^{16} n cm⁻² s⁻¹ flux region, also shown in Fig. VII. 40. One of these is for use as an experimental facility, the other for isotope production. Both are 10 cm diameter and both can be flooded when not in use. The pneumatic capsule piping, cooling etc., will be built into an insert which fits the 10 cm tube and which may be withdrawn for maintenance or replacement. The piping to carry the capsule will be 1/2 in.

6. Shielding

6.1 General

The shielding for the thermal neutron facility is designed to reduce all radiation incident on the experimental working floor to a level that will permit continuous occupation by personnel. It is not the primary aim to reduce radiation to a very low background level for experimental purposes. Indications from the Berkeley Bevatron⁴⁹ are that the spectrum of neutrons leaving the shield is approximately $1/E_n$ up to 20 MeV and is similar to a cosmic ray spectrum above 20 MeV. More than 50% of the total dose outside a thick shield is below 2 MeV, and less than 10% of the dose is from γ -rays and charged particles. A cross-section of the shielding arrangement is shown in Fig. VII.42.

The proton beam approaches the target building horizontally and just above ground level. It is directed to the top of the shield by bending it upwards 20° by a magnet outside the target building and is turned down into the target tube by a 110° magnet above the shielding. Shielding is required for the beam itself, around the magnets, and beam dumps are provided in case of magnet failures. The shielding around the target incorporates horizontal beam holes to provide experimental, collimated, beams of thermal neutrons. It is essential that the length of these beam holes be kept to a minimum to limit inverse-square-law attenuation and, in this plane, the shielding criterion is therefore that the shielding be of minimum thickness. In other directions the shielding may be optimized on a minimum cost criterion.

6.2 Source Strength

For each 1000 MeV protons hitting the target, 0.8 neutrons with energy greater than 100 MeV emerge. The angular distribution of the cascade neutrons is peaked in the forward direction and the intensity at 90° to the proton direction is 0.75 of the average over all angles. Thus, the current of high energy neutrons ($E_n \geq 100$ MeV) at the outside mid-plane of the moderator tank (i. e. at 120 cm radius) will be $\sim 3 \times 10^{11}$ $\text{n cm}^{-2} \text{s}^{-1}$, after reduction by the inverse-square-law and an attenuation of a factor of 4 by the moderator.

6.3 Permissible Doses

In the reference design the tolerance level at the outside edge of the thermal facility shield has been set at $2 \text{ n cm}^{-2} \text{s}^{-1}$, of high energy neutrons. The area on top of the main shield is not an occupation area and the flux in this area is limited to $10 \text{ n cm}^{-2} \text{s}^{-1}$.

⁴⁹ R.H. Thomas, The Radiation Field Observed Around High-Energy Nuclear Accelerators, report UCRL-16267 (1965).

FIG. VII. 42 Target shield elevation.

6.4 Shield Material

The attenuation thicknesses of a number of possible shield materials have been determined. (See chapter VIII). Steel loaded concrete with a density of approximately 350 lbs ft^{-3} is a mixture of about 15% ordinary concrete and 85% steel punchings. It is expected to have a 1/10 attenuation thickness of 21 in. The mixtures and costs of various concretes are⁵⁰:

<u>Type of Concrete</u>	<u>Cost</u>
Ordinary	2 cents/ lb.
Ilmenite	4 1/2 cents/lb (for small shields)
Ilmenite	4 cents/ lb (for large shields)
Ferrophosphorus	10 cents/ lb
Steel loaded	20 cents/ lb

6.5 Main Shield

At the centre is the moderator tank, surrounding the target, and the 1.75 inch thick wall of this stainless steel tank necessarily acts as the first layer of shielding. Only about 8% of the thermal neutrons incident on the inner face of this tank penetrate the tank wall. The cascade neutron flux, however, is attenuated very little by the tank wall and most of the heat generated by these neutrons appears in the next one and a half feet of shielding. Since the experimental beam holes dictate that the shield in the beam hole plane shall be as thin as reasonably possible, the choice for this area is solid iron. The thickness of the iron is calculated as follows:

$$\begin{aligned} \text{Let } \phi_{120} &= \text{high energy neutron flux at 120 cm. rad.} \\ &= 3 \times 10^{11} \end{aligned}$$

$$\begin{aligned} \text{Let } \phi_e &= \text{emerging flux} \\ &= 2 \text{ n cm}^{-2} \text{ s}^{-1} \end{aligned}$$

$$\text{and } R = \text{radius of shield}$$

$$\text{Then } \phi = \phi_{120} \frac{120^2}{R^2} \times 10^{-((R-120)/(45))}$$

$$\text{and } R \approx 560 \text{ cm.} = 18.4 \text{ ft.}$$

⁵⁰ Q.A. Walker, A Shield for a Thermal Neutron Facility, report FSD/ING-43 (1966).

The iron shield is therefore $560 - 120 = 440$ cm thick. An equivalent shield of steel loaded concrete would be 540 cm thick. However, a direct comparison cannot be made without considering the water content of the shield.

Water is necessary to cool the shield and thermalize neutrons. Estimates of the cooling requirements are dealt with below. Fig. VII. 43 shows the optimum fraction of hydrogen for minimum thickness shields, for the neutron spectrum produced by bombarding Be with 350-660 MeV protons⁵¹. The results are strictly valid only for shields of approximately the same thickness as were used in the experimental measurements. For thicker shields the optimum hydrogen fraction will shift to lower values, and for the thermal neutron facility shield a value of 0.15% was used. This value is equivalent to 1.3% water and this water content will be achieved by encasing the iron block shield in a large water tank. The iron blocks shown in Fig. VII. 44 include spacers to give a 1/2 inch gap per 5.25 inch block of iron. The result is an additional 1.6 ft.

In the detailed design, it may prove more economical, or convenient, to replace some of the water with a metal hydride, or polyethylene, in areas where the water necessary to thermalize neutrons exceeds the water necessary for cooling. Normally 1 - 2% (by weight) of water is trapped in concrete after curing and this should be adequate for neutron thermalization. Sealers may be necessary to prevent escape of this water through exposed surfaces.

The top of the shielding forms an area, the 'Top Deck', which will not be occupied when the generator is operating. Here the flux from the shielding has been chosen to be $10 \text{ n cm}^{-2} \text{ s}^{-1}$, and a calculation similar to that made for the plane of the experimental beams shows that 13.5 ft of iron shield will be required, plus water or other hydrogenous material. The required shielding in this direction is reduced a little by the forward peaking of the flux in the target.

As noted above, the only region in which the shielding is exposed to a high rate of heating is a relatively small volume of the shield adjacent to the moderator. In this region, the shielding is designed in three distinctly different arrangements, each to accommodate the local heating.

The first layer of shielding is the moderator tank wall. This wall is adequately cooled on the inside by the D_2O flow through the passages provided for cobalt pellets. The tank wall itself is stainless steel, 1 1/2 inches thick, and cooling of the outside of the wall is provided

⁵¹ B.S. Sychev, et al., Passage of High Energy Neutrons in Iron-aqueous Mixtures, report JINR-P-2359 (1965).

FIG. VII. 43 Relation between iron-aqueous shielding and hydrogen concentration (1-calculated with respect to permissible flux; 2-calculated with respect to permissible dose).

FIG. VII. 44 Cast iron shielding block.

by a water jacket made of 1/4 inch stainless steel. The total thickness of steel in the wall is therefore 1 3/4 inches.

The next layer of shielding surrounds the moderator tank and consists of three concentric steel cylinders. These cylinders are made of 3 inch, 5 inch and 6 inch plate with passages for cooling water between them. A similar arrangement of plates is used above and below the moderator tank to form a complete shell around the tank. This shield absorbs the majority of the heat produced by cascade neutrons.

Outside of this is a large annular tank containing cast iron blocks immersed in water. The tank has an outside diameter of 39 ft, an inside diameter of 11 ft and a depth of 12 ft. Within the tank are 29 annular walls of interlocking cast iron blocks of the type shown in Fig. VII. 44. Each block weighs approximately 80 lbs and has two ribs or separators which ensure a 1/2 inch water annulus between adjacent walls. Heat production in the blocks of this shield is comparatively low and therefore water circulation will not be critical, especially towards the outside of the shield. However, some circulation will be required, and positive circulation will be provided for the inner wall and the inner layers of block. Towards the outer diameter, convection will provide adequate cooling.

Since the iron block method of shielding is relatively expensive, its use has been limited to areas where the shield thickness is the most important criterion. It has been used in a 10 ft belt around the target where close approach to the target is required for experiments. Above and below the iron shield are layers of steel loaded concrete, and above and below these are layers of less dense concrete. Ilmenite and ordinary concrete have been used wherever possible because they are cheaper than other shield materials.

The portion of the shield immediately below the target tank has not been studied in detail, but the shield shown in Fig. VII. 42 is estimated to be sufficient to prevent activation of equipment in the tunnel where pipe couplings are located, although work in this area may be done remotely. A total of 3 1/2 ft of water-cooled steel plate has been included as a thermal shield on which the target tank rests. Below this is 12 ft of water-cooled steel-loaded concrete, used here because its good thermal conductivity will help to carry off the extra heat produced by the forward peak in the cascade neutron distribution. The shielding below the moderator is to be removable, to a diameter slightly larger than the tank, to allow removal of the tank.

Above the moderator tank is a series of removable steel shields with water cooling passages. They are pierced by a central hole for the beam tube and a number of vertical (and near vertical) holes

for irradiation and experimental facilities. Two service spaces are provided. The upper one, for connections to experimental equipment, is adequately shielded from the target to prevent activation. The shielding above this space is just adequate to protect personnel from activity that may accumulate in, say, the coolant system of an irradiation facility. The lower service space is just large enough to accommodate the vaned head and its connections. Equipment here will suffer activation. The head will, however, be active from contamination by spallation products and some shielding between it and the upper service space is therefore essential.

All other areas of shielding shown in Fig. VII. 42 are ilmenite concrete with an overall diameter of 42 ft.

To the left of the main shield (as shown in Fig. VII. 42 is a pipe chase carrying the lead-bismuth circuit. This pipe chase will pass outside the main shield and will be housed in a demountable concrete shield. An airtight duct will surround the Pb-Bi piping, inside the concrete shield, and will connect with the enclosed Pb-Bi area in the basement. Any active material released through a fault in the Pb-Bi piping will therefore be prevented from escaping through the removable pipe shielding.

6.6 Beam Tubes and Gates

Beam tubes and plug gates will be built into the shield tank before the erection of the block walls. Also, pockets or recesses in the outer face of the tank are provided at the locations where the experimental beams emerge. These will be 6 ft high, 6 ft wide and 4 ft deep and will be filled with removable steel blocks. By removing the blocks, it will be possible to burrow into the shielding 4 ft. This will allow an experiment to be placed closer to the source - at the expense of exposure to a higher flux.

The beam tubes, gates and pockets are described here as parts of a single, massive steel tank. More detailed structural design may show that it is preferable to construct this tank in six pie-shaped segments, one segment between each pair of experimental beams. In this case the beam tube and gate may form a separate assembly between two tank segments. In either case, the tank must be fitted around, or include, structural support for the concrete shielding above.

The experimental beam holes passing horizontally through the iron-block shield will be stepped in diameter at least once. The nominal height of the experimental beam tubes above the floor is 8 ft but one beam, the radial one, will be 8 in below this level and the straight-through tangential beam will be 8 in above this level.

The beams are to be closed by a solid plug formed by the surface of a movable wedge of shielding driven into place hydraulically (see Fig. VII. 42). The reason for adopting this type of gate is that no voids are left in the shield when the gate is shut. It is desirable that the plug be kept as small as possible, and it is anticipated that an 8 ft plug will reduce fields sufficiently to permit access to experimental equipment.

The length of the plug was calculated by considering that one of the tubes looks directly at the target i.e. a source of 2×10^{17} high energy neutrons per second. Also, in order to keep the plug as short as possible, it is suggested that a tungsten alloy such as Heavymet or Mallory 1000 be used. This is a 90% W 7% Ni alloy covered by A.S.T.M. 346-59T and having a density of 16.5 g cm^{-3} . The 1/10 attenuation thickness is estimated to be $\sim 14.1 \text{ in.}$

This gives a plug approximately 8 ft long, to reduce the high energy neutrons leaving the beam hole to about $1500 \text{ n cm}^{-2} \text{ s}^{-1}$. However, as in the case of the main shield, some hydrogen will be needed and could be added as paraffin wax to the back of the plug. The cooling requirements for the nose of the plug have not been calculated, but some form of water cooling will be necessary.

The neutron beams are carried across the experimental floor in 2 ft and 3 ft diameter steel pipes, from the target shielding to their individual beam stops. Volume is not important for the beam stops and they may be made of ilmenite or ordinary concrete.

Shielding will be required around experimental apparatus, and the amount required will depend on the particular experiment. It is intended that shielding requirements be determined for each experiment and that the necessary thickness and geometry be made up by piling movable shielding blocks around the experimental equipment. These blocks may be either steel or concrete, depending upon availability and convenience, and will be handled by the overhead cranes.

6.7 Shield Cooling

Heat is produced in the shield by the prompt γ -rays from the target, by the thermal neutrons and by the high energy neutrons.

The prompt γ -rays can be neglected since absorption by the moderator will reduce the amount of this radiation reaching the tank wall to a negligible value. This heat is therefore removed in the moderator.

The heating by thermal neutrons may be calculated as follows:

The target provides a source of $\sim 10^{19} \text{ n s}^{-1}$ of which 40% leak out through the sides in a sinusoidal distribution. Hence

$$\int_0^h S_o \sin \pi \frac{x}{h} = 0.4 \times 10^{19} \text{ n s}^{-1} \text{ and } S_o = 2.62 \times 10^{16} \text{ n s}^{-1} \text{ for a tank of } h = \text{height} = 240 \text{ cm.}$$

Then the neutron peak current, at tank mid-height is

$$f = \frac{S_o}{\pi D} = 3.5 \times 10^{13} \text{ n cm}^{-2} \text{ s}^{-1}$$

for a tank of diameter $D = 240 \text{ cm}$.

Assuming that the capture γ -ray energy per neutron in iron (mostly ^{56}Fe capture) is $\sim 8 \text{ MeV}$, the power flow into an Fe shield will be:

$$f_o = 45 \text{ W cm}^{-2}.$$

Where x is distance into the shield in cm:-

$$f = f_o e^{-vx} \text{ where } v \approx 0.55 \text{ cm}^{-1}.$$

Thus:

X, cm	0	1	2	3	4	4.6	5
f, W cm ⁻²	45	26	15	8.6	4.9	3.6	2.9

The maximum heating rate, in the first cm of Fe at tank mid-height is $56-32 = 19 \text{ W cm}^{-2}$. The total heat generated in the full $1 \frac{3}{4}$ inches (4.6 cm) of tank wall, at mid-height, is $45-3.6 = \sim 41 \text{ W cm}^{-2}$. That is, 91% of the thermal neutron heating occurs in the tank wall. The total heating of the shield by thermal neutrons, is $0.4 \times 10^{19} \times 8 \times 1.6 \times 10^{-6} \times 10^{-7} = 5.1 \times 10^6 \text{ W}$. The heating of the tank walls will be 91% of this, or 4.7 MW.

If the thermal neutrons are attenuated by an order of magnitude by a cobalt blanket then cooling must be applied to the cobalt instead of to the tank wall.

For an average cascade neutron current into the shield of $5 \times 10^{12} \text{ n cm}^{-2} \text{ s}^{-1}$ (see Eq. VII.1), with an average neutron energy of 100 MeV, the power flow is 81 W cm^{-2} . The total power carried into the shield is then 13.7 MW but this is distributed in depth through the shield as shown in Fig. VII.45. This figure is based upon the average values of

FIG. VII 45 Heat production in iron shielding of thermal neutron facility by cascade neutrons.

flux and energy of the cascade neutrons emerging from the Pb-Bi target. The rate of heat production in the horizontal mid-plane of the shield would be lower than 81 W cm^{-2} because of attenuation by the moderator and the anisotropy of the high energy neutrons.

From the above calculations, the maximum heating occurs in the tank walls where, at mid-height, thermal neutron heating amounts to 41 W cm^{-2} and cascade neutron heating is about $2.2 \text{ W cm}^{-3} \times 4.6 \text{ cm} = 10.1 \text{ W cm}^{-2}$ (using the average value of the power density and the wall thickness) for a total of $\sim 51 \text{ W cm}^{-2}$.

The total heat flow into the tank walls is 6.4 MW, or 6100 BTU s^{-1} . For a cooling water temperature rise of 35°F , a cooling flow of 1050 IGPM of D_2O must be provided and a valve of 1100 IGPM is used for the design. To cool the wall alone, a cooling jacket on the outside of the 1 1/2 inch tank wall can be attached so that any leak in the jacket will be into the inter-shielding space, and not into the moderator, and this outer jacket can then be cooled with H_2O . This reduces the cooling flow required, for the inner wall face, to 550 IGPM. However, when the annular passage inside the tank is filled with cobalt, the heat will appear in the cobalt and the full flow of 1100 IGPM of D_2O must be provided to the cobalt. The required flows are therefore 1100 IGPM of D_2O to the inner face and at least 550 IGPM to the outer face of the tank wall.

Considering the 1100 IGPM flow of D_2O at the tank mid-height, where the heating rate is a maximum at 51 W cm^{-2} or $45 \text{ BTU ft}^{-2} \text{ s}^{-1}$. Passing the D_2O through an empty 3/8 inch annulus between an inner liner and the inner face of the wall will result in a D_2O velocity of 4 ft s^{-1} and a temperature difference of 85°F between the D_2O and the wall surface. Since the D_2O enters at 85°F and leaves at 120°F , its temperature at this point will be approximately 100°F and the wall temperature about 185°F , which is satisfactory. On the outer face, however, a flow of 550 IGPM of H_2O through a similar annulus would result in a local maximum wall temperature of about 250°F . This is unacceptably high because of the very low coolant velocity of about 2 ft s^{-1} . The cooling will be improved by putting baffles in the cooling annulus to increase the coolant velocity. A baffle to force the coolant to flow in a spiral path around the tank can be easily installed and will allow any desired velocity. The 550 IGPM flow is therefore satisfactory.

When the inner annulus is filled with cobalt pellets, the velocity there will be greatly increased and the cobalt surface temperature will be lower than the 185°F calculated for the wall. It will therefore be possible to reduce the 1100 IGPM flow of D_2O when cobalt is loaded into the annulus, if there is any advantage in doing so.

The cooling of the shielding immediately outside the moderator tank will be comparatively simple because the heating is less,

by an order of magnitude, than at the tank inner face. In addition, cooling will be with H_2O and therefore much less critical as to flow and coolant inventory. Considering, as a conservative assumption, that all of the 13.7 MW of cascade neutron heating occurs in this shielding, and using a cooling water temperature rise of $40^\circ F$, then the required cooling flow will be 1950 IGPM. It is expected that detailed design will show that it is not convenient to arrange cooling passages so that all of the coolant is equally effective and that this inefficient cooling, in some places, will require an increase in the coolant flow. Where this occurs, the cost of more complex cooling passages can be compared with the cost of increased coolant flow and the most economical solution can be adopted.

6.8 Proton Beam Transport Shielding

An iron shield, 3.5 ft thick, is proposed for the proton beam where it passes through the building to reach the top of the target assembly. This shielding is based on an assumed spill rate of 5 pA m^{-1} for this section of the beam transport system.

It is also assumed that, in the event of a magnet failure, or any failure that can cause the beam to leave its proper path and strike the shielding, the proton beam can be turned off reliably in $50 \mu s$ or less. This being the case, the shielding thickness for the beam is fixed by scattering, rather than by the emergency loss of beam control. As in the case of the main shield, the proton beam shielding is designed to allow a 40 hour week for personnel on the experimental floor.

The 20° magnet outside the target building must be provided with the same shielding as the proton beam. Here space is no problem and a shielding material less expensive than iron can readily be used. A beam stop composed of 9 ft of ordinary concrete would be satisfactory.

The 110° magnet above the target will also require shielding equivalent to that of the proton beam. In addition, this magnet will be exposed to a beam of cascade neutrons emerging from the target in the backward direction and passing upwards through the proton beam inlet. This beam is estimated to be $3 \times 10^{12} \text{ cascade n s}^{-1}$. Assuming that personnel are not allowed closer than 15 ft when the facility is operating, approximately 9 ft of iron are required for the direct beam stop, with side shielding of 6 ft. Also, to avoid damage to the magnet windings, a clear path must be provided through the magnet assembly and the beginning of the beam stop must be about 1 meter from the windings. The required beam stop therefore consists of an egg-shaped iron shield fitted to the cylindrical shield required for the proton beam.

The shielding around the 110° magnet will be made of iron in order to minimize its size and to allow as much access as possible to the vertical tubes into the moderator. The shielding around the proton beam, as it crosses the target building, can be made more economically of ilmenite. This will increase the required shield thickness to 6.6 ft and will result in a total diameter of 14 to 14 1/2 ft for the beam plus shielding. Since the proton beam is located midway between two of the experimental neutron beams, and is elevated well above the floor, this will not interfere with access to the experimental facilities and is acceptable.

6.9 Inert Gas System

Spaces will exist in the shielding assembly between the moderator tank and the inner shield, between the inner and the outer shields, and in the pipe chases for hydraulic capsule facilities. The flux in these spaces, particularly adjacent to the moderator tank, will cause activation and corrosion if the spaces are filled with air. An inert gas system will therefore be provided to keep these spaces flushed free of air and water vapor. A CO_2 system is presently considered to be the most attractive, the gas to be circulated, cooled and filtered. Seals will be required at a number of points in the shielding, such as around a beam tube, to make this a completely-contained gas system.

7. Layout

7.1 General

The layout of the complete target area is shown in Figs. VII.46 to VII.48. Fig. VII.46 is the basement plan, Fig. VII.47 is the main floor plan, and Fig. VII.48 shows an elevation cross-section through the complete target and building.

The components that form the target proper are the liquid metal target, the surrounding moderator, and the shielding. They form a block approximately 42 ft. in diameter, rising 32 ft. above the main floor level. This block is situated in the centre of the square experimental floor which is 180 ft. by 180 ft. The target building is 180 ft. by 230 ft. and the 50 ft. by 180 ft. area, outside the experimental floor, is occupied by offices, a control room and a storage area. The storage area is for equipment not in use, for portable shielding, and for plug storage.

The plug storage consists of vertical tubes in a block sunk in the floor. Plugs from the vertical tubes into the moderator will be raised into a flask and transported to the storage by means of the 50 ton overhead crane. Plugs from horizontal tubes will be similarly dealt with, using a horizontal flask support frame. Some of these plugs will be 20 to 24 ft. long, depending upon function, so that the plug storage block will extend from the experimental floor down through the basement to about the same elevation as the building foundations.

Three truck entrances are provided to the target building, each entrance serving two experimental neutron beams. Every beam is thus accessible by truck without disturbing any other beam. Each entrance allows the truck to be placed beneath the central 50 ton crane, so that equipment may be lifted over adjacent beams and delivered to other parts of the building. Maximum flexibility must be maintained in facilities for handling heavy equipment because much of the experimental floor will be taken up by experimental equipment.

The proton beam leaves the accelerator through a tunnel built above ground level and shielded by a mound of earth or sand. It approaches the target building at right angles to and in the centre of one side and, just before reaching the building, passes through a bending magnet which turns the beam up to an angle of 20° with the horizontal. The elevation of the proton beam therefore increases as it traverses the target building until, just above the target, it enters a 110° bending magnet and is turned vertically downwards into the centre of the target.

Above the target itself a relatively large clearance must be maintained in order to allow for the installation of a fully assembled target tube, from the vaned head at the top to the disconnecting flange at the

FIG. VII. 46 Plan of thermal neutron target building basement.

FIG. VII.47 Plan of thermal neutron target building main floor.

VII. A

FIG. VII. 48 Elevation of thermal neutron target building.

bottom. This fully assembled target tube will be about 35 ft. in length. The areas of the building not immediately above the target itself do not require such a high roof because it will be necessary only to have room to handle experimental equipment. As a result, the target building is built in three bays at right angles to the proton beam. The central bay is 80 ft. wide and provides a clearance of 65 ft. from the operating floor to the under side of the crane hook. The crane provided for this bay will have a capacity of 50 tons. The two lower side bays, each 50 ft. wide, provide a clearance from operating floor to crane hook of 38 ft. The 38 ft. is necessary for the bay through which the proton beam transport system passes in order to allow the crane to clear the shielding for the proton beam. The opposite bay is identical although the height to the crane could be reduced by 5 to 10 ft. if any significant economic advantage were realized by doing so. The bays have been placed at right angles to the proton beam in order that the high bay crane can be utilized to transport either replacement target tubes, or various plugs from the vertical experimental holes and irradiation facilities, to storage or handling facilities on either side of the target. If the bay were aligned with the proton beam a significant amount of the useful area beneath the high crane would be obscured by the shielding for the proton beam.

7.2 Neutron Beams

The experimental beams radiate from the target assembly at 60° intervals, giving 6 directions of beam in all. To minimize interference between the incoming proton beam and these experimental beams, the proton beam has been brought in exactly between two of the experimental beams so that these two beams run back generally in the direction of the accelerator, one on each side of the proton beam, and making an angle of 30° with it. Since the proton beam elevation is quite high as it approaches the target, this allows ample room for even bulky experimental equipment in each of the experimental beam paths. The floor arrangement is illustrated in Fig. VII.47. Here it will be seen that the experimental beams are conducted from the point where they leave the target shielding, across the experimental floor, to beam stops which are located just outside the target building.

7.3 Liquid Metal System

All target systems are contained, where possible, in separated areas in the basement, shown in Fig. VII.46.

The Pb-Bi system is entirely contained within a sealed-off section of the basement. The system includes the Pb-Bi dump tank, pumps, heat exchanger, and the various auxiliary systems and control devices. The only component which is not in this area is the pipe which must carry the Pb-Bi to the top of the target, and the target tube itself which returns the Pb-Bi through the target. The tunnel beneath the target forms a part of

the lead bismuth area. The area is sealed off from the rest of the basement by continuous concrete walls with access only through shield doors which are, in addition, provided with air-tight seals. It is anticipated that the area will be accessible for normal maintenance. The sealing will prevent the spread of any contamination in the event of a failure of any of the piping or the heat exchanger.

To make maintenance easier, the Pb-Bi pumps and the heat exchanger are located in individual enclosures, separated from the main Pb-Bi area by shielding doors. In general each of these components will be connected to the Pb-Bi piping by two flanges, one at the inlet and one at the outlet of the component. It is currently anticipated that reliably-leak-tight couplings can be used for this purpose, and that these couplings can be so designed that their couplings are not soldered together by the liquid metal. Experience by others and experiments conducted by AECL confirm that such couplings are quite practical.

Provided that the Pb-Bi can be thoroughly drained from these components, maintenance will be quite straightforward and a man will be able to handle these parts without any difficulty. However, calculations of the activity of the Pb-Bi after a reasonably prolonged irradiation show that a field of approximately 0.026 R/hr at a distance of 1 meter will be produced by 1 gm of the activated Pb-Bi. The activity of a given component, such as a pump, will therefore depend very largely upon the amount of mixture left in it after the system has been dumped. If the system is relatively clear, then a very thin film, amounting to approximately 1 to 2 thousandths of an inch thick, will be left on all the wetted surfaces of the pump. If it has not been possible to drain the pump completely, or if a significant deposit of solid material has accumulated on some surface, the resulting activity will be very much greater. In this case, remote handling of the pump will be essential.

The pumps will require several service connections, electrical power input to operate the electric motor, inert gas to maintain the liquid level in the pump, electrical power for the resistance heaters wound around the lower part of the pump, controls for the heaters and the liquid level system, and inlets and outlets for a cooling water jacket for the motor and its bearings. All of these services will be provided through an umbilical cord long enough to reach from the pump, through the shielding door of its compartment, to a plug-in station outside in the general area. This umbilical cord will carry all the power and control wiring and flexible hoses for inert gas and the cooling water. It will therefore be possible to disconnect completely all the services from outside the pump compartment, before any attempt is made to work on the pump itself. In addition, the connections between the pump and the Pb-Bi piping at the pump inlet and outlet will be of the Graylock Coupling type in which the clamping band of the coupling is supported by a linkage system attached to the pipe. From this connection, shafts will lead through the shielding walls and rotation of these

shafts will open the clamping bands on the coupling and thus free the pump from the piping, again without any necessity to enter the pump compartment.

Within the pump compartment it is proposed that the pump be permanently attached to an overhead monorail from which it is hung on a small carriage. This carriage will include means for raising and lowering the pump by about an inch to make or break the couplings that connect it with the piping. With the services disconnected and the couplings free, the shielding door to the compartment will then be opened and the carriage actuated to lift the pump clear of the coupling flanges. The pump may then run out of its compartment on its monorail without any need for the staff to be near. If necessary, remote means can be used to drive the carriage to carry the pump from its compartment, along the monorail which crosses the service area, and into the adjacent hot cell for maintenance. Once in the hot cell, normal methods of dismantling and decontamination can be used.

To simplify handling, and to reduce the cost of the hot cell, it is proposed that the pumps be worked on horizontally in the cell. For this purpose an intermediate handling carriage will be provided, capable of accepting the pump in a vertical position, lowering it to the horizontal, and then running it into the cell. It will also carry the pump horizontally out of the cell and stand it up vertically again for replacement on the overhead monorail before it is returned to operation.

The handling of the Pb-Bi heat exchanger will be a simpler problem, in that the heat exchanger requires only preheaters and a certain amount of instrumentation for temperature and pressure drop. The size and weight of the heat exchanger will not be greatly different from the size and weight of the Pb-Bi pumps. It is not proposed that any maintenance shall be carried out on the heat exchanger and if there is any serious trouble it will be replaced by a new one.

Against the chance that a broken pipe or connection might allow Pb-Bi to run out onto the floor, the compartments containing each of the Pb-Bi pumps and the heat exchanger will each be provided with a sunken floor lined with a mild steel tank. This arrangement will serve to contain the spilled Pb-Bi in a reasonably restricted area for emergency disposal. No specific system is proposed for the disposal of Pb-Bi which is spilled into these containers, nor is any special provision made for the replacement of the piping between pumps and exchanger and the target. In the event of such an accident it will be necessary to remove all possible components, such as undamaged pumps or an undamaged exchanger, and to remove damaged items. The Pb-Bi will then be cleaned up by the most convenient means considering the particular difficulty that has occurred. Heaters will not be supplied for melting the Pb-Bi in these drip pans because, should heating be required, a resistance heater can quite easily be hung over the side of such a pan.

7.4 D₂O System

The D₂O system is dealt with in a manner very similar to that of the Pb-Bi system and the circuit is contained in a completely separate area of the basement. Access to this area will be through an active shower room, as for any other possibly active area. The moderator will leave this area only to be supplied to, or to return from, the moderator tank. All pumps, heat exchangers, degasser, recombination unit, flow controls etc. will be contained in this area. As in the case of the Pb-Bi system, the area will be supplied with its own separate air conditioning and ventilation system. In the case of the D₂O area ventilation system however, an additional water-condensation unit will be added for the purpose of recovering heavy water from the air in the event of a serious leak. Unlike the Pb-Bi area, the normal activity in this area is not expected to be so high as to preclude normal maintenance procedures, unless a heavy water leak occurs. In this respect the moderator system will be very similar to that for a reactor.

The shield cooling system will be very similar to that for any reactor and the installation, handling, and maintenance of the components of this system will be similar as well.

The remainder of the basement will be utilized for stores or shops for the maintenance of various target facilities, and for the installation of building services such as heating and ventilating equipment.

7.5 Top Deck

The top of the shielding of the target provides an area which, for simplicity of reference, may be called the Top Deck and which is in many ways similar to the area above a reactor like NRU. A major difference is that the proton beam must be passed through the deck to reach the target itself. The beam itself is of relatively modest dimensions and even the 110° turning magnet does not obscure much of the available space. The shielding required for the proton beam and for the turning magnet, however, occupy a very great deal of space and considerably restrict access to the top of the target as compared to the very ready access which is available on the top of NRU. At the same time, many of the facilities which are available in NRU are desirable in this case. In particular it is desired to have a number of holes which extend down through the shielding and into the moderator tank to allow the installation of pneumatic and hydraulic capsule facilities and more general purpose irradiation facilities. A number of holes permit vertical access to the L- and T-shaped experimental beam tubes. The latter holes reaching the beam tubes will allow the installation of targets for use in conjunction with the horizontal experimental holes. The inner end of the experimental holes will be only 12 cm outside the outer diameter of the Be blanket and this blanket must be removable through the top of the moderator tank. The access which must be provided through the top of the tank therefore, plus

the necessary flanges for connections to this tank extension, are of such a diameter that a vertical line drawn from the inner end of an experimental beam tube must necessarily foul some of this structure above. As a result, it is not possible to provide a perfectly vertical access to the inner end of a beam tube, and therefore these "vertical" access tubes will slant out from the vertical centre line of the moderator tank at an angle between 6 and 10°. Six degrees appears to be the minimum angle and 10° appears to be quite enough to provide an excellent clearance in all cases. The final angle of these tubes will be determined by the detailed design of the flange structure at the top of the moderator tank extension. Other vertical access tubes, such as those for irradiation and pneumatic capsule facilities, will be generally out at a larger radius and can be vertical. All of these vertical holes however, terminate within a relatively small radius of the centre of the incoming proton beam. As a result, they all fall to some extent under the shielding provided for this beam tube. It therefore becomes necessary to provide shielding for the tube such that it can be readily removed for rapid access to the vertical holes. As a result of this arrangement, it will not be possible to have access to the vertical holes while the facility is running because shielding can not be removed under such circumstances.

Ready access is provided by splitting the shielding around the 110° magnet along the arc length of the magnet and by pivoting the shielding, at the end most distant from the centre of the target, on two vertical hinges. The shield therefore opens like a clam shell - each half swinging away from the magnet to clear the top of the moderator tank completely. This shielding includes that required to stop the beam of fast neutrons which comes vertically back up through the evacuated centre of the target tube. An alternative to the pivoted arrangement, for ready opening of this shielding, is to split the shielding in the same way (in a vertical plane containing the proton beam) but to carry each half away from the magnet on a set of rails. The rails would thus run across the Top Deck in the same direction as the overhead crane. Either pivot or rails could satisfactorily remove the shielding in a very brief period of time, certainly less than 5 minutes.

With the shielding removed, the way will be clear for the carriage (which handles all devices inserted into vertical holes) to be run forward to insert or remove plugs or equipment. This carriage will be mounted on a table which can rotate to any angular position required and the carriage itself will then move radially on this rotating table to come above the desired vertical hole. The carriage will carry a flask capable of accepting the equipment inserted in the appropriate hole, and it will be capable of either holding this flask vertically or tilting it to an angle between 6 and 10° as required by the hole which it is servicing.

It is anticipated that it will not often be necessary to use this procedure to insert or remove equipment from the vertical holes. In general these holes will be filled, with shielding plugs in the case of the access holes to the horizontal experimental beam tubes, and with hydraulic

or pneumatic capsule facilities in the case of the irradiation holes. The capsules will be available for use at all times whether the target is running or not, and without any manoeuvring of shielding. Therefore irradiation for experiment or for commercial production may be carried on continuously. As will be seen from Fig. VII.47, a service space is provided below the Top Deck in order to allow connections for instrumentation, cooling water, and the pneumatic and hydraulic capsule piping.

For the removal and replacement of the target core (the target tube itself, the central tube of the moderator tank, and the Be multiplier) it will be necessary to remove the proton beam tube and the magnet. For this purpose, couplings will be provided in the proton beam tube at the ends of the magnet, and the magnet itself will be supported by a three-point frame or suspension system. The three support points of the magnet frame will be tapered locating pins in the Top Deck to give lateral and transverse location. The frame will be supported vertically by contact with shimmed pads. This arrangement will allow the magnet to be removed, put to one side, and replaced, without losing its alignment. Replacement to within approximately .010" of its correct position is expected without difficulty.

With the magnet disconnected and set aside, the target tube will be removed by disconnecting the flanges at the Pb-Bi inlet to the vaned head and at the flange at the target tube exit (accessible just below the shielding in a service tunnel). An additional coupling which must be disconnected is the duct which goes from the vaned head to the vacuum pump. With these connections broken, the target tube will be raised into a flask carried by the same carriage which is used to service the vertical holes through the moderator tank. The flask used in this case will, however, be different. Furthermore, it is anticipated that the target tube will be raised until the vaned head comes into a flask provided specifically for it. At this point the target tube will be supported and the vaned head separated from the remainder of the straight piping section of the target tube. The vaned head will be set aside for use again while the target tube is then lifted into a more slender flask for disposal.

With the target tube removed, the coupling flanges at the top of the central tube of the moderator tank, and at the bottom, may be undone and the central tube removed. With the central tube removed, the Be multiplier and its annular shield may be lifted out. All three of these items may then be replaced. While these three items are now being considered as individual pieces, it is unlikely that there will be an occasion to replace one item and return the other two. Detailed design may therefore indicate that it will be simpler to make this entire core a single unit.

8. Operation

8.1 Liquid Metal System

The Pb-Bi eutectic is loaded into the dump tank and both tank and Pb-Bi are degassed by holding the tank and its contents at 450°C under vacuum, for at least 24 hours. The tank, above the Pb-Bi, may then be filled with inert gas. Nitrogen will be used as the inert gas in this system. The complete liquid metal system will be provided with trace heating capable of raising all components, except the target tube, to 325°C. The system will be raised to 325°C by the trace heating and held under vacuum for 24 hours for degassing. It is then kept under vacuum, but not heated, as its normal condition when not filled with Pb-Bi. The target system is isolated from the accelerator, when the beam is off, by a vacuum valve in the beam tube above the target.

It is not practical to provide trace heating for the target tube since it passes through a region where the flux intensity is such as to damage the wires of resistance or induction heaters. To heat by passing a current through the target tube itself is unattractive because of the large currents involved. In addition, both methods of heating would complicate the mechanical design of the tube. Fortunately, such heating is not needed. The relative heat capacities of the tube and the Pb-Bi required to fill it are such that, if the tube at 60°F (15 °C) is filled with Pb-Bi at 400°F (205°C), the equilibrium temperature for tube and Pb-Bi will be 375°F (191°C). The tube will therefore be heated by filling it with hot Pb-Bi.

The system is filled by heating the dump tank (and Pb-Bi) and the system to a temperature safely above the Pb-Bi melting point of 125°C. A temperature of 200°C is expected to be satisfactory, but any temperature up to 325°C can be used if there is doubt about the possible existence of a cold spot. The vacuum system is turned on to ensure an established vacuum of 10^{-5} torr. With the system hot and evacuated, the dump valve is opened and the Pb-Bi raised into the system by pressurizing the dump tank with inert gas (see Fig. VII.21). Since the level to which the Pb-Bi must be raised is about 55 ft above the dump tank, a final inert gas pressure of 250 psi will be required.

As the Pb-Bi is raised into the system, it will fill the lower piping and the pumps first. The level will rise in the pumps until it reaches a predetermined level in the pump body (and in the level control tank) and a level control system will then hold the liquid metal at this level by admitting inert gas to the space in the pump above the liquid metal. With the system filled, the inert gas pressure will have risen to about 45 ft. of Pb-Bi, or 200 psi. Since the target level depends upon filling the system with the correct volume of liquid metal (subject to final adjustment by relatively small changes in the level in the level control tank) the system

will be filled to a predetermined level as sensed by a Filling Level Sensor located in the pipe from the heat exchanger to the vaned head. This Filling Level Sensor will provide a signal to close the dump valve, isolating the system from the dump tank, and will then play no further part in the control of loop operation. At this point both the vertical supply pipe and the target tube will be filled with liquid metal to the level of the vaned head, leaving a void in the horizontal supply pipe to the vaned head. The inert gas pressure is vented from the dump tank to allow the liquid metal to fall back down the pipe and leave the lower side of the dump valve in a vacuum and free of liquid metal. This is to minimize corrosion of the valve bellows, which is on this side of the valve.

The liquid metal pumps are then started. The mass of liquid metal in the system is relatively great and, to avoid temporary cavitation at pump inlet, and large pressure fluctuations around the circuit, the pumps may have to be started slowly, or one at a time. When the pumps are running, the void in the system will move to the upper target tube, below the vaned head. The trace heating may be turned off since the pump H.P. is adequate to maintain the temperature of an insulated system. The proton beam may be turned on after opening the vacuum valve in the beam tube above the target.

The intermediate coolant will be preheated to its minimum operating temperature at the same time that the system piping is preheated. The coolant pump will be started at the same time as the Pb-Bi pumps. The coolant temperature will be controlled by a bypass which controls the flow of intermediate coolant through the river water exchanger so as to maintain the design coolant temperature at the exit from the Pb-Bi heat exchanger. This will automatically take care of changes in heat load due to changes in proton beam power. Full river water cooling flow may be used at all times when the intermediate coolant system is on, or, if it proves worth doing so, river water flow may be reduced proportionately when the bypass is open.

When the beam is shut off for a short period of time no action need be taken to adjust the liquid metal system. It will operate satisfactorily as described above for the case where the system is running but the beam is not on. The same is true of operation with the beam at reduced power.

For shut-down over a long period, the target system will be dumped. A dump makes it necessary to degass the system, as noted below, so that dumping will not be used for short shut-downs. To dump the system, the vacuum valve is closed in the proton beam tube immediately above the target so as to isolate the beam transport system from the target. The vacuum system is left running. The control system of the intermediate coolant system will automatically use bypass circuits (and trace heating if necessary) to maintain its temperature. The dump valve is opened and the Pb-Bi returns to the dump tank by gravity. To ensure that all lines and

tank are clear, the dump tank and the line from it to the system are maintained at 200°C at all times when the system is filled. As the liquid metal level in the system falls below the operating level, the level controls on the pumps will reduce the inert gas pressure in the pump body to keep a constant level in the pumps. However, as the gas pressure approaches atmospheric it will no longer be practical to vent the gas. Therefore the control system must have a reference pressure, say 15 psia, as a lower operating limit at which it closes the valves on both inlet and vent lines. The gas remaining in the pump bodies will then be released into the empty liquid metal piping, as the liquid level continues to fall. Since the gas is inert, no contamination or oxidation problem will result, but the vacuum will be lost until the vacuum pumps can remove this gas. The dump valve will be left open, and the vacuum system on, until a vacuum is re-established. The vacuum pumps will then automatically shut-off, if the system is still set at dump. The dump valve remains open, and the intermediate cooling system is shut-down as the dump is completed.

An emergency dump will be initiated by:

- a) Total power failure or target power failure.
- b) Loss of target level control. This could be from control failure, dump valve failure, or a serious leak in the system.
- c) Any temperature or pressure excursion beyond preset limits.
- d) Loss of Pb-Bi circulation or intermediate coolant circulation or loss of river water flow.

For this operation, emergency power will be needed to signal for shut-off of the proton beam, to operate pump level controls, to operate the intermediate coolant bypass, and to close the vacuum valve and open the dump valve. Vacuum and dump valves will be operated by hydraulic accumulators.

In the event of the total failure of the Pb-Bi circulation, say by loss of pump power, while the proton beam remains on, the liquid metal flow will continue briefly while the liquid in the flowing film and in the vanned head continues to fall. The target level will rise at a rate of about 15 feet per second. To avoid an excessive change in the target elevation, the beam should therefore be shut-off in about one tenth of a second.

In the event of a burst pipe, or similar failure, the Pb-Bi will be discharged into the reservoir formed by the sunken floor provided under pumps, heat exchanger, etc. The beam should be shut-off promptly, but no danger to personnel will result if it is not, since it will simply pass through the empty target tube into a beam dump provided below the target. If the beam is not shut-off promptly, however, it will damage the bend in the Pb-Bi piping immediately below the target.

8.2 Cooling Systems

All cooling systems other than that for the Pb-Bi system and the cobalt system may be turned on, and their satisfactory operation may be verified, before the proton beam is turned on. Here satisfactory operation will mean that the pumps are running, and producing the required flow, and that there are no leaks. The temperatures of the systems will be monitored during the running to provide warning of any malfunction.

8.3 Moderator System

As in the case of the cooling systems, the moderator circuit may be put into operation, and its flow checked, before turning on the proton beam. As noted under the section describing this system, the recombination unit is a component which must automatically adjust itself to operation at any point between zero and full load. It cannot be checked for satisfactory operation until after the proton beam is turned on. It will be necessary to start the beam at low power and to increase power gradually, to verify that the target level control and the recombiner are working properly. Since failure of the recombination unit will result in an accumulation of gas in the moderator, with a resultant decrease in moderator density and an increase in pressure, such a failure cannot be tolerated for very long. The time available for switching off the proton beam however, will be long compared to the time available in the case of most other failures and will be of the order of minutes.

8.4 Cobalt System

The cobalt system, and other irradiation facilities installed in the vertical tubes in the moderator, will require cooling after the proton beam has been shut-off. Hence, the cooling system for this irradiated material will run continuously. To reduce the possibility of a failure of this system, the normal reactor procedure, of using back-up and standby equipment, will be adopted. Emergency power will be required to keep this system operating in the event of a power failure. As a final back-up, provision for cooling with H_2O may be made to handle the case where a series of failures result in complete loss of the D_2O system.

B. RESONANCE NEUTRON FACILITY

1. Introduction

The major components of a resonance-neutron time-of-flight system are a pulsed source, moderator, flight paths, targets, detectors, electronic circuits to record detected events, and a computer for data reduction. In the ING facility the characteristics of the source are largely dictated by those of the pulsed beam of 1-GeV protons. A versatile splitter system would be needed to form macropulses - each containing several micropulses - at repetition rates up to 10 kHz. Given this, ING could produce resonance neutrons in intensities two orders of magnitude greater at energies above 1 keV than its present-day counterpart, the Nevis cyclotron at Columbia University. With eventual incorporation of a storage ring, even greater intensities might be achieved. With a 1-km flight path, good neutron intensities and resolutions roughly equal to the Doppler width are possible to ~ 1 MeV.

A heavy-element target bombarded with micropulses of 1-GeV protons emits a "white" spectrum of neutrons: $\sim 80\%$ are evaporation neutrons at energies up to 15 MeV and $\sim 20\%$ are cascade neutrons at energies up to 1 GeV. The typical spectrum shown in Fig. VII.49 would be transformed by a thin hydrogenous moderator into one that peaks in the region of 1 eV; its high-energy tail would decrease roughly as E^{-n} where the value of n depends on the source and moderator geometry and is usually near unity, e.g. it is 0.78 for the Harwell linac and 0.9 for the Nevis cyclotron⁵⁴. The width of the initial unmoderated pulse of neutrons is essentially equal to that of the machine's proton pulse, but the moderated neutrons will be spread in time. The time distribution for any energy is a function of the length of the initial burst and of the original spectral distribution and moderation times of neutrons reaching that energy from higher energies. The number of neutrons in each energy interval and the degree of smearing of the pulse in time are both open to some control by judicious selection of the materials and geometry of the moderator⁵⁵.

The performance of a time-of-flight system can be judged in terms of the instantaneous peak neutron intensity, the irreducible timing uncertainty, the repetition rate, and the background between pulses.

⁵⁴ W.M. Good and E.R. Rae, Pulsed Accelerator Time-of-Flight Spectrometers, AERE-NP/Gen 21, (1962) and corrigenda, (February, 1963).

⁵⁵ A. Michaudon, Reactor Sci. and Tech. (J. Nuclear Energy A and B) 17, 165 (1963).

FIG. VII. 49 Theoretical neutron spectrum averaged over all angles.
(Ref. to Milton & Fraser AECL-2259 in Sec VII A. 1).

Recent analyses of the performance of existing systems in terms of these various variables have been made by Good and Rae⁵⁴ and by Harvey⁵⁶.

The expression for the flux, F (in $n \text{ cm}^{-2} \text{ s}^{-1}$) in the resolution width ΔE at energy E (in eV) at the end of a flight path of length ℓ is

$$F = \frac{E I(E) \Delta E f n \Delta t}{4\pi \ell^2} = \frac{E I(E) f n \Delta t R^3}{16\pi [(\Delta \ell)^2 + v^2 \sum (\Delta t_i)^2]} \quad \text{VII.7}$$

where $I(E) \Delta E$ is the instantaneous neutron intensity (in n/s) from the moderator in ΔE at E , f is the macropulse repetition rate (in Hz), Δt is the width a single machine micropulse (in s), n is the number of micropulses in a macropulse, v is the neutron velocity (in cm/s), $\Delta \ell$ is the uncertainty in the length of the flight path, and the Δt_i are the various individual contributions to the total timing uncertainty, including detector jitter, finite analyser channel width, moderation time spread and the macropulse width. R is the resolution given explicitly by

$$R = \frac{\Delta E}{E} = \frac{2[\Delta \ell^2 + v^2 \sum (\Delta t_i)^2]^{\frac{1}{2}}}{\ell} \quad \text{VII.8}$$

Eqn. VII.7 shows that the flux at a given resolution increases with $I(E)$ and f , and also with $n \Delta t$ provided the macropulse, $v \Delta t_1$, is small compared to other terms in the denominator. Here the macropulse width is $\Delta t_1 = \Delta t + (n - 1)/f_1$ where f_1 (in Hz) is the micropulse frequency.

2. Characteristics of the System

The neutron intensity $I(E)$ in Eqn. VII.7 is related to the total peak neutron intensity, I , by

$$\int_0^{E_{\max}} I(E) dE = \eta I \quad \text{VII.9}$$

⁵⁶ J.A. Harvey, Proc. Symposium on Pulsed High Intensity Fission Neutron Sources, (Washington) CONF-650217, 124 (1965).

where $E_{\max}$ is the maximum neutron energy of the source and η is the efficiency of the moderator including the solid angle subtended by it at the source. A rough evaluation of the intensity, $I(E)$ can be made from a comparison with the Nevis cyclotron⁵⁷. We shall assume that both devices employ 8-in.-long lead targets and identical moderators. The peak evaporation neutron intensity for Nevis is $I = 5 \times 10^{18}$ n/s. At 1 GeV, 8 in. corresponds to about one interaction length for protons in lead, whence from yields discussed in Section VII. A and assuming a $\sim 12\%$ micropulse duty cycle at the resonance neutron target, it follows that the peak intensity in a micropulse from the ING resonance-neutron source is 3.3×10^{19} n/s. Although it is unlikely that the energy dependence⁵⁸

$$I(E) = C E^{-0.9}$$

is valid throughout the energy range of neutrons from both sources, it is not unreasonable to use it here for a rough evaluation. Assuming also that the efficiencies of the Nevis and ING moderators are equal in spite of the different ranges of neutron energies, it follows from Eqn. VII. 9 that

$$I(E)_{\text{ING}} = 6.0 I(E)_{\text{Nevis}}$$

From flux evaluations given by Good and Rae⁵⁴ for the ultimate performance of the Nevis cyclotron we deduce

$$I(E)_{\text{Nevis}} = 1.47 \times 10^{14} \text{ n s}^{-1} \text{ eV}^{-1} \text{ at } 10 \text{ eV}$$

$$\text{whence } I(E)_{\text{ING}} = 8.8 \times 10^{14} \text{ n s}^{-1} \text{ eV}^{-1} \text{ at } 10 \text{ eV}$$

$$\text{or } I(E) = 7.1 \times 10^{15} E^{-0.9} \text{ n s}^{-1} \text{ eV}^{-1}.$$

The frequency, f , of proton pulses delivered to the ING target is in principle open to adjustment to suit any particular operating conditions. This flexibility is a most valuable and unique feature of the facility. We assume that the beam splitter available in the ING transport will be capable of operating at any required rate up to 10 kHz and will deliver micropulses to the target either singly or in groups. In order to avoid "frame overlap" in any given measurement, $1/f$, must exceed the

⁵⁷ J. Rainwater, et al., Rev. Sci. Instr. 35, 263 (1964).

⁵⁸ J. Rainwater, et al., Rev. Sci. Instr. 31, 481 (1960).

flight time of the slowest neutrons of interest in the measurement. The low-energy cut-off may be controlled by a filter (e.g. boron) or by a rotating shutter⁵⁷. For the purpose of establishing reasonable working values of f it will be assumed that, for measurements centered at velocity v , the lowest velocity of interest is $\frac{1}{4}v$ and that the upper limit of f , set by the speed of a rotating shutter, is 10 kHz, i.e.

$$f = \frac{v}{4\ell} \leq 10 \text{ kHz} \quad \text{VII.10}$$

Of the various timing uncertainties, the one that is caused by the moderation time, Δt_2 , is clearly energy-dependent. Following Harvey⁵⁶ we write

$$\Delta t_2 = \frac{1400}{\sqrt{E \text{ (in eV)}}} \text{ ns}$$

The timing uncertainty, Δt_3 , introduced by the finite detector thickness (detector jitter) depends on the experimental arrangement and the specific detector used, but may be assumed to be roughly comparable to the moderator time, whence

$$\sqrt{(\Delta T)^2} = \frac{2000}{\sqrt{E \text{ (in eV)}}} \text{ ns}$$

$$\text{where } (\Delta T)^2 = (\Delta t_2)^2 + (\Delta t_3)^2$$

The machine pulse width, Δt , is limited by the phase acceptance and operating frequency of the accelerator. At the design frequency 50 MHz, with a duty factor at the target of 12%, $\Delta t = 2.4 \text{ ns}$. The macropulse width is $\Delta t_1 = (20 n - 17.6) \text{ ns}$.

It is advantageous to select n so that

$$\frac{n}{(20 n - 17.6)^2 + (\Delta T)^2}$$

is a maximum i.e. $n = 0.05 \sqrt{(\Delta T)^2 + 310}$

In this derivation and in the evaluation below it is assumed that all other contributions to timing uncertainty in Eqn. VII.7 are small compared to Δt_1 , Δt_2 , and Δt_3 and that path-length uncertainties $\Delta \ell$, not already treated as part of the moderator and detector timing uncertainties, are negligible compared to $v\Delta T$.

The flight path length is fixed by the installation. It is proposed that ING be provided with flight paths up to 1 km. This limit is arbitrary, but longer flight paths would be expensive and difficult to site.

The resolution for a given set of operating conditions and flight path length is given by Eqn. VII.8. A criterion for the maximum resolution required at energy E is provided by the resonance Doppler broadening which, at thermal conditions ($kT \approx 0.025$ eV), has the value

$$\Delta = (E/10A)^{\frac{1}{2}} \quad \text{VII.11}$$

where Δ and E are in eV and A is the mass number of the material under investigation.

3. Evaluation of Performance

3.1 Flux Available at Doppler Width

In this subsection we estimate, as a function of energy, the neutron flux delivered at the end of the flight path in energy interval equal to the Doppler broadening. The size of the macropulse, the repetition rate and the length of the flight path are allowed to vary to achieve the maximum possible flux. The procedure is: first, to determine ℓ from Eqn. VII.8 and VII.11; second, to determine f from Eqn. VII.10; and third, to obtain F from Eqn. VII.7.

The values of various parameters of interest computed for neutron energies from 10 eV to 1 MeV are given in Table VII.B.1. In the third column the resolution is presented (in ns/m). The last column gives the approximate proton beam current deflected to the target by the splitter. All other column headings are defined above. The values of flux and flight path length are plotted as curves $F(\text{MP})$ and $\ell(\text{MP})$ in Fig. VII.50. The curves are terminated at ~ 300 keV where $\ell(\text{MP})$ reaches the 1 km limit. It would be possible to operate at higher energies with the 1 km flight path and reduced resolution.

The calculation is carried out for $A = 100$. The flux and flight path length for other A may be obtained with the aid of the relations

$$F = aA^{-1}$$

$$\ell = bA^{\frac{1}{2}}$$

where a and b are constants of proportionality.

FIG. VII. 50 Performance of resonance neutron time-of-flight facilities.

TABLE VII. B. 1

TIME-OF-FLIGHT PARAMETERS FOR $R = \Delta/E$

E eV	R		n	ℓ m	f Hz	F $\text{cm}^{-2} \text{s}^{-1}$	i μA
	Δ/E	ns/m					
10	10^{-2}	1.13×10^2	32	7.7	1410	1300	59
10^2	3.16×10^{-3}	1.13×10^1	10	24	1460	18	19
10^3	10^{-3}	1.13	3	66	1650	0.30	6.5
10^4	3.16×10^{-4}	1.13×10^{-1}	1	180	1970	6.9×10^{-3}	2.5
10^5	10^{-4}	1.13×10^{-2}	1	590	1850	2.2×10^{-4}	2.3
10^6	3.16×10^{-5}	1.13×10^{-3}	1	2700	1280	3.0×10^{-6}	1.6

Several conclusions may be derived from the data of Table VII. B. 1 and Fig. VII. 50:

- The macropulse compatible with other timing uncertainties at 10 eV contains 32 micropulses and has a total width of 623 ns.
- The sharp 2.4-ns burst provided by a single micropulse can be used to advantage only above about 5 keV.
- Fixing the flight path length at 1 km has the effect of increasing R to $\sim 2.7 \Delta$ at 1 MeV.
- The repetition rate remains well within the adopted upper limit of 10 kHz throughout the energy range to 1 MeV.
- Neutron fluxes greater than $10^{-5} \text{ cm}^{-2} \text{ s}^{-1}$ are obtainable and should make possible high-resolution measurements over most of the log E range to 1 MeV.

3.2 Comparison with other Resonance-Neutron Facilities

A graphical presentation has been used by Good and Rae⁵⁴ to compare the Harwell linac and Nevis time-of-flight system under different operating conditions. Although these curves may soon be made obsolete by

improvements in these systems, they form a convenient framework for comparing ING with other devices. Figure VII.51 shows two such plots of flux F in the resolution width ΔE as a function of E for fixed resolutions $\Delta E/E$ equal to 1.6×10^{-3} and 4×10^{-4} . The upper set of curves are computed for a flight path length of 50 m and the lower set for 200 m at $E \approx 1$ eV. The curves marked HB-250 and HB-1000 represent the Harwell linac⁵⁹ with boosted target and machine pulse lengths of 250 and 1000 ns respectively. The curves marked H-10 represent the same linac with a pulse of 10 ns and maximum repetition rate of 600 Hz. The dashed curve H10 ES is a conservative estimate of the ultimate performance of the linac for higher-energy neutrons. The two curves C-120 and C-20 represent two modes of operation of the Columbia Nevis cyclotron. Bracketed numbers (a, b) on the curves give the repetition rate, a, and the flight path length, b (in meters), at various energies. On each graph a curve for ING has been added; these curves are based on the relative $I(E)$ values and the limiting repetition rates and macropulse widths defined in subsection 2 above. The curves show that ING would exceed the performance of the other devices by about one order of magnitude below 100 eV and by about two orders of magnitude above 1000 eV.

Another rough comparison of the ING micropulse resonance neutron capability with those of existing and planned intense neutron sources at other laboratories has been reported by Bartholomew⁶⁰. Each facility was assigned a figure of merit $M = Nf(\Delta t)^{-2}$, where N is the number of neutrons per burst and f and Δt are the repetition rate and machine pulse width as defined earlier. Table VII.B.2, adapted from a table in that report*, presents the figure of merit for both the ING micropulse facility and the ING storage-ring facility; the latter is discussed further in subsection 6.1 below. In spite of the admitted crudity of the comparison, this table shows that ING would compete well with all other facilities both existing and planned.

⁵⁹ M. J. Poole and E. R. Wiblin, Proc. 2nd Intl. Conf. Peaceful Uses of Atomic Energy, (Geneva) 14, 266 (1958).

⁶⁰ G. A. Bartholomew, Accelerator-Based Very Intense Neutron Sources, Proc. Intl. Conf. Nuclear Physics with Neutrons, (Antwerp, 1965) (North Holland Publishing Co.: 1966).

* A point not brought out in ref. 60 is that extraction of individual micropulses, $\Delta t \approx 2 \times 10^{-11}$ s, is also possible with electron linacs such as those at the Universities of Toronto and Saskatchewan. Although in practice it is difficult to take full advantage of such short bursts in the resonance region, the figure of merit in Table VII.B.2 gives a conservative picture of the potential of such devices.

FIG. VII. 51 Neutron flux in a resolution width ΔE for $\Delta E/E = 1.6 \times 10^{-3}$ (upper graph) and $\Delta E/E = 4 \times 10^{-4}$ (lower graph).

TABLE VII. B. 2

PARAMETERS OF VERY INTENSE NEUTRON SOURCES

Facility	Δt s	f Hz	I n/s	N	M	Ref.
U. of Toronto linac *	1.10^{-8}	1000	7.10^{16}	7.10^8	7.10^{27}	
R. P. I. Linac	9.10^{-9}	720	4.10^{17}	4.10^9	4.10^{28}	b
U. of Sask. linac	8.10^{-9}	1400	4.10^{18}	3.10^9	6.10^{28}	
ORNL Linac *	3.10^{-9}	2.10^3	3.10^{18}	9.10^9	2.10^{30}	a
PERMEX	2.10^{-7}	750	3.10^{19}	6.10^{12}	1.10^{29}	c
PERMEX (44 MeV) *	6.10^{-9}	750	9.10^{19}	5.10^{11}	1.10^{31}	c
Harwell linac (booster)	1.10^{-7}	600	1.10^{18}	1.10^{11}	6.10^{27}	d, e
G. A. linac (fast booster) *	1.10^{-5}	100	5.10^{20}	5.10^{15}	5.10^{27}	f
IBR	4.10^{-5}	83	6.10^{16}	2.10^{12}	1.10^{23}	g
SORA *	5.10^{-5}	100	2.10^{18}	8.10^{13}	3.10^{24}	h
NRU (chopper) *	5.10^{-6}	10^3	2.10^{15}	1.10^{10}	4.10^{23}	
Harwell SC	1.10^{-8}	200	5.10^{18}	5.10^{10}	1.10^{29}	i
Karlsruhe SFC	2.10^{-9}	2.10^4	7.10^{17}	1.10^9	1.10^{31}	j
Hypothet. SFC *	2.10^{-9}	10^5	8.10^{18}	1.10^{10}	5.10^{32}	j
Nevis SC	2.10^{-8}	60	5.10^{18}	1.10^{11}	2.10^{28}	k
LAMPF *	1.10^{-8}	90	2.10^{19}	2.10^{11}	2.10^{29}	l
ING (microst) *	$2.4.10^{-9}$	10^4	3.10^{19}	1.10^{11}	2.10^{32}	
ING (st. ring) *	$1.5.10^{-7}$	500	1.10^{23}	2.10^{16}	4.10^{32}	

* = Projected Capability

- a J. A. Harvey, private communication (1966).
- b E. R. Gaerttner, et al., IRE Trans. Nucl. Sci. NS-9, (5), 23 (1962).
- c H. T. Motz, CONF 650217, p. 77 (1965) and private communication.
- d M. J. Poole and E. R. Wiblin, Proc. 2nd U. N. Intl. Conf. Peaceful Uses Atomic Energy (Geneva) 14, 266 (1958).
- e M. J. Poole, private communication (30 July 1965).
- f J. R. Beyster and J. L. Russell, General Atomic report GA-6168 (1965).
- g G. E. Blokhin, et al., Atomnaya Energiya 10, 437 (1961).
- h V. Raievski, The SORA Reactor, Euratom report EUR 1643.e. 51 (1964).
- i A. Langsford, et al., Intl. Conf. Study of Nuclear Structure with Neutrons (Antwerp, 1965), North Holland, paper No. 158, page 562.
- j S. Cierjacks and K. H. Beckurts, Intl. Conf. Study of Nuclear Structure with Neutrons (Antwerp, 1965), North Holland, paper No. 157, page 562.
- k J. Rainwater, et al., Rev. Sci. Instr. 35, 263, (1964).
- l Proposal for a High Flux Meson Facility at Los Alamos, New Mexico (Los Alamos Scientific Laboratory, Los Alamos, New Mexico: 1964).

4. Effect of Change of Accelerator Frequency

The resonance-neutron time-of-flight facility can, in principle, operate at other machine frequencies with fluxes delivered to the end of the flight path essentially the same as those given for 50 MHz in Table VII.B.1. For example, the principle effect of increasing the frequency to 200 MHz is to multiply the listed values of n for $E < 10^5$ eV by a factor of 4; for neutron energies $\geq 8 \times 10^4$ eV, n remains unity. Beam splitting (section VII.H.2) will be more difficult at 200 than at 50 MHz because of the sharper pulse requirements.

5. General Design of Time-of-Flight Facility

Figure VI.3 shows the layout of the beam tunnel and target room for the time-of-flight facility. Four flight paths of length 50, 120, 250, and 1000 m are shown as the initial requirement for this facility and may be expected to satisfy the demand at the beginning of operations. The target-room design and site layout include provision for the addition of other flight paths as required. It is anticipated that as many as ten flight tubes of various lengths, may eventually be needed. The flight path is contained in a steel tube which may be evacuated or filled with helium to reduce losses by scattering. The walls and roof of the target room are constructed of 4 ft of heavy concrete and covered by 13 ft of sand.

The proton target, moderator and other parts of the time-of-flight system have not been designed, but features of similar arrangements are described in the literature^{55, 57}. The proton target is a water-cooled slab of lead which presents a thickness of about 20 cm to the incident proton beam. With proton beam currents of the order of 50 μ A, the heat deposited in the lead target will be about 20 kW. Immediately below the target is a block of polyethylene - or other hydrogenous material - which is a few centimeters thick and forms the moderator for the system. The direction of incidence of the proton beam at the source, an arrangement which minimizes the uncertainty in flight path length contributed by the finite size of the proton target itself. The line of sight is restricted by collimation in the shielding wall so that only the moderator can be seen from the end of the flight path. The proton-target and moderator designs and the target-room geometry are chosen to minimize the scattering of unwanted neutrons into the beam from materials other than the moderator. The flight-path tube is sealed by a thin window of mylar or magnesium to reduce resonance absorption effects. At a selected point along the flight path a rotating mechanical shutter screens out unwanted slow (overlap) neutrons.

6. Future Extension of Resonance-Neutron Facilities

6.1 Storage Ring

An attempt will be made here to assess briefly the capability of a resonance-neutron time-of-flight facility based on the thermal target (Chapter VII, Section A) pulsed from a storage ring. It is assumed that it will ultimately be feasible to store the full beam current of 65 mA for 2 ms and to discharge it in bursts of 0.15 μ s at a fixed repetition rate of 500 Hz. Under these conditions, the power dissipated in the thermal target will be unchanged from CW operation but the instantaneous peak current in the pulse will be increased to 850 A. It is also assumed that the moderator assembly can be adapted at one experimental hole for efficient production of resonance neutrons with a minimum background of thermal neutrons. The 1-km flight path shown by a broken line in Fig. IX.1 is assumed to be available.

For a moderator with efficiency similar to that in the micro-pulse facility, we deduce that the peak total intensity from the storage-ring source is $I = 1.3 \times 10^{23}$ n/s and that the energy dependence is $I(E) = 3.8 \times 10^{19} E^{-0.9}$ n s⁻¹ eV⁻¹. The flux at the end of the flight path, and the flight path length to give a resolution equal to the Doppler width, may be calculated as for the micropulse system, Table VII. B.1. The results, for a nucleus $A = 100$ are summarized by the curves $F(SR)$ and $\ell(SR)$ in Fig. VII.50.

The storage ring would give a neutron flux at the end of the flight path some three orders of magnitude greater than that of the micro-pulse facility and would provide resolutions comparable to the Doppler width for $E < 8$ keV. The restriction of the flight path to a maximum length of 1 km results in a restriction of maximum resolution to 13 and 130 times the Doppler width at 100 keV and 1 MeV respectively. It is worth noting that, although the flight path might conceivably be extended somewhat beyond the arbitrary limit of 1 km, it is not practical to match the resolution to the Doppler width to 1 MeV, since $F(SR)$ at that energy is reduced to 1.7×10^{-4} n cm⁻² s⁻¹, (which is no more than comparable to $F(MP)$), while the flight path $\ell(SR)$ required would be 130 km.

6.2 Polarized Neutrons

The application of polarized neutrons⁶¹ in the resonance range has so far been limited to energies below ~ 15 eV. Techniques for obtaining polarized neutrons at higher energies are only now being developed. Among promising methods are the transmission of neutrons through a polarized proton target in the form of a monocrystal of lanthanum magnesium nitrate $\text{La}_2\text{Mg}_3(\text{NO}_3)_{12} \cdot 24\text{H}_2\text{O}$ cooled to 1.5 °K in field of 10 kG. This method⁶² is

⁶¹ V. L. Sailor, Use of Polarized Beams, Proc. Symp. Pulsed High Intensity Fission Neutron Sources, CONF 650217, p. 111 (1965).

⁶² P. Draghicescu, et al., Phys. Letters 12, 334 (1964).

applicable in the energy range 1 eV - 10 keV and, with suitably chosen crystals, polarizations of 85% and 63% with transmissions of 7% and 20% are predicted for thermal and resonance energies respectively. For the energy range 10 - 700 keV, a method has recently been described⁶³ in which the unmoderated neutrons from the source are first polarized by scattering at 90° from liquid helium and subsequently moderated in graphite. The scattering properties of graphite are such (small p- and d-wave phase shifts) that little depolarization occurs during the moderation process. Beginning with an evaporation spectrum peaked at 1.2 MeV, neutrons are predicted with 50-60% polarization, a median energy ~700 keV and an intensity 0.5% of that before the scatterer. With both methods the intensities of polarized neutrons available at the end of the flight path would depend very much on the overall geometry of the system but, with the high initial intensities available from ING, the capability for experiments in this field should be substantial.

⁶³ J. W. T. Dabbs and J. A. Harvey, Bull. Am. Phys. Soc. 10, 498 (1965).

C. MESON FACILITIES

1. General

A target for the production of mesons consists basically of a slab of material placed in the path of the beam, so that the beam in passing through the slab generates, by collisions with the nuclei of the slab, positive, negative and neutral pi mesons. The charged pions emerging, at 10° to 20° from the proton beam, from the downstream face of the slab, are introduced into a beam transport system for use at a distance from the target. The neutral pions have such a short half-life that they can only be used at the target, if at all. Targets in beam 1 must be of the order of 0.1 g cm^{-2} ; for beam 2 they may be up to 100 g cm^{-2} . Light elements are preferred for targets because they give the largest pion output for a given energy loss in the proton beam and also they have the best ratio of pion-to-neutron production. Beryllium and carbon are most frequently considered.

It is proposed to introduce two targets into beam 1 of ING (see Fig. VI. 3) to accommodate both pion and muon experimental facilities. The muons are formed from the decay in flight of pions. In addition it is proposed to have one or more meson targets in beam 2. The thickness of the targets in beam 1 is limited by the degrading effect which the target has on the emittance of the beam. The targets in beam 2 will be about 100 times thicker, so that the average meson output from the two sets of targets will be about the same. However, beam 1 targets will give a burst of mesons on each beam micropulse and beam 2 targets will give a pulse 100 times larger, on every hundredth beam pulse. These two conditions of meson output are suited to different kinds of experiment. (See sec. VII. C. 3 below).

The beam transport systems required for producing a pure pion beam, and for collecting a pure muon beam from pion decay, are different and can be combined only at a sacrifice in yield.

For targets in beam 1, the initial magnets defining the pion beams will be located in the tunnel and in the shielding wall. From there the transport system will take the pion beam into the experimental area (Fig. VI. 3) where experimental equipment can be located as required. For muon beams, the pions are allowed to pass into a muon channel, a series of wide aperture quadrupoles which collect a fraction of muons from pion decay and conduct them to experimental targets.

The shielding of the tunnel in the vicinity of the meson beams will be made of movable blocks so that modifications for fast or slow, or stopped, pions and muons can be accommodated.

A steering magnet can be used at the end of the meson channels to direct the beams into one of several experiments, on a time sharing basis.

The beam transport systems and shielding for targets in beam 2 (Fig. VI. 3) will be similar. Since the targets will be thick, time sharing in the use of the proton beam for the production of mesons and neutrons may be necessary.

2. Yields

The table of yields (Table VII. C. 1) is derived from similar tables given in the Los Alamos^{64a} and University of California^{64b} 'meson-factory' proposals, adapted for the currents proposed for ING. For beam 1, it is assumed that the target thickness is 0.1 g cm^{-2} . For beam 2, the yields are for the target thicknesses shown, which are close to the optimum for the listed pion energy. Optimum thickness targets cannot be used in beam 1 because of beam loss and the increase in beam emittance. Their use in beam 2 will depend on whether there are other downstream requirements for this beam.

Figure VII. 52 shows the cross-section for π^+ production as a function of accelerator energy. The curves for π^- production have about the same shape, and about $1/5$ the cross-section. Figure VII. 53 shows some spectra for pion production at various proton energies. The important feature of these curves is that the position of the peak of the spectrum does not change very rapidly with bombardment energy. The total number of pions produced, and the number of pions that can be collected in a given energy band from an optimized thick target, vary approximately linearly with bombarding energy. The angular distribution for pion production is strongly peaked in the forward direction.

It has been argued that, because of the background of neutrons associated with pion production, the optimum proton energy is about 500 MeV⁶⁴, for the production of stopped pions and muons. For meson experiments in which the background constitutes a limitation, the 400 MeV staging energy of the SOC could well be a valuable asset.

As shown in Fig. VI. 53 all possible energies are present in the pion target output. The energy spread in the meson beam delivered to the experimental equipment is a function of the beam analysing magnets or the beam transport system.

Although the pions are produced mostly in the forward direction with respect to the proton beam, the production angle is large enough that the emittance of the pion beam is determined by the solid

^{64a} A Proposal for a High Flux Meson Facility at Los Alamos, LASL, (1964)

^{64b} R. W. Richardson, Pion Facility, A High Energy Cyclotron for Negative Ions, report UCLA-TID-20822 (1964)

TABLE VII. C.1
SOME SECONDARY BEAMS AVAILABLE FROM ING

Type	Energy MeV	Current	Target	Flight Path Δp or ΔE Solid Angle	Intensity s^{-1}
High Energy Neutrons	1000	Beam-2 1 mA	40 cm liq. D ₂	20 ft. $\Delta E = 14$ MeV	$5 \times 10^7 \text{ cm}^{-2}$
	> 200		400 gm cm^{-2} of Bi	50 ft.	$\sim 5 \times 10^7 \text{ cm}^{-2}$
π^+	200-400	Beam-1 65 mA	0.1 gm cm^{-2} of Be	40 ft. $\Delta p/p = .07$ $\Delta \Omega = 3 \times 10^{-3}$ ster.	10^9 in $\Delta \Omega$
π^-					2×10^8 in $\Delta \Omega$
π^+	150	Beam-2 1 mA	100 gm cm^{-2} of carbon	40 ft. $\Delta p/p = .07$ $\Delta \Omega = 3 \times 10^{-3}$ ster.	10^{10} in $\Delta \Omega$
π^-					2×10^9 in $\Delta \Omega$
$\pi_0 \rightarrow 2\gamma$	0-500	Beam-2 1 mA	100 gm cm^{-2} of carbon		$2 \times 10^{14} \gamma' s/\text{ster}$
μ^+	125-400	Beam-1 65 mA	0.1 gm cm^{-2} of carbon	100 ft. $\Delta p/p = 0.25$	10^9 cm^{-2}
μ^-					10^8 cm^{-2}
μ^+	0	Beam-2 1 mA	100 gm cm^{-2} of carbon	50 ft.	10^8 cm^{-2}
μ^-					10^7 cm^{-2}
ν_μ	125-240	Beam-2 1 mA	100 gm cm^{-2} of carbon	25 ft. (neutrino horn)	10^8 cm^{-2}
$\bar{\nu}_\mu$					10^7 cm^{-2}
Polarized Protons $P \approx .50$	400 1000	Beam-1 65 mA	0.1 gm cm^{-2} of Be	$\Delta \Omega = 5 \times 10^{-5}$ ster.	2×10^{10} in $\Delta \Omega$

FIG. VII. 52 π^+ production cross section vs proton energy.

3296-C

FIG. VII. 53 π^+ production spectra for several proton energies.

angle of the effective aperture of the pion channel and the diameter of the source-spot on the target. The former may be of the order of 10^{-7} . The latter is limited, by heating of the target and the limitations in the proton beam transport system, to about 2 to 3 cm. The emittance is therefore about 0.2 cm. radian.

The minimum duration of a single burst of pions, and hence muons, is ~ 2 ns, given by the length of the micropulse at the target. This pulse length is sufficiently short to allow the pion and muon bursts to be separated by time-of-flight, at least for meson energies below a few hundred MeV. For example, a typical momentum analyser on the pion beams selecting pions of velocity $0.7c$ ($E_{\pi} = 139$ MeV, the mass of the pion) will also pass muons of $0.9c$. Over a π 30 foot flight path, about the minimum distance for extracting mesons at a small production angle and transporting them through the shielding wall, the pion flight time will be 43 ns, that of the muons, 33 ns. This time difference is much greater than the length of the burst, permitting selection of either muons or pions. At higher energies selection becomes more difficult. For the spatial separation of the components of the secondary beams, crossed E- and H-field devices or travelling wave mass-separators could be used.

Charged pions have a lifetime, in the rest frame of 2.6×10^{-8} s. The decay products are muons, electrons and neutrinos. This lifetime sets a limit to the distance that pion beams can be transported, and to the purity of pion beams that can be obtained. The mean distance for decay of a 100 MeV pion in flight is 34.9 ft, which is sufficient for the time-of-flight selection system. More energetic pions have a longer mean decay distance, e.g. at 500 MeV, the distance is 111.6 ft. ^{64a}.

Similarly, muons decay with a half life of $2.2 \mu\text{s}$; the decay products are electrons and neutrinos. Consequently, muon beams can be handled over distances of the order of hundreds of feet, if necessary, but they will be contaminated with electrons.

When pions are stopped and captured, as will occur for example, with stray pions in the walls of the beam transport system or the shielding, they produce about one neutron per stopped pion. Shielding against these neutrons must be provided. (Chap. VIII).

The optimum angle for collection of pions from the beam is 0° . In order to use this angle, the target must be followed by a magnetic field which separates the emerging protons from the pions. This arrangement is not practicable for beam-1, and may not be practicable for beam-2. A collection angle of about 15° is assumed to be practical.

3. Choice of Beam-1 or Beam-2 Targets

The beam-2 meson target can give a higher instantaneous output than the beam-1 target. However, for a given experiment, the

the choice between the two may depend on the pulse structures of the two beams. For devices such as bubble chambers, and perhaps spark chambers, a recovery time as high as seconds between beam burst is needed. This will require the use of the intermittent beam-2. Since each beam-2 pulse may yield as many as 10^4 pions or 10^3 muons, it is apparent that one may perform only experiments in which a small fraction of the mesons produce recorded events.

Experiments in which arrays of counters are used in coincidence are limited by background and random coincidences. As more counters are used in coincidence, as in counter telescope arrays, the ratio of true-to-random coincidences improves. However, for a given experiment, this ratio varies as I^{-n+1} , where I is the instantaneous value of the beam current, and n is the number of counters in the array. For these systems, it is advantageous to spread the counting time as much as possible, that is, the duty cycle of the beam should be as high as possible. Here beam-1 is clearly superior.

4. Technical Problems, Beam-1 Target

The Beam-1 targets, with 65 mA passing through them, must be 0.1 gm thick in order to give them a meson output comparable to the LAMPF targets (6 gm thick, beryllium or carbon). The most difficult problems will be heat dissipation, destruction of the target by radiation, and the effect of the target on the beam quality downstream.

4.1 Heat Dissipation

The beam will generate about 15 kw in the target, within the beam diameter which is expected to be of the order of one inch. For the beam-1 target, cooling by means of a water channel through a fixed target block is marginal. Two solutions appear to be practicable,^{6 5} a wheel with a beryllium oxide or carbon rim cooled by radiation and internal water channels, and a beryllium band cooled by passing it over cooled pulleys. The band can either be continuous, as in a band saw, or a ribbon which is wound and unwound from storage drums, as in a tape recorder. The choice will depend on life under bombardment, ease of replacement and the optimum temperature for long target life. This temperature may be as high as 600°C.

4.2 Target Life

If a band target is used, its life will be determined by embrittlement under irradiation. If it can be operated over 500°C,

^{6 5} B. C. Stonehill, private communication, (May 18, 1966)

embrittlement by knock-on beryllium atoms will anneal out, and will not be serious. The limit of irradiation may be set by the formation of helium from nuclear reactions, for which a limit of $.047 \text{ cm}^3 \text{ cm}^{-3}$ has been given^{6 6}. With the crude assumptions, that every nuclear reaction on beryllium creates one helium atom, and that momentum is equally and isotropically divided between the alpha particle, a deuteron and two neutrons, the life of a 0.1 gm cm^{-2} target is estimated to be $0.5 \times 10^5 \text{ s}$. A 10 m-long belt would then last 200 days. If the belt can be run at a temperature 600°C , the life is increased by a factor of about 300.

At elevated temperatures, oxygen embrittlement will become serious, so that a compromise temperature will have to be found.

A target in the form of beryllia or carbon on the rim of a wheel would be expected to withstand more irradiation per cm^2 , because it can be left in the beam until extensive swelling terminates in disintegration. However its total target length will be only of the order of 1 m.

Aluminum or iron could be used with only a small increase in neutrons per meson produced, if they confer any advantage for target life.

4.3 Shielding of Targets

The targets will be inside a steel enclosure which is assumed to be 5 ft-thick. This enclosure, in conjunction with the general tunnel shielding will reduce the radiation hazard to acceptable levels. The meson target will constitute a source of secondary radiation which will be able to pass in either direction along the proton transport at least as far as the nearest bending magnet. It will be desirable to introduce apertures or 'beam scrapers', in the beam lines to limit the amount of this radiation striking quadrupole magnets and other beam line components and escaping from the high activity tunnel. The scrapers must be carefully designed to assure that they do not introduce more scattered beam than they remove; they must also be cooled.

The reels, wheels, or pulleys associated with the targets, apertures, and the first magnet in the meson transport system will become highly active. Remote handling will be required for servicing them.

^{6 6} R. Piercy, private communication, (30 May, 1966).

At each bend in the meson beam transport system there will be a re-entrant hole in the shielding to entrap neutrons travelling with the meson beam.

4.4 Effect on the Emittance of the Beam

The effect of the meson target on the proton beam will be to introduce spreads in energy and angle, the former caused by straggle, the latter caused by multiple, nuclear, and coulomb scattering. Small changes in energy or direction of the beam particles can be accommodated by the beam transport system downstream from the targets. As mentioned above, strongly perturbed protons will have to be removed by beam scrapers and magnetic analysis.

4.4.1 Straggling

The energy loss of Beam-1 in a meson-producing target will be 0.23 MeV. The r.m.s. fluctuation in this energy loss is about 0.023 MeV, an entirely negligible value in comparison with the energy spread of 7.5 MeV in the beam incident on the target.

4.4.2 Multiple Scattering

The r.m.s. scattering angle has been estimated at 0.02° , in agreement with the estimate given in the Yale meson factory proposal⁶⁷. The estimate was based on the theory of Rossi and Greisen, which is known to over-estimate multiple scattering for such thin targets⁶⁸. If the emittance of the beam is 10π mm-mrad then at the position of the meson target where the diameter is about 2.5 cm, the beam angular spread is about 0.06° . Multiple scattering will thus add appreciably to the beam emittance.

4.4.3 Nuclear Scattering

Interactions between the beam protons and the nuclei of the target lead to either a complete loss of the proton, a large change in energy and angle, or in the case of elastic scattering, to a large angular deflection. In all but a negligible number of cases, the beam transport system will not accommodate the scattered protons. Estimates have been made of loss, using the cross-sections of Coor, et al.⁶⁹, taken for 1.4 GeV

⁶⁷ A Final Report on the Design of a Very High-Intensity Proton Linear Accelerator as a Meson Factory at an Energy of 750 MeV, report TID-21282 (1964).

⁶⁸ B. Rossi and K. Greisen, Rev. Mod. Phys. 13, 240 (1941)

⁶⁹ T. Coor, et al., Phys. Rev. 98, 1369 (1955)

protons. Non-elastic scattering will remove 0.10%. These losses will produce a background inside the target enclosure of about 10^{15} to 10^{16} n s^{-1} .

4.4.4 Coulomb Scattering

Protons scattered in the forward direction by Coulomb scattering from the target nuclei will have small energy loss and so can be accepted by the beam transport system, if the angle is small enough. It has been assumed that protons scattered through angles less than 0.06° , the beam angular spread, will be accepted. The loss of particles is then estimated to be 0.3%. Thus Coulomb scattering contributes as much to the beam emittance as multiple scattering, and as much to beam loss and consequent background as nuclear scattering.

To summarize, the acceptance of the beam transport system downstream from the meson target probably will have to be increased by the order of 50%. If this can be done, the beam loss at the target and the subsequent beam defining aperture will be about 0.5%. This will produce a background source of about 10^{16} n s^{-1} , part of which will be localized at the target itself, and part at the beam defining aperture that follows the target.

5. Technical Problems of Beam-2 Targets

The targets in Beam-2 are assumed to be from 5 to 50 gm cm^{-2} . Although the total heat generated will be from 10 to 100 kw it is distributed over a volume 50 to 500 times greater than for Beam-1. Consequently cooling by water channels is possible. The rate of radiation damage per unit volume of target is reduced by a factor of 65 which makes it tolerable.

If the average meson production in Beam-2 is the same as in Beam-1, the beam spill caused by nuclear and Coulomb scattering will also be the same. The problem of designing a beam aperture and the downstream beam transport system will then be the same, except that the beam does not have to travel so far. It must be refocussed on the fast neutron target, or if neutrons are not being used, it must be carried to the beam dump.

6. Polarized Protons

It has been shown^{64a} that elastic scattering of protons from Be at small angles ($\sim 9^\circ$) results in polarization of the scattered beam. Polarizations of about 50%, with beam intensities of 2×10^{10} protons s^{-1} could be obtained from the Beam-1 meson target.

D. FAST NEUTRON FACILITIES

1. General Description

The fast neutron facility is shown in Fig. VII. 54. Beam-2 strikes a target in a heavily shielded enclosure near the end of Beam Tunnel No. 2. Neutrons produced from (p, n) reactions are collimated by apertures in the beam deflecting magnet and the shielding at the end of the tunnel, to produce a clean beam in the experimental area. The field of the deflecting magnet will act as a sufficient clearing magnet for charged particles coming from the target. The most intense beams will be at 0° to the proton beam, but useful beams, including polarized beams, are obtainable at angles up to about 90° .

2. Production of Fast Neutrons

2.1 Unpolarized Neutrons

At the SOC staging energies of 400 MeV and 1000 MeV, fairly monoenergetic neutron beams can be produced by the $D(p, n)2p$ reaction. The (p, n) reaction on deuterium has been shown to give a neutron beam at 0° with a full width at half maximum in the energy spectrum of about 14 MeV. With an additional energy spread of 7.5 MeV introduced by the proton beam from the third stage, the neutron energy spread will increase to ~ 16 MeV. This would be satisfactory for many experiments. Beryllium also gives a high energy peak, about 90 MeV wide, accompanied by a wider lower energy peak extending down to zero. Where a wide spread of neutron energies may be tolerated (p, xn) reactions on heavy elements can be used.

The fast neutron fluxes available from Beam-2 for neutron energies 200 MeV and greater are shown in Table VII. C.1. Here it is assumed that the neutrons can be used at 0° to the proton beam. The fast portions of the spectrum, from all targets, are strongly forward-peaked.

For neutron energies up to about 20 MeV, the evaporation spectrum can be used at an angle of 90° or more where the fast component (over 100 MeV) is reduced by an order of magnitude. Thus at 90° , ING could be a very useful source of neutrons in the MeV range. Assuming a required energy resolution of 100 keV, and an overall time resolution of 3 ns, an average current of 1 mA, and a proton energy of 1 GeV, a reasonable target size is 10 cm diam by 20 cm long. With these assumptions ING cannot compete above a neutron energy (E_n) of about 14 MeV with a hypothetical 6 MeV accelerator, at 1 mA average, using the T-D reaction to give 1 ns bursts of monoenergetic neutrons⁷⁰

⁷⁰ W. G. Cross, private communication (1965).

FIG. VII. 54 Fast neutron facility and beam dump for Beam 2.

However at about $E_n = 7$ MeV it is comparable with such a low energy accelerator delivering an average current of 1 mA to produce neutrons by the D-D reaction. Below this energy the low energy accelerator would have to be capable of even larger currents. Near the peak of the evaporation spectrum, 3.5 MeV, about 10 to 100 mA (average) of deuterons would be required to equal ING. This would pose formidable target problems since thin targets are required. The thick ING target would be required to dissipate 350 kW.

2.2 Polarized Neutrons ^{64a}

There have been experiments on the production of polarized neutron beams by (p, n) reactions in which the neutrons are observed at a small angle, e. g. 30° , to the incident protons. From information on n-p scattering it can be estimated that the D(p, n)2p reaction will produce neutrons with 25% polarization, and intensity about an order of magnitude less than the unpolarized beam obtainable at 0° . Aluminum and carbon have been also suggested as other less-promising targets for producing polarized neutrons.

3. Targets

The neutron-producing targets consist of thin walled vessels containing liquid deuterium for monoenergetic neutrons, solid targets of heavy elements for continuous-spectra, and beryllium targets for polarized neutrons.

Neutron production from the liquid deuterium target is limited by boiling caused by beam energy loss in the target. In the LAMPF proposal ^{64a} it is suggested that a beam energy dissipation of 1.5 kW in liquid deuterium is close to the limit of present technology. This will require, typically, a 100 μ A beam with a target about 40 cm long.

Heat production in solid targets presents the same problem for neutron as for meson targets (see Section VII. C above).

For fast nucleon scattering experiments, the 16 MeV resolution given by the liquid deuterium target will be adequate. It may also suffice for some nuclear structure experiments. For better resolution of the energy of incident neutrons, time-of-flight resolution must be used. This will rely on timing the interval between the beam pulse on the neutron-producing target and some identifiable event from the experimental target.

Near 1000 MeV, the possibilities for use of time-of-flight methods for direct measurement of, for example, neutron energy loss in inelastic scattering, are limited. Because of relativistic effects,

at 1000 MeV, $(dE/E)/(dv/v) \sim 3$. Consequently, if energies are to be measured to better than the $\overline{16}$ MeV attainable with the liquid deuterium target, with time-of-flight resolutions of the order of 2 ns, flight paths of 500 ft. are required.

E. BEAM DUMP AND IRRADIATION FACILITY

The present proposal calls for a 1 mA current in Beam-2. Although some of the targets in this beam may be relatively thick (50 gm cm^{-2}) most of this beam will be discharged into a beam dump. Shielding between the dump and the experimental areas must reduce the back streaming radiation below health tolerance and shielding around the dump must control the soil activation. To allow for a future increase in intensity of Beam-2 the dump should be capable of handling a current of a few mA.

The proposed beam dump is shown in Fig. VII. 54. The stacked steel plates will stop all of the incident primary protons and provide an attenuation of 10^{-2} or more for the high energy secondary neutrons produced in the forward direction. Water will remove heat and thermalize the neutrons produced in the steel plates. Virtually all of the neutrons produced will be thermalized and reabsorbed within the stainless steel tank.

The proton beam will be allowed to expand to $\sim 25 \text{ cm}$ diameter before passing through the window separating the evacuated beam tube and the water filled dump. For a current of 1 mA the life of the window will be approximately 1 year if the material can tolerate $4 \times 10^{20} \text{ p/cm}^{-2}$ before significant damage is done. To ensure safety a double window will be required.

The 25 ft of heavy concrete between the beam dump and the experimental area will reduce the radiation below health tolerance. The 10 ft of heavy concrete shielding around and beneath the beam dump will maintain the total equilibrium soil activity at no more than a few curies. The backscattering of high energy neutrons up the proton inlet pipe will have to be carefully controlled to maintain the purity of the monoenergetic neutron beam. This may require bending the beam twice; by a few degrees in the horizontal plane and then through 90° into the beam dump.

An irradiation facility for radiation damage studies could be installed near the beam dump window. Access to this area would be required for operation of the irradiation facility as well as for maintenance of the window. The radiation from the radioactive plates of the beam stop could be reduced to a tolerable level by lowering them to the bottom of a tank filled with clean water. The radiation field from the window itself (estimated to be about 200 R/hr after 10 hr cooling) is sufficiently high to require the use of a remote-handling device for replacement of the window.

F. NUCLEAR POWER TECHNOLOGY FACILITY

The nuclear power technology facility is conceived as playing a role analogous to that of ZEEP or ZED-2 in the development of high power research and power reactors. That is, it would be a simple low power target and moderator tank that could be used for the study of neutron slowing-down and capture in different arrangements of fertile and fissile material.

The facility would thus be very similar to the ZED-2 lattice-test reactor and could in fact make use of much of the technology that is already developed, and conceivably take over much of the actual material and equipment if the ZED-2 programme were terminated.

The main addition would be a beam channel to bring a very small fraction of the main accelerated proton beam axially (preferably vertically) into the moderator tank. Only sufficient beam to produce neutron fluxes of $\sim 10^8 - 10^9 \text{ n cm}^{-2}$ in the moderator will be used so that a minimum of shielding will be required, and a minimum of activity will be generated in the fuel and structure. A major item in the cost would be the magnet to bend the beam into the vertical direction. A second problem would be the initial beam splitter to remove and deflect a small fraction of the main beam to the facility, but this must also be solved in connection with other ING facilities, and possibly the same splitter unit could serve a number of different facilities.

CHAPTER VIII

SHIELDING AND ACTIVATION

A.	RADIATION LEVELS AND TOLERANCES (I. M. Thorson)	VIII. 1
1.	Biological Tolerances	1
2.	Radiation Levels	3
B.	RADIATION PRODUCTION AND ATTENUATION (I. M. Thorson)	4
1.	Radiation Production	4
2.	Cascade Neutrons	5
3.	Fast Neutron Attenuation and Moderation	9
4.	Gamma Ray Production and Attenuation	10
5.	Neutron Skyshine	10
6.	Interstitial Gas Production	11
7.	Heat Production in Shields	11
C.	ACTIVATION (G. T. Ewan, D. C. Santry)	14
1.	Spallation	14
2.	Neutron Capture	19
3.	Active Effluents	19
APPENDIX VIII. 1	Neutron Attenuation with Build-Up (I. M. Thorson)	21
VIII. 2	Heat Production in ING Shields (I. M. Thorson)	24

VIII. SHIELDING AND ACTIVATION

A. RADIATION LEVELS AND TOLERANCES

1. Biological Tolerances

At the Chalk River Nuclear Laboratory the maximum permissible, whole body, dosages of γ -rays and neutrons are

0.6 rems in any two week period,
3.0 rems in any 14 week period,
5.0 rems in any one year period.

Radiation levels throughout the ING facility have been designed to enable all personnel to operate well within these figures.

The γ -radiations around ING are basically the same as those found around lower energy accelerators or reactors. The only exceptional γ -rays encountered in ING are those of 67 to 500 MeV from the decay of the short lived (mean life $\sim 10^{-16}$) π^0 mesons. Their production will occur predominantly toward the inside of the thick shields and electron pair production will shortly convert them to multiple quanta of approximately the same energy as capture γ -radiation.

The neutrons of energies greater than ~ 20 MeV do, however, present a problem not encountered in other facilities at Chalk River. Table VIII.A.1 lists an estimate¹ of the relationship between the dose-equivalent and the neutron flux for the energies up to 10 MeV². Table VIII.A.2 defines an estimate^{3, 4} of the relationship for nucleons at the higher energies encountered in ING.

Although the radiation attenuation characteristics of bulk shields around ~ 1 GeV accelerators are determined primarily by the non-elastic nuclear collisions of the high energy neutrons, the secondary particles and γ -rays from such collisions contribute most of the radiation dose outside these shields. The predominant component, often constituting more than 50% of the total dose⁵, is from fast neutrons of a few MeV energy. This fast neutron leakage can be suppressed by including low

¹ W.G. Cross, private communication, (Dec. 6, 1965), who used the results from the three following references.

² Protection Against Neutron Radiation up to 30 MeV, National Bureau of Standards Handbook no. 63 (1957).

³ J.E. Turner, et. al., Health Physics, 10, 783 (1964).

⁴ C.D. Zerby and W.E. Kinney, Nuclear Instr. and Methods 36, 125 (1965).

⁵ J. Baarli and A.H. Sullivan, Health Phys. 11, 353 (1965).

TABLE VIII. A. 1
NEUTRON FLUX TO DELIVER 2.5 MREM HR⁻¹

Neutron Energy	Flux n cm ⁻² s ⁻¹
Thermal	670
100 eV	500
5 keV	570
20 keV	280
100 keV	80
500 keV	30
1.0 MeV	18
2.5 MeV	20
5.0 MeV	18
7.5 MeV	17
10 MeV	17

TABLE VIII. A. 2
CALCULATED FLUX TO GIVE MAXIMUM DOSE
EQUIVALENT OF 100 MREM IN 40 HOURS

Nuclear Energy MeV	Flux-nucleons cm ⁻² s ⁻¹	
	Protons	Neutrons
50	0.9	10
100	1.0	10
200	1.4	8.7
250	3.6	8.3
400	4.1	7.3

atomic weight materials such as water, paraffin or a metal hydride near the outside of such shields. The thermalized neutrons can then be absorbed, preferably in a material which does not emit or which self-absorbs capture γ -rays. It is expected that, if neutron thermalization and capture are treated in detail in the final shield designs, the dose rates from secondary neutrons and capture γ -rays will be ~ 0.5 of the total dose rate.

Proton spill in the ING facility can activate the air in the accelerator vault and beam transport tunnels. The maximum permissible concentration of airborne activities is dependent on the decay characteristics of the radio-nuclides and in particular on their β -ray energy. For the most common activities, concentration limits of a few $\mu\text{ Ci m}^{-3}$ apply for continuous occupation by working personnel. For example, the maximum permissible concentration of tritium as water vapour is $5\mu\text{ Ci m}^{-3}$ and for ^{41}Ar , $2\mu\text{ Ci m}^{-3}$. The tolerance level of activation of ground water and soil from beam dumps is much more difficult to determine. An estimate of the equilibrium activity with half-lives longer than one week, for a proton beam spill of $1\mu\text{A}$ of 1000 MeV protons, into the sand found at Chalk River gives a total source of $\sim 20\text{ Ci}$. Thus, even several μA of distributed proton spill should not present a serious hazard since nearly all of this activity will be trapped in the soil.

2. Radiation Levels

Several types of areas in the ING facility were considered for shielding requirements. For permanent working areas such as the thermal neutron facility hall, the dose rate must be less than 0.5 mrem hr^{-1} . For continuous access areas, where occupation is limited to $\sim 10\%$ of the working time or less, the total dose rate with the machine operating must not exceed 2.5 mrem hr^{-1} . For limited access areas, such as the RF galleries for the accelerator, total dose rates of $50\text{--}100\text{ mrem hr}^{-1}$ were assumed when the machine was operating. These areas are all continuously habitable when the accelerator is not operating.

The main accelerator vault, beam transport system tunnels, and other areas which contain beams of high energy protons, will not be accessible when those facilities are operating. Very high radiation fields from induced activity will exist indefinitely after shutdown of the machine, at some points throughout the beam transport system. It is intended that these points will be shielded by removable local shielding of sufficient attenuation that residual radiation fields outside these shields, a few hours after machine shut-down, will at worst be a few tens of mrem hr^{-1} . Remote handling should then be required only for removal of activated components and local shielding blocks and not for installation of new components.

B. RADIATION PRODUCTION AND ATTENUATION

1. Radiation Production

The attenuation of high energy protons and charged mesons is accomplished by two mechanisms, energy loss by ionization and nuclear interactions. The attenuation of neutrons is achieved by nuclear interactions only. The range for a 1 GeV proton to stop by ionization varies from $\sim 370 \text{ g cm}^{-2}$ in carbon to $\sim 630 \text{ g cm}^{-2}$ in lead; at 200 MeV their range has fallen to $\sim 29 \text{ g cm}^{-2}$ and $\sim 53 \text{ g cm}^{-2}$ respectively. The ionizing range of mesons produced by these protons is approximately the same as for the protons themselves. Since the shield thicknesses that are required to provide adequate attenuation for the high energy neutron flux are much greater than these ranges, consideration of charged particle phenomena in shielding can be limited to neutron and heat production. Only the high energy protons can produce significant quantities of neutrons.

In general, when a high energy nucleon (proton or neutron) suffers an inelastic collision with the nucleus of an atom, the following types of radiation are produced directly:

- (a) high energy (cascade) nucleons, energies up to the incident nucleon energy,
- (b) fast (evaporation) nucleons with mean energy of a few MeV,
- (c) charged, multiple-nucleon fragments such as deuterons, tritons, ^3He and alpha particles, of somewhat higher mean energy than fast nucleons,
- (d) mesons,
- (e) γ -rays.

The residual nucleus is usually unstable and will later decay by one or more of the various β -decay modes which may or may not be accompanied by further γ -ray emission. Elastic scattering of high energy nucleons does not change their energy or direction significantly and the phenomena can usually be ignored in high energy nucleon shielding.

Non-elastic cross-sections have been measured^{6,7,8,9} for a number of elements and over quite a wide energy range. Fig. VIII.1 shows the non-elastic mean free path for neutrons of 30 MeV and 140 MeV. Fig. VIII.2 shows the non-elastic cross-sections of C, Al, Cu and Pb as a function of neutron energy, taken from the references cited. The non-elastic nuclear collision cross-sections for protons have been measured at 860 MeV¹⁰ and are the same within the experimental errors as the value found by interpolation of the neutron data. The same variation of non-elastic cross-section with energy is assumed for protons as for neutrons.

2. Cascade Neutrons

In estimating the effective attenuation of a shield, account must be taken of the transport of the secondary neutrons. This, in the general case is a very difficult problem requiring much more detailed information than is generally available, on the number, spectra and angular distributions of these neutrons. The available experimental evidence has been substantially augmented in recent years by the results from Monte Carlo calculations of intra-nuclear cascades.^{11,12}

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- ⁶ R.G.P. Voss and R. Wilson, Proc. Roy. Soc. (London), A 236, 41, (1956)
- ⁷ W.P. Ball, Nuclear Scattering of 300 MeV Neutrons, report U.C.R.L. - 1938 (1952)
- ⁸ M.H. MacGregor et al., Phys. Rev. 111, 1155 (1958)
- ⁹ T. Coor et al., Phys. Rev., 98, 1369 (1955).
- ¹⁰ F.F. Chen, et al., Phys. Rev. 99, 857 (1955)
- ¹¹ H.W. Bertini, Phys. Rev., 131, 1801 (1963); and Phys. Rev., 138, AB2 (1965)
- ¹² N. Metropolis, et al., Phys. Rev. 110, 185 (1958)

FIG. VIII. 1 The Non-Elastic Mean Free Path λ_i for 30 MeV and 140 MeV Neutrons, as a Function of Atomic Weight A. (The experimental points are taken from references (6) and (8). The curves are empirical fits to the data, of the form.

$$\lambda_i = C \cdot A^{1/3} \quad \text{where}$$

C = 20.8 for 30 MeV neutrons

C = 35.8 for 140 MeV neutrons).

FIG. VIII. 2 The non-Elastic Cross-sections for C, Al, Cu and Pb, as a function of Neutron Energy (Data from references 6, 7, 8, 9, ; data for 860 MeV protons from reference 10).

Experimental measurements of the bulk shield attenuation factors¹³ are difficult to perform with sufficient precision and in sufficient detail that the results can be applied with confidence to estimates of the attenuation factors several decades beyond that of the measurements. Present day high energy nuclear intensities usually limit the measurements to attenuation factors of 10^{-4} or larger but, for the thermal neutron facility of ING, factors of 10^{-10} to 10^{-11} are required. The measured attenuation length for 1 to 2 GeV nucleons in heavy concrete¹³ is close to that expected on the basis of removal by one or two non-elastic collisions. Other estimates of attenuation length in standard concrete¹⁴ are more pessimistic and are believed to be excessively conservative.

The attenuation lengths in various materials used to estimate the shield requirements for ING were based on those deduced from the measured or interpolated (from Fig. VIII. 1) non-elastic nucleon cross sections at 140 MeV, with a 10% increase in the mean-free path to allow for secondary particle buildup. Using as a guide the Monte Carlo results for Pb targets of 20 cm diameter, 2 or 3 cascade neutrons were assumed produced by each high energy proton, in any material. These numbers agree with Bertini's results¹¹ on copper within a factor of ~ 2 and do not affect the overall estimates by more than the probable errors on the attenuation factors. Table VIII. B.1 lists the $1/2$ and $1/10$ attenuation lengths in various shield materials and the relative attenuation lengths normalized to unity for heavy concrete.

In general, when long range secondary neutrons are produced by inelastic collisions, the attenuation is no longer exponential with distance¹³. A more detailed and less optimistic estimate of the attenuation is given in Appendix VIII-1. This estimate is sensitive to the input data and assumptions regarding primary and secondary spectra, and the angular distributions and some more calculations are required to establish the absolute attenuation factors.

¹³ S. J. Lindenbaum, Ann. Rev. Nuclear Sci. 11, 213 (1961).

¹⁴ B. J. Moyer, et al., Character of the Radiation Field and Shielding at the 184" Cyclotron, report AECD-2149 (1947); and H. W. Patterson, University of California Radiation Laboratory Synchrocyclotron, proc. Conf. Shielding of High-Energy Accelerators (New York); TID 7545 p. 3 (1957).

TABLE VIII. B. 1

Element or Mat'l	1/2 att. length cm	1/10 att length M	Relative Att. length
C	30.7	1.02	1.24
Al	30.2	1.00	1.22
Fe	13.5	0.45	0.54
Cu	12.4	0.41	0.50
Pb	13.7	0.46	0.55
*Heavy Concrete $\rho = 3.5 \text{ g cm}^{-3}$	24.9	0.83	1.0
*Std. Concrete $\rho = 2.3 \text{ g cm}^{-3}$	32.8	1.09	1.3
**Sand $\rho = 1.7 \text{ g cm}^{-3}$	44.7	1.48	1.8
*Composition of concrete from CRP 578			
**Fractional composition of sand was assumed the same as standard concrete.			

3. Fast Neutron Attenuation and Moderation

In thick shields the evaporation neutrons produced, as well as the lower energy cascade neutrons, are degraded in energy first by non-elastic collisions which produce particles and γ -rays, and second by inelastic (n, n' γ) reactions at lower energies. The inelastic mean free path for such collisions in iron is nearly constant at 9.5 cm over the energy range 3-30 MeV. In the common shield materials only elastic scattering is important in moderating the neutrons with energies below 1 MeV, thus it is necessary to include some low A material, preferably hydrogen, for neutron thermalization. This is particularly important with an iron shield where the very small scattering cross-section around 26 keV makes the slowing down length extremely long.

The fraction of hydrogen required for minimum overall shield thickness is dependent on the neutron spectrum and the total attenuation of the shield. Using the results of experimental work¹⁵ for 350 and 660 MeV protons on Be as a guide, the fraction of hydrogen required is in the range 0.05 to 0.15% H/Fe by weight for attenuation factors of 10^{-10} to 10^{-5} respectively.

¹⁵ B.S. Sychev, et al., Passage of High Energy Neutrons in Iron-Water Mixtures, JINR-P-2359 (1965) translated by V. Poppe, N.R.C. Ottawa, 1966.

4. Gamma Ray Production and Attenuation

Measurements have been made of the direct γ -ray production from non-elastic collisions between 160 MeV protons and several different elements¹⁶. Assuming similar results for other materials and incident nucleon energies, the direct γ -ray production is only a small fraction of that from inelastic collisions of the evaporation neutrons and from neutron capture. Self-absorption substantially suppresses the escape of γ -radiation produced by inelastic neutron collisions in shields or bulk structures because the attenuation length for γ -rays is substantially shorter¹⁷ than the mean free path between inelastic collisions of the neutrons. Capture γ -radiation production is very sensitive to local geometry and materials, especially when the hydrogen concentration is high, as in cooling water channels.

5. Neutron Skyshine

Radiation which is initially directed upward and is scattered by the air back to ground level is generally referred to as 'skyshine'. Usually the only significant skyshine problem comes from neutrons.

The total flux, f , at a field-point a distance r from a directed source of monoenergetic neutrons, can be calculated from the expression

$$f(r, \theta) = \int K(E, \theta, r) dE$$

where K is the kernel for the medium relating the flux at an energy E to r and to θ , the angle between the source neutron direction and the source-point-to-field-point direction. Such kernels have been computed for 14 MeV source neutrons, in air¹⁸.

Based on these data the flux $f(r, \theta)$ is approximately 2×10^{-9} n cm⁻² per source neutron, for $\theta = 90^\circ$ and $r = 100$ ft. For r values between 10 and 100 ft the flux varies approximately as $1/r$.

For a source of 14 MeV neutrons, emitted isotropically on an absorbing surface, an integration of the kernel over all angles leads again to a flux at $r = 100$ of approximately 2×10^{-9} n cm⁻² per source neutron.

In estimating the neutron skyshine intensities around ING it was assumed that the $1/r$ dependence holds for $r > 100$ ft. This is conservative since the dependence at very large distances is at least $1/r^2$

¹⁶ W. Zobel, et al., Spectra of Gamma Rays produced by the Interaction of ~160 MeV Protons with Be, C, O, Al, Co and Bi. ORNL-3506 UC-34-Physics, TID-4500 (37th ed) (1965)

¹⁷ W. J. Henderson and A. C. Whittier, Handbook of Shielding and Heat Production Calculations for the NRU Reactor, CRR-578 (Rev.) AECL 403 (1957)

¹⁸ E. P. Blizard (editor), Reactor Handbook 3 (B), Interscience Publishers, 239-246 (1962)

For neutron energies higher than 14 MeV, two opposing effects will probably combine to maintain the kernel values quite constant at distances of 10' to 100' but will enlarge the area where the $1/r$ dependence holds. These effects are an increase in the mean free path between collisions and an increase in the number of secondary neutrons at each collision.

The acceptable flux level arising from 14 MeV neutrons is $\sim 0.1 \text{ n cm}^{-2} \text{ s}^{-1}$ in laboratories where sensitive NaI detectors are used. To allow for a harder spectrum from the higher energy source neutrons, the acceptable level should probably be reduced by a factor of 2 or 3. The total flux of neutrons above 1 MeV from cosmic rays is approximately $0.01 \text{ n cm}^{-2} \text{ s}^{-1}$ at sea level.

6. Interstitial Gas Production

When high energy neutrons suffer inelastic collisions, the hydrogen and helium production from the resulting cascade protons, and evaporation protons, deuterons, tritons and alpha particles, may be significant. Fig. VIII. 3 shows the effective cross-sections for such production as a function of incident neutron energy, for C^{12} , Al^{27} , Cu^{65} and Ru^{100} , based on Bertini's results¹². In calculating the proton production cross-sections the evaporation and cascade components were used since inelastic collisions by the protons would in general not alter the total proton production significantly.

7. Heat Production in Shields

When thermal neutrons are captured the binding energy of the neutron is released as γ -radiation the calculation of the spatial distribution of this heat production divides then into an estimate of the spatial distribution of neutron captures and an estimate of the spatial distribution of the heat produced by γ -ray ionization. The problem has been treated previously for thermal neutron reactors.¹⁹

Fast neutrons which are below the threshold for charged particle emission release their kinetic energy, as recoil energy of the scattering nucleus in elastic scattering, and as recoil energy plus γ -ray energy in inelastic scattering. The binding energy of the neutron is released as γ -radiation at capture just as for thermal neutrons.

For high energy neutrons the total energy release is the sum of the neutron kinetic energy, plus the binding energy for one neutron, less the binding energy for all the stopped charged particles emitted during the inter-nuclear cascade. The spatial distribution of the heat production depends on the details of the inter-nuclear cascade but, for

¹⁹ *ibid* reference (17) pp 32-37.

FIG. VIII. 3 Hydrogen - and Helium-production Cross-sections as a function of Incident Neutron Energy for C^{12} , Al^{27} , Cu^{65} and Ru^{100} (Data from reference 11; cascade protons, evaporation protons, deuterons and tritons included in hydrogen production; α particles and He^3 included in helium production).

purposes of estimating the shield heating for ING, the simple procedure outlined in Appendix VIII. 2 should be adequate. Based on the procedure of Appendix VIII. 2 the heat production in the shields of the thermal neutron facility is given by

$$H(\chi) = \left[\frac{P_1}{17.5} + \frac{P_2}{7.5} \left(1 - e^{-\left(\frac{\chi}{10.0} - \frac{\chi}{17.5} \right)} \right) \right] e^{-\frac{\chi}{17.5}} \left(\frac{120}{\chi + 120} \right)$$

H is heat production in the iron shield in W cm^{-3}

χ is distance from inside shield face in cm

where $P_1 = 20 \text{ W cm}^{-3}$

and $P_2 = 16 \text{ W cm}^{-3}$

for a moderator tank diameter of 120 cm and a proton beam current of 65 mA.

C. ACTIVATION

1. Spallation

The induced radioactivities in the ING facility can reach a very high level if an appreciable fraction of the beam of high energy protons is spilt and strikes construction materials. The high γ -radiation fields resulting from the induced radio-activities could result in a serious health hazard, even when the machine is shut-down. This could greatly complicate the servicing operations. Already, activation problems of this type are being encountered at the CERN 660 MeV proton synchrocyclotron where the maximum beam current is $\sim 2\mu\text{A}$. When this beam strikes an internal target it is all spilt inside the machine. The beam current in the ING facilities is 30,000 times greater than at CERN, so it is obvious that one can afford to have very little of the beam in the accelerator or the beam transport system.

Approximate estimates of the induced radiation fields can be made by using available experimental information on spallation cross-sections for the production of various activities by high energy protons. Fulmer et al²⁰ made such estimates in connection with the design study of the Mc^2 cyclotron proposed at Oak Ridge²¹. They compared their results with experimental measurements made by Barbier²² at CERN and obtained good agreement with the observed decay curves, and reasonable agreement with the absolute levels. Barbier²³ has made extensive calculations of the activation of a large number of materials using the spallation cross-sections from a semi-empirical formula of Rudstam²⁴. Bower and Ewan²⁵ have used data on experimental cross-sections to calculate radiation levels in connection with the ING facilities. Their computer programme calculates the radiation levels for a number of materials, under different conditions of irradiation and decay period after shut-down. The calculation is straightforward and is outlined in FSD/ING-25, along with a brief discussion of the limitations of the calculations. The results of the various calculations listed above are essentially similar, although they vary in detail.

²⁰ C. B. Fulmer, et al., Nuclear Instr. and Methods, 31, 45 (1964)

²¹ A Proposal for the Mc^2 Isochronous Cyclotron, report ORNL-3540, (1964)

²² M. Barbier, Private communication quoted in reference 20.

²³ M. Barbier, and A. Cooper, Estimate of Induced Radioactivities in Accelerators, report CERN 65-34 (Geneva 1965) and earlier reports in CERN series.

²⁴ G. Rudstam, Inorganic and Nuclear Chem. (to be published), quoted in reference 22.

²⁵ R. H. J. Bower and G. T. Ewan, Activation of Materials by High Energy Protons, report FSD/ING-25 (1965)

Table VIII. C.1 gives typical results for a series of materials calculated by Bower & Ewan. This table gives the calculated field in mR hr^{-1} at a distance of 10 cm from 1 g of the material after 6 months' irradiation by a flux of $6 \times 10^8 \text{ p cm}^{-2}$, i.e. $\sim 10^{-4} \mu\text{A cm}^{-2}$. The fields quoted are those calculated 100 hours after shut-down. It must be remembered that the mean free path of 1 GeV protons for activation is $\sim 100\text{-}150 \text{ g cm}^{-2}$ for most of these materials and so the levels will be considerably higher than given in Table VIII. C.1. In detailed calculations the distribution of activities and self-shielding effects must be considered. A typical result is given later.

Figs. VIII. 4 and 5 show the decay curves of the activation produced after 6 months irradiation, as a function of time after shut-down. For convenience in application to various geometries, these curves are expressed in terms of an activation parameter C. For example the field at a distance produced by a proton flux of $f \text{ cm}^{-2}$ is equal to

$C \times f \times \frac{1}{4\pi x^2} \text{ R hr}^{-1}$. The important features of these curves are the relative activation levels of different materials and the slow rate of decay of the induced radioactivities after shut-down. The latter is caused by the build-up of long-lived activities in long irradiations. For iron the level 10 days after shut-down is only $\sim 1/2$ that for 1 day after shut-down. Thus if the machine cannot be serviced a few hours after it is turned off, very little can be gained by waiting several weeks. Considering the absolute level per g of various materials and their decay curves, carbon and oxygen are the most suitable materials and calcium is better than aluminum or iron.

TABLE VIII. C. 1

RADIATION FIELDS FROM IRRADIATED MATERIAL	
<u>Material</u>	<u>mR hr⁻¹ at 10 cm per g</u>
Carbon	.021
Oxygen	.015
Aluminum	.090
Calcium	.016
Iron	.57
Copper	.48
Zirconium	.62
Bismuth	1.00

*In practice a large number of grams of material are activated. The mean nuclear interaction length of 1 GeV protons is $\sim 100 - 150 \text{ g cm}^{-2}$.

FIG. VIII. 4 Decay of Induced Activity in O. C. Ca and Al as a function of Elapsed Time after Beam Shut-down, following 6 months' continuous operation. (To obtain the exposure rate per gm in R/hr at any point, these numbers should be multiplied by the proton flux and the appropriate solid angle factor i. e. at distance X the field/gm is

$$F = C \cdot \frac{1}{4 \pi X^2} \cdot (\text{flux/cm}^2) \text{ in R/hr.}$$

FIG. VIII. 5 Decay of Induced Activity in Bi, Fe^{56} , Cu^{63} and Zr as a Function of Elapsed Time after Beam Shut-down following 6 months' continuous operation.

It is relatively simple to calculate the levels per g and the decay curves of the activation produced. The calculation of radiation levels in the machine is much more complicated because it depends on the detailed geometrical distribution of the machine components which can give γ -ray shielding, the angle of incidence of the protons on the material being activated (so that self-shielding effects can be estimated) and on several other effects. In addition, many of the spallation cross-sections are not known accurately and most values given in the literature are for thin targets, whereas in the machine the materials being activated are mostly thick and the secondary effects can be important. The limitations of calculations of absolute levels are discussed briefly in FSD/ING-25. It is estimated that if the geometrical distribution of machine components is specified, and the angle of scattering of the protons is known, it should be possible to estimate radiation levels to within a factor of 3.

As an indication of the levels to be expected, an estimate has been made of the field between the pole-faces of the machine, one week after shut-down following six months continuous operation. As pointed out above, the field one week after shut-down is not a large factor lower than that a few hours after shut-down. If $10 \mu\text{A}$ of the beam is scattered so that it falls uniformly over the pole-faces, the estimated field between the pole-faces is $\sim 1.8 \text{ R hr}^{-1}$, allowing for self-shielding effects. This is the order of magnitude of fields that could be encountered between the pole-faces while servicing the machine. If, as would probably be the case, the beam was not scattered uniformly there would be local hot-spots where the fields would be much greater.

It has been pointed out by Barbier that lining the machine with suitable material could reduce the radiation fields. He suggested either carbon or marble. By suitably positioning carbon blocks in the proposed machine it would probably be possible to reduce the fields by a factor of ~ 5 .

The best way of minimizing the activation levels is to design the machine so that the spill is as small as possible. The amount of spill that can be tolerated is extremely small and depends on the geometrical location. It is estimated that if $< 50 \mu\text{A}$ of the beam is spilled, the activation levels can be handled relatively easily, although there may be local hot-spots requiring special precautions. A spill of $\sim 50 \mu\text{A}$ could probably be tolerated in a suitably designed machine using carbon or marble absorbers as suggested by Barbier. If it is not possible to prevent a spill of $> 50 \mu\text{A}$ the activation problem would be extremely serious and could probably only be handled by use of complicated and costly remote-handling devices.

The estimates given in this section are only approximate. Significantly improved estimates will require a more detailed knowledge of the level and distribution of the proton beam spill in the machine. It may be necessary to do some experimental work on thick target yields and self-shielding effects.

2. Neutron Capture

There are two principal regions where activation by thermal neutron capture may be comparable with that produced by spallation reactions from high energy nucleons. The first region is the neutron experimental area where high fluxes of thermal neutrons emerge from the beam holes. The problems associated with these are similar to those encountered at NRU except that the beams will be ~ 50 times more intense. There is considerable experience at Chalk River in handling problems of this type. Experimental apparatus will have to be designed so as to minimize its activation.

A second source of thermal neutrons will be in the walls struck by high energy nucleons. Neutrons produced by spallation reactions can be thermalized in the walls and can escape into the room. The activation produced will depend on the material irradiated because thermal neutron capture cross-sections vary over a wide range. Cochran et al²⁶, when considering the radiation fields around the Los Alamos Meson Physics Facility, estimated that the level may be comparable to that produced directly by spallation reactions. The thermal neutrons from the walls can be greatly reduced by lining the inside surface with a good thermal neutron absorber. This procedure is recommended for regions in the ING facility where problems of this sort may be encountered.

3. Active Effluents

Some of the radioactivity produced in and around the neutron generator will require special treatment. This includes the volatile fission and spallation products in the target, and induced activities in the surrounding air, soil, cooling water, the CO_2 inert atmosphere, and the heavy water moderator.

The greatest source of volatile active products will be the thermal neutron facility target which is itself a high temperature liquid under operating conditions. Selected examples of volatile activities produced are; 4.2-day ^{124}I (30 mCi s^{-1}), 12.3-year tritium (4 mCi s^{-1}) and 18-hour ^{125}Xe (200 mCi s^{-1}). The cold trap in the target circuit will partially remove condensable products like iodine. In subsequent clean-up of the cold trap these products can be converted, when necessary, into solid wastes for disposal. The cold trap will not be effective in "freezing out" activities like tritium or some inert gases. Special adsorbents may be required to do this.

²⁶ D.R.F. Cochran, et al., Shielding Considerations for Proposed Los Alamos Meson Physics Facility, proc. First AEC Symp. Accelerator Radiation Dosimeters and Experience (1965)

The addition of a degassing unit to the lead-bismuth circulating system would permit the removal and dispersion of the volatile activities on a continuous basis, or else after one year of operation ~ 100 kCi of tritium would have built up in the target system.

The CO_2 blanket between the target tube and the moderator tank tube will be activated by the fast neutron flux. The only activity of concern is the 20-min. ^{11}C formed by the $^{12}\text{C}(n, 2n)^{11}\text{C}$ reaction. The saturation level for this activity in the CO_2 blanket will be ~ 60 Ci. The relatively short half-life of this activity suggests that, following a delay period, the filtered CO_2 gas could be vented.

Tritium will be produced by neutron capture in the heavy water moderator. Since the neutron flux in ING is a factor of 100 greater than in the NRX reactor, and the heavy water volume is about a factor of two less, a fifty-fold increase in tritium can be expected in ING. The special handling routine used for heavy water in the NRX reactor could be scaled up to meet the requirements for the ING system.

Activation of the air along the beam transport system and in the target vault will be caused by the presence of tritium, 2-min ^{15}O , 10-min ^{13}N , 20-min ^{11}C and 1.8-hr ^{41}Ar . In addition, 15-hr ^{24}Na , 2.6-hr ^{56}Mn and 53-day ^7Be activities will be carried by airborne dust particles. Assuming a spill of 1 μA of beam into an area where the average proton path in the air is 10 m then tritium production will be $\sim 2 \times 10^{-4} \mu\text{Ci s}^{-1}$. Since the maximum allowable concentration of tritium is $5 \mu\text{Ci m}^{-3}$, a very small airflow will suffice to control this activity. Estimates of the production of 20-min ^{11}C activity by such protons in the air indicate an equilibrium source of 0.1 Ci. Since the radiation fields in the beam transport and target areas will not permit the entry of personnel, it is advisable that these areas not be ventilated during operation of the machine. A suitable delay period, for radioactive decay of the short-lived activities, followed by filtered ventilation, would then be required before entry is permitted.

A continuous spill of 1 μA of 1000 MeV protons into the soil around ING would be expected to maintain a total source ~ 20 Ci of γ -ray activities with half-lives greater than one week. Such activities would form an integral part of the soil with a resultant high retention and would show only slow movements in the ground water. A possible exception is the ~ 10 mCi of tritium produced per day, but even this activity should not be a hazard if it is released because it will diffuse into a relatively large volume of air or ground water.

The target system maintenance in hot cells will require features similar to those used in handling irradiated reactor fuels; filters and traps for the volatile active gases and dust; active drains with water storage areas; and a waste disposal system for both liquids and solids of various radiation levels.

APPENDIX VIII.1

NEUTRON ATTENUATION WITH BUILD-UP

In general when long range secondary products are created in inelastic collisions, the attenuation is no longer exponential with distance¹³. If one makes the conservative assumption that all secondary neutrons emerge in the forward direction, then the effective attenuation factor A_n for neutrons in energy group n can be written as

$$A_n = e^{-\frac{x}{\lambda_n}} \left[N_n + \left(\sum_{i=1}^{n-1} \frac{N_i f_{in}}{\lambda_i} \right) \frac{x}{1!} + \left(\sum_{i=1}^{n-2} N_i \sum_{j=i+1}^{n-1} \frac{f_{ij}}{\lambda_i \lambda_j} \right) \frac{x^2}{2!} + \left(\sum_{i=1}^{n-3} N_i \sum_{j=i+1}^{n-2} \sum_{k=j+1}^{n-1} \frac{f_{ij} f_{jk} f_{kn}}{\lambda_i \lambda_j \lambda_k} \right) \frac{x^3}{3!} + \dots + \frac{N_1 f_{1,2} f_{2,3} \dots f_{n-1,n}}{\lambda_1 \lambda_2 \dots \lambda_{n-1}} \frac{x^n}{n!} \right]$$

where $\lambda_i = \frac{\lambda_{in}(E_i)}{1 - f_{ii}}$

$\lambda_{in}(E_i)$ is the non-elastic mean free path at energy E_i

N_i is the fraction of all neutrons incident on the shield in energy group i ,

f_{ij} is the number of secondary neutrons produced in energy group j by the collision of a neutron in energy group i ,

x is the shield thickness.

The expression for A_n given above must be modified if $x(\frac{1}{\lambda_i} - \frac{1}{\lambda_j})$ is not small, so as to take account of the neglect of the exponential factor in integrals like

$$\int x^n e^{-x} \left(\frac{1}{\lambda_i} - \frac{1}{\lambda_j} \right) dx$$

The estimate of A_n is conservative provided $\lambda_j > \lambda_i$.

Table VIII.1 lists the values of f_{ij} based on Bertini's copper data. Also listed are the λ_i values, based on the inelastic cross-section of iron but modified by the f_{ii} values taken from the copper data. Table VIII.1 also lists a representative incident spectrum N_i and the effective attenuation factors provided by 5.0 m of iron for each energy group.

This estimate ignores the secondary cascade proton component at all stages, but since the proton range is only 0.8 inelastic mean free paths at 400 MeV, falling to 0.3 at 200 MeV, and the number of cascade protons for neutrons incident is only 0.5 that of secondary neutrons, the error is not likely to be significant. It is difficult to estimate the error involved in assuming that all cascade secondary neutrons are emitted in the forward direction, but in spherical geometry the attenuation factors, at least for energy groups above 100 MeV, are expected to be reasonably good.

TABLE VIII.1

PARAMETERS FOR NEUTRON ATTENUATION

E_i Range MeV	350-	250-350	150-250	100-150	50-100	25-50	
N_i	.05	.08	.19	.18	.29	.21	
λ_i cm	19.0	20.0	20.6	20.7	16.6	11.3	
j	i f_{ij}	0	1	2	3	4	5
0		.08					
1		.24	.13				
2		.30	.31	.15			
3		.20	.22	.21	.16		
4		.30	.31	.32	.31	.17	
5		.28	.27	.26	.25	.23	.11
$A_i(500)$	1.8×10^{-13}	5.3×10^{-12}	6.8×10^{-11}	2.4×10^{-10}	3.0×10^{-10}	1.5×10^{-10}	

APPENDIX VIII.2

HEAT PRODUCTION IN ING SHIELDS

To estimate the heat production in thick ING shields, the following assumptions were made:

- 1) all the kinetic energy of evaporation neutrons and charged particles, and the direct γ -ray energy, are converted to heat at the point of the inelastic collision producing such particles,
- 2) the thermalized evaporation neutrons are all recaptured at their point of production,
- 3) the cascade protons release their kinetic energy to heat at the inelastic collision point,
- 4) the secondary cascade neutrons are all assumed to be at the mean energy for such particles, and to be emitted in the forward direction,
- 5) the inter-nuclear cascade collisions of the high energy neutrons are followed until the mean energy of the secondary cascade neutrons falls below ~ 20 MeV. At this point they are treated in the same manner as evaporation neutrons.

The spatial dependence of the heat production is then given by

$$H(x) = N_0 f(x) \cdot g(x)$$

where $f(x) = (P_1/\lambda_1) \exp(-x/\lambda_1)$ if only one collision is required

$$= (P_1/\lambda_1) \exp(-x/\lambda_1) + [N_1^s P_2 / (\lambda_1 - \lambda_2)] \cdot [\exp(-x/\lambda_1) - \exp(-x/\lambda_2)]$$

if two collisions are required and

$$P_i = N_i^e (\bar{E}_i^e + B.E.) + N_i^c \bar{E}_i^c + \gamma_i + N_i^s (\bar{E}_i^s + B.E.)$$

where the last term in the expression for P_i is included only for the final one of the i collisions required to reduce the mean secondary cascade neutron energy below ~ 20 MeV.

- N_i^e - number of secondary evaporation neutrons
- $\bar{E}_i^e$ - average kinetic energy of the secondary evaporation neutrons
- B. E. - binding energy of the neutrons in the capturing material
- N_i^s - number of secondary cascade neutrons
- $\bar{E}_i^s$ - average energy of the cascade neutrons
- N_i^c - number of secondary charged particles
- E_i^c - average energy of the secondary charged particles
- γ_i - is the direct γ -ray energy produced in the inelastic collision
- λ_i - is the inelastic mean free path for the (i-1) generation neutrons
- N_o - is the incident primary neutron current per unit shield area
- $g(x)$ - is the geometry factor, e.g., for spherical geometry $g(x) = [a/(a+x)]^2$ where a is the inside shield radius.

The most serious inadequacy of the above recipe is in the treatment of neutron thermalization and capture. The energy release in both neutron thermalization and capture will be peaked at cooling water channels and at other hydrogen enhanced regions that have been put in for thermalization purposes. This peaking will facilitate heat removal by the cooling channels but will require a more detailed analysis for the final shield design.

CHAPTER IX

SITE LAYOUT AND SERVICES

IX.1

A. REFERENCE SITE (T.A. Creaney, et al., The Shawinigan Engineering Co. Ltd.)	1
1. General	1
2. Site Requirements	1
3. Site Selection at CRNL	2
B. LAYOUT (G.A. Bartholomew, T.A. Creaney, et al., SECo)	10
1. Experimental Requirements (Plan)	10
2. Ancillary Facilities Requirements (Plan)	14
3. Elevation Requirements	15
C. BUILDINGS (T.A. Creaney, et al., SECo, R.D. Sage)	20
1. Design Considerations	20
2. Accelerator	25
3. Maintenance and Assembly Building	30
4. Low Energy Experimental Facility	30
5. Meson Experimental Facility	31
6. High Activity Tunnel	34
7. Beam Tunnel No.2	35
8. Hot Cells	36
9. Beam Tunnel No.3	36
10. Advance Power Technology	38
11. Resonance Neutron Facility	38
12. Thermal Neutron Facility Tunnel	38
13. Thermal Neutron Facility	38
14. Main Control Center-Offices and Laboratories	43
15. Auxiliary Buildings	43
D. SERVICES (R.D. Sage, J. Mullin)	45
1. Utilities and Auxiliary Services	45
2. Support Laboratories	60

IX. SITE LAYOUT & SERVICES

A. REFERENCE SITE

1. General

The proposed Intense Neutron Generator, like any other construction undertaking, must be engineered and costed in order to be considered for development by financing authorities.

The choice of geographical location for ING is a question to be decided later by the scientific research groups that intend to contribute to and utilize the research facilities provided by the machine.

To determine the engineering and operating problems associated with ING and to form a basis on which an estimate of capital and operating costs can be made, it is necessary to establish a reference site.

For the purpose of this study, it was decided that this site should be at Chalk River and located within the property boundaries of the CRNL establishment.

A list of ideal site characteristics was drawn up to satisfy engineering and future development requirements and a site was chosen to fulfill as many of them as possible.

As the study proceeded, certain requirements assumed greater importance than others. As stated in Section 3, the selected reference site is not now the best available at CRNL and other potential sites should be investigated if the Chalk River area is finally decided upon.

2. Site Requirements

An ideal site for ING (SOC reference design) is one that:

- 2.1 Is located in an area free of seismic disturbances.
- 2.2 Has accelerator foundation structures sufficiently distant from any source of appreciable vibration, for example -
 - 2.2.1 at least one mile from any railway;
 - 2.2.2 200-300 yards from a highway;
 - 2.2.3 approximately three miles from any rock quarry, mines or any other potential source of detonations.

- 2.3 Is sufficiently distant from radio communication centres or similar establishments to eliminate interference or nuisance from RF.
- 2.4 Is sufficiently distant from any neighbouring research establishments where delicate radiation measurements are carried out to minimise the effects of sky-shine.
- 2.5 Is so situated that neighbouring communities will not be subject to any risk of contamination from stack fumes carried by prevailing winds.
- 2.6 Provides an exclusion area with a boundary not less than $\frac{1}{2}$ mile from the plant.
- 2.7 Is in an area where leaching of the ground water activated by earth-shine or underground beam dumps would not contaminate local wells, streams or any source of drinking water.
- 2.8 Is near to an area suitable for the disposal of active waste materials.
- 2.9 Is in an area where a reliable power of 210 MVA at 80% load factor can be provided. (If possible from two sources.)
- 2.10 Provides 150 acres of flat land (approximately 15' variation in ground elevation considered reasonable) of which 55 acres (1400 x 1700') is required for ING and a further 95 acres for future development.

Several narrow strips of land of varying lengths up to 3000' are required for the resonance and thermal neutron flight paths.

- 2.11 Is located where there is a reasonably flat outcrop of competent bedrock free from abrupt changes in slope extending over an area large enough to support the machines' foundation structures. An overburden layer of up to 15' of sand or proximity to a sand source would be an advantage for the provision of cheap shielding material.
- 2.12 Is close to a source of water (river or lake) that could dissipate approximately 175 MW of heat, equivalent to a flow of 50,000 US gpm, with a temperature rise of 24°F. The elevation of the lake or river relative to the machine should be such that pumping costs would be small.

3. Site Selection at CRNL

3.1 Alternative Sites

FIG. IX. 1 Site Location.

Three possible sites Nos. 1, 2 and 3 were considered, within the CRNL boundary. An overriding feature that favoured the selection of the third as the reference site for ING was the space that it provided for future expansion.

As the study has proceeded it has become clear that the most important engineering requirement is that the SOC's should be founded directly on bedrock. It was considered that a future large diameter synchrotron, a possible facility in the expansion area, would not necessarily have to be located on flat ground but could be wholly or partly constructed below ground level. Surficial geological maps of the Chalk River area indicate several potential sites within or near to CRNL that may better suit the necessary site requirements for ING. It must be emphasized, therefore, that the selected site is not necessarily the best site within the boundaries of CRNL for the proposed ING.

3.2 Geology

3.2.1 General

An outline of the geological conditions expected in the Chalk River area has been documented. It is based on the work of Gadd¹, personal communications from members of the staff of the Geological Survey of Canada, general knowledge of what is to be expected in an area underlain by Precambrian rocks, and the sparse data obtained from the minimal program of diamond drilling and soil sampling carried out during the early winter of 1965-66². The G. S. C. has not, as far as can be ascertained carried out any detailed geological survey of the area.

Gadd describes the bedrock as follows:-

"Bedrock at the AECL plant and generally in the Ottawa Valley north of Pembroke is a complex of Precambrian rocks. Within the plant area most of the rocks are granitic (pink, red, grey granites, granite gneisses, splites and pegmatites). Also abundant are greenish grey metamorphic rocks of granitic composition; amphibolite lenses are few and small, but good.

¹ Gadd, Geological Aspects of Radioactive Waste Disposal, Chalk River, Ontario (Preliminary Report), February 1958.

² T.A. Creaney, et al., The Shawinigan Engineering Co. Ltd. ING, Site Layout & Services, Costs, Schedule & Alternate Linac FSD/ING-61, 1966 Section IX.A. 3.2.

examples are seen readily in road cuts along the the plant access highway. Few large masses of unfractured rock occur. Generally the bedrock of the area is much faulted and fractured, major faults trend northwesterly parallel to the Ottawa River and establish the major topographic control; there are very numerous cross-fractures."

Three bore-holes and one test pit were sunk in the vicinity of the reference site during December 1965 and January 1966 (see Fig. IX.2). As Borehole No. 65-3-2 was the only one in which bedrock was proved and as it was located in an area where topographical characteristics appeared to be fairly uniform, the information derived from it was used as a basis for the reference design. Core recovery from this hole indicated bedrock at a depth of approximately 50' with an overburden of very dense till and sand approximately 40' and 10' thick respectively.

3.2.2. Conclusions and Recommendations

For structures containing very sensitive equipment, such as the proposed ING, the foundation material should have the best dimensional stability obtainable. In the Chalk River area the most probable areas of most competent bedrock are those knolls or ridges of granitic bedrock where slopes are gradual and rounded and free from all abrupt changes in slope.

It is recommended that a geological reconnaissance be carried out in the general site area in order to delineate those areas of more favourable bedrock for the structure foundations. The more attractive of these areas should then be subjected to a detailed geological investigation to establish the competency of the rock.

3.3 Seismic Hazards

A broader appraisal of the seismic hazards that must be taken into consideration has been documented³.

The Chalk River area is underlain by Precambrian rocks which when unfaulted and unfractured are extremely competent and strong. The overburden in the area consists of glacial till, sands, gravels, and some silty clay. Data from the Dominion Observatory indicates that between 1961 and 1964 some 9 disturbances of magnitude up to 5.0 occurred in the Chalk River area.

3

T.A. Creaney, et al, The Shawinigan Engineering Co. Ltd. ING, Site Layout & Services, Costs, Schedule & Alternate Linac FSD/ING-61, 1966 Section IX.A.3.3.

No positive assurance can be given that any specific location in Canada will not, sometime in the future, be subject to a damaging seismic disturbance but the probability of a damaging earthquake occurring at a specific location or of a severe earthquake occurring close enough to a specific location, to cause damage to structures founded on or in sound igneous or metamorphic bedrock within the next 15 to 25 years is extremely remote. The Baie St. Paul area northeast of Quebec City and a zone along the islands of the Pacific coast are possible exceptions to this statement.

For an earthquake of a given magnitude, the extent of damage to properly designed and built structures is largely a function of local geology and there is no reason, based on seismic considerations, to eliminate the Chalk River area as a site for the proposed accelerator structures provided that they are founded in or on sound Precambrian rock of the area.

In view of the importance and the sensitivity of the proposed installation, it is recommended that appropriate seismic instrumentation be installed to monitor the bedrock response in the site area.

3.4 Reference Site

This site (see Fig. IX.1) approximately $3\frac{1}{2}$ miles northwest of CRNL and to the west of the old Mattawa road, was chosen as the reference site because it was considered to meet the basic requirements established at the outset of the study. Its greatest asset was the very large flat area that it provided for expansion.

Referring to the requirements listed in Section 2 in order.

- 3.4.1 All sites at Chalk River are within the same seismic zone. This site has no advantages over others in this respect although it is recognized that seismic effects are less severe on structures founded on rock than those founded on overburden material. (See Section IX.A.3.3).
- 3.4.2 The site is sufficiently distant from highways, railroads and quarries.
- 3.4.3 The site is at least $3\frac{1}{2}$ miles away from any centre using radio, and any RF interference can be reduced still further by good RF shielding.
- 3.4.4 This site is well remote from the existing facility to eliminate any problems of sky-shine.
- 3.4.5 and 3.4.6 There are no neighbouring establishments within $\frac{1}{2}$ mile of the plant.

FIG. IX. 2 Location of Boreholes.

- 3.4.7 Available topography indicates that ground water flow is directed away from the Ottawa River toward Maskinonge Lake to the SW.
- 3.4.8 Existing active waste disposal areas can be utilized.
- 3.4.9 HEPCO can provide power requirements from their plant at Rapids-des-Joachims 15 miles upstream.
- 3.4.10 Adequate flat land is available for the ING facility, with plenty of room for expansion.
- 3.4.11 This is the only requirement that cannot ideally be met at this site. Rock is approximately 50' below ground level so that special precautions in design will be necessary, particularly for the foundations of the SOC structures - which are sensitive to external vibrations.
- 3.4.12 Located $\frac{3}{4}$ miles away from the Ottawa River and 180' above it, this site permits the utilization of the river for the cooling water system. A better arrangement is the incorporation of a bank of cooling towers drawing their 'make up' water from the Ottawa River.

This site although $3\frac{1}{2}$ miles from the existing CRNL plant, can still draw on the existing facilities for its support services such as administrative offices, cafeteria, basic stores, library, transport, etc., although additional workshops, workshop stores and laboratories are required. All other utilities and support services are to be provided at the reference site as shown in Fig. IX.3.

FIG. IX. 3 Site Layout.

B. LAYOUT

The layout of the buildings comprising the full machine was chosen to meet experimental requirements. Offices, workshops, stores and other ancillary buildings were located around the machine to suit the requirements of operation and maintenance.

1. Experimental Requirements (Plan)

The layout of research facilities evolved as a compromise between requirements for large working areas, with large spaces between individual facilities, and the economic requirement to minimize the outlay of expensive items such as beam transport magnets and special shielding.

The principle considerations governing the size and placement of research working spaces are that adequate space be available not only for the fully developed facility as presently conceived but also for expansion, particularly of facilities in fields which are expected to grow rapidly. For example, it is anticipated that the number and variety of experiments and the number of people involved in meson physics will show a rapid increase when intense proton beams become available. Other activities which may undergo rapid expansion are resonance neutron physics, nuclear power technology, and development of new proton accelerating structures. At a still later stage of development, the storage ring for pulsing the thermal neutron target will require space comparable with that occupied by the third stage SOC, and a synchrotron ring, for accelerating part of the beam to high energies, would occupy a still-larger area. A second consideration in providing adequate space between facilities is to cut down background effects between one experimental area and another, by reducing solid angles and by leaving room for thick shielding walls where required. For example, it is conceivable that neutrons generated in the meson, fast neutron, or resonance neutron targets could cause serious background problems for some experiments in the thermal neutron experimental area.

Among the main items that affect the cost of transport systems are quadrupole magnets, bending magnets, splitters, and heavy shielding. It is important to keep the numbers of these items to the minimum consistent with satisfying the space requirements.

1.1 Full Machine

Figure IX. 4 (including areas outlined with broken lines) shows the overall plan of the ING project . Details of the beam tunnels and

G.A. Bartholomew, "ING Layout Requirements", FSD/ING-32, 1966.

FIG. IX. 4 General Arrangement of Machine.

experimental areas are shown in Figures IX.9 - 12, Section IX. C. The considerations underlying this layout for the experimental areas may be summarized as follows:

- a) The output from stage 1 may be diverted completely (by a bending magnet) or in part (by a beam splitter) to the low energy experimental area. It is anticipated that this area may be particularly useful for preliminary tests during commissioning of stage 1. It may also be used with a split beam, on a regular basis, after all stages are operating.
- b) The output from stage 2 may be diverted directly to the meson area by a bending magnet and a transport system not shown in Fig. IX.4. This system, or alternatively a transport that bypasses stage 3 and delivers the output of stage 2 into the main beam tunnel, may be very useful for initial commissioning tests of stage 2. In subsequent operation, a permanent splitter in the stage 2 - stage 3 transport could be used to deliver a 400 MeV beam to the meson area.
- c) The main proton beam, beam No. 1, proceeds directly from the accelerator exit to the thermal neutron facility. In the high-activity tunnel it passes through one or more thin (transmission) meson targets which absorb approximately 1% of the current. Subsidiary beams, No. 2, supplying the pulsed meson and fast neutron areas and No. 3, the resonance neutron and nuclear power technology areas, are split off from beam No. 1 by a system of two two-way beam splitters (Section VI.H. 2), operating in series. The approximate beam current requirements for the various targets are summarized in Table IX.1. The combination of two splitters shown in Figs. IX.9 and XI.11 appear to be the most direct way (involving a minimum of beam transport components) for supplying the required beam currents to all five areas in simultaneous operation.

TABLE IX. 1

Target	Required Proton Beam Current	Beam No.
Thermal neutron	~65 mA	1
Transmission meson	~0.6 mA	1
Pulsed meson	~1 mA	2
Fast neutrons	~1 mA	2
Resonance neutrons	~50 μ A	3 a
Nuclear power technology	~0.1 μ A	3 b

- d) The transmission meson targets in beam No. 1, the first beam splitter, and the pulsed meson targets in beam No. 2 are all sources of extremely high radiation fields and are enclosed in massive shielding (Section VI. I). Less shielding is required for the unimpeded beam No. 1 in the thermal neutron facility tunnel and for the relatively low-current beam No. 3. The proposed layout therefore effectively groups together areas requiring remote handling tooling, hot cells, and other special equipment.
- e) Beam No. 2 serves meson experimental areas on both sides of No. 2 beam tunnel. Room is available for expansion of both floor areas to meet future demand.
- f) The length of beam transport No. 3 between the two splitters, is set at 200 ft. to allow room for eventual expansion of the meson area to the east side of beam No. 1 and to provide ample clearance for any facility which may eventually make use of beam No. 3C (Figure IX. 11) which is at present unassigned.
- g) The length of the thermal neutron facility tunnel is set at 300 ft to help reduce background in that area, as discussed above, and to allow room for installation of a storage ring between the high activity tunnel and the thermal neutron area.
- h) The research laboratories and offices are placed near the meson and thermal neutron buildings to provide ease of access for the greater number of personnel. As a further reason for this arrangement, it is anticipated that recently developed techniques for guiding very low energy neutrons through internally reflecting pipes over long distances² may be used to conduct beams of neutrons from the thermal neutron facility to low-background laboratories in the laboratory building.
- i) The flight paths, up to 1 km long, for both the resonance neutron target and for the projected pulsed-mode application of the thermal target driven by the storage ring, are arranged to make use of the same terrain. Space for some 6 to 10 flight paths of various lengths, from a few meters to 1 km, is required around the resonance neutron target building; only four flight paths are shown as part of the Full Machine, Fig. IX. 4.

2

H. Maier-Leibnitz and T. Springer, Reactor Sci. and Tech.

J. Nuclear Energy Parts A and B, 17, 217 (1963).

- j) A rectangular space 4000 ft. by 1500 ft. to the south of the accelerator complex in Fig. IX. 1 is reserved for future injector development and for the possible future high energy accelerator and experimental area discussed in section XIII. D.

1.2 Basic Machine

The basic plan (accelerator plus beam transport and experimental areas shown by full lines to the right of the accelerator exit tunnel in Fig. IX. 4) is the facility required at the commencement of operations. The experimental areas include the low energy experimental area, the thermal neutron building, and the pion channel facility. (Fig. IX. 9). It is anticipated that the resonance neutron time-of-flight facility, the advanced power technology facility, the fast neutron area, the muon channel and other meson facilities will be added as required over a period of about five years following start-up. These additions will be accompanied by expansion of the main offices and laboratories building. No attempt is made in this report to detail the order in which these various facilities will be added.

2. Ancillary Facilities Requirements (Plan)

The main considerations in selecting the layout of ancillary facilities (Fig. IX. 3) are as follows:

- a) The complex is located on the reference site to meet anticipated needs of future expansion, ancillary buildings being located away from areas around the machine where flight paths could eventually be incorporated.
- b) Where resonance neutron flight paths traverse the road, an earth fill ramp is provided, with the flight tube passing through culverts in the ramp to permit the circulation of traffic at all times. The two 3000 ft. flight paths run parallel to each other at the same level and in the same direction.
- c) Advantage is taken of local topographical conditions to locate the stack on a hill at the north end of the site. Both the stack and cooling towers are positioned to take advantage of the prevailing northwest wind in order to reduce nuisance from both active gases and vapour. Foundation drains are provided around all buildings constructed below grade. These drains lead to a sump at the south end where the water is pumped into a surface ditch draining towards Maskinonge Lake.
- d) The main office block containing laboratories and main control centre is located to the west of the machine between the thermal neutron and Meson facilities. An underground passage connects these three latter buildings. Sufficient area is left to the south of the office block for future expansion.

- e) The 230 kV switchyard is situated in the southwest corner of the site to meet the high voltage transmission lines from the west. Workshops, workshop stores and lunchroom are centrally located on the west side of the machine near the main access.
- f) Main access to the plant is via the old Mattawa road which is widened to suit traffic requirements between CRNL and Deep River. Paved roads are provided around the plant, together with hardstandings and carparks. The entire plant is to be fenced in with a single entrance at the centre of the west end.
- g) A pump house on the bank of the Ottawa River supplies the make-up water for the cooling system and normal needs of the plant. A water treatment plant adjacent to the thermal power plant provides demineralized and drinking water to the facility.

3. Elevation Requirements

A longitudinal section through accelerator and experimental facilities (fig. IX. 5) shows the variation in level of the beam from the pre-injector to its main destination in the target of the thermal neutron facility.

The elevations shown are applicable to the reference site only. Ground levels at each particular building will be graded to suit. The beam leaves the pre-injector building (Fig. IX. 6) horizontally at EL 544' -6" after which it is bent downwards to EL 536' -6" whence it passes into and around the stage-1 SOC, leaving horizontally at the same elevation at 50 MeV through a tunnel to enter stage-2 SOC through its outer ring wall. (see Fig. IX. 7). Part of this beam can be directed into a low energy experimental building located between stages -1 and -2. It is again bent downwards to EL 526' -6" moving into and around this SOC from which it passes, through the outer ring wall, to stage-3, at 300 MeV. Here it enters under the outer ring wall of stage-3, is bent upwards to EL. 549' -0", orbits the stage-3, and passes into the high activity tunnel four feet above floor level, at 1000 MeV.

A maintenance and assembly building serves each stage of the accelerator and is linked to them by large tunnels for equipment access.

Experimental beams, from the pion and muon targets located in the high activity tunnel, will be directed into the meson experimental building at the same level. Supplementary beams Nos. 2 & 3 will also travel at the EL 549' -0". (see Figs. IX. 9 and 11 for

FIG. IX. 5 Longitudinal Section along Beam.

FIG. IX. 6 Stage 1 SOC & Pre-Injector Building Plan & Section.

details of layout of meson experimental building, beam tunnel No. 3 and facilities.)

Still at the same level the main beam passes through the high activity tunnel into the thermal neutron facility tunnel at the end of which it is bent upwards at 20° through the thermal neutron facility building to the centre where it is directed downwards into the target. The six experimental beams from this facility are located at EL 551'-0", six feet above experimental floor level. Each of these experimental beams is provided with a beam stop and two stops are removable for neutron flight experiments.

The relative levels of the floors of the structures are approximately as follows:

Pre-Injector	EL. 531'-6"
Stage-1 SOC	529'-0"
Stage-2 SOC	519'-0"
Stage-3 SOC	541'-6"
Main Beam Transport	545'-0"
Meson Experimental Bldg.	545'-0"
Thermal Neutron Facility	545'-0"

C. BUILDINGS

This section describes the main buildings of ING, their general arrangement, design considerations and loading, together with a brief description of shielding materials.

1. Design Considerations

1.1 Introduction

The design of buildings for ING will follow accepted relevant codes and practices of the engineering industry.

This section deals with some of the more unusual aspects of their design and outlines methods for solving the various problems. The greatest single problem is in the design of the SOC foundations where fine tolerances govern the types of foundation system to be utilized. It was mentioned in subsection IX. A. 3 that another site could be found within the property boundaries of CRNL that would satisfy more completely the present site requirements; in particular one that would provide, without caissons, a direct support to bedrock for the accelerator foundations. In this case it is unlikely that an expensive isolation system, such as that at present devised for the SOC's, would be required.

1.2 Machine Foundations

1.2.1 Separated Orbit Cyclotron

Small relative movements between the foundations of the different stages are not significant because minor correcting magnets in the connecting beam transport tunnels can adjust the beam. However, because the magnets in the individual cyclotrons have to be aligned to about 0.01", the machine foundations have to be extremely stable. Misalignment could be caused by gradual movements, such as settlement, shrinkage, creep, and expansion or contraction of foundations from changes in temperature and ground water level, or by sudden movements such as the vibrations from earthquakes, detonations, nearby traffic, etc. Seismic trips will be installed so that the beam is cut off immediately an intolerable disturbance begins, but it is necessary that the SOC should not normally be misaligned.

To satisfy these requirements, an isolation system has been devised for the reference design.

The steel framework which supports the SOC magnets and cavities bears upon a concrete ring beam, which in turn is supported by spring assemblies incorporating load adjusting devices and dampers. The beam is stiff, so that distortions caused by non-uniform load distri-

bution above, or non-uniform support distribution below, are kept to tolerable limits. There is one bank of springs for each magnet and all banks sit on an annular pile-cap, supported on large diameter caissons to bedrock. The pile-cap itself is a rigid circular beam. (See Fig. IX.8).

The heat transfer to the ring beam from machine components will not be constant over its surface, so it will be necessary to circulate water around it, to minimize temperature gradients and the resultant distortions. In order to eliminate non-uniform shrinkage initially, several equal segments of the beam, with gaps of about 4' between them, will be poured at roughly the same time. After initial shrinkage has taken place, the locking segments will be poured. A substantial part of the shrinkage must be completed before construction of the SOC starts - this could take many months. A ring beam constructed in structural steel appears to offer several advantages over one in reinforced concrete but this has not yet been studied in sufficient detail.

When considering the effects of seismic disturbances, the caissons and pile-caps, the isolation system and ring beam, and the steel framework supporting the SOC must be considered together, since each has its own fundamental periods of vibration. Each isolator has three fundamental periods: vertical, horizontal, and rotational, and if any of these frequencies coincide with that of an earthquake, then the vibration would be amplified. In order to support the ring beam uniformly, a load-sensing and a levelling sub-assembly will be incorporated in each isolator. The ring beam will then be uniformly supported automatically, even if the pile-cap should sink slightly because of alterations in the length of the caissons. Special horizontal and vertical dampers will be installed to reduce vibration of the ring beam.

The borings for the caissons will be large enough for a man to inspect the rock surface at the bottom. To reduce the vibrations, a 4" layer of isolating material will separate the caissons from the surrounding glacial till. Although present studies indicate that the isolation system should be wholly satisfactory, this is by no means certain. Additional safeguards may be required to control the thermal movement of the caissons. The caissons must be of equal length to minimize differential creep and thermal movement, the concrete must be uniformly graded, and the caissons may require to be cooled throughout their lengths. To preserve dimensional stability of the ring beam pile-cap system, reinforced concrete 'spokes' may be required.

1.2.2 Beam Transport

No special foundations are required for the beam transport system because the line of the beam can be adjusted by correcting elements.

FIG. IX. 8 Stages 2 and 3 SOC Sections.

1.2.3 Thermal Neutron Target

The foundation structure for the heavy thermal neutron target is supported on a heavily reinforced thick circular mat bearing on glacial till. The bearing pressure is limited to 5000 psf so as to restrict settlement to tolerable limits. This structure is independent of the rest of the surrounding foundation structure of the thermal neutron facility.

1.3 Building Foundations

As the reference site is covered with an overburden of glacial till with an assumed bearing capacity of about 10,000 psf it is not necessary to transfer the weight of any building structures to rock.

The foundation of the separated orbit cyclotron and thermal neutron target buildings are designed to restrict settlement to acceptable civil engineering tolerances.

The foundation walls and floors of these structures will be constructed as completely integrated units as a precaution against seismic disturbances. Special expansion joints are to be made between the foundations of the main SOC vault and those supporting the machine, to permit independent movement.

The foundations for all of the other buildings are conventional strip or spread footings. Careful field investigation is needed to ensure that no pockets of sand or other unacceptable material occur in the overburden since, although it may generally indicate sufficient bearing capacity, compaction may occur under load, resulting in cracks in the concrete.

Drains will be installed around all buildings that are constructed below grade to lower the watertable and prevent seepage into the building.

1.4 Building Superstructures

1.4.1 Introduction

The provisions in the National Building Code of Canada can be adopted as the minimum design criteria, and will be applicable to such conventional buildings, as warehouses, the meson buildings, etc. More detailed analysis will be required for all unconventional buildings.

1. 4. 2 Separated Orbit Cyclotron

As the ring buildings are approximately square in cross section and are surrounded by sand fill, they are very prone to damage from earthquake. Detailed calculations will be necessary to find the natural period of oscillation of the building and the surrounding sand.

By compacting the sand well, both its temporary and permanent movements will be substantially reduced. Stiffening the walls will increase their resistance to earthquakes. Above the cranes at the springing line, reinforced concrete beams serve to restrain the arch and walls during and after the placing of the sand fill. These beams also serve to stiffen the walls against any sudden earth movements. Uniform placing of the sand fill around and over the structure is an important requirement of construction.

1. 4. 3 Beam Transport Tunnels

Similar comments to those for the SOC buildings apply to beam transport tunnels which consist of concrete walls, surrounded by sand. The sections made of pre-cast beams and blocks require further consideration, in that good, positive connections must be made to prevent slight relative movements (from earthquakes) which could perhaps cause damage to plumbing, remote handling equipment, etc. These connections should be very easy to fit and remove.

1. 4. 4 Thermal Neutron Facility

Those parts of this structure whose failure could cause a nuclear incident will be designed to withstand the maximum conceivable earthquake. This includes all pumps, piping, etc., that carry dangerously radio-active liquids such as lead-bismuth eutectic. Even so the lead-bismuth will be dumped immediately the beam is cut by the accelerators seismic trip.

1. 5 Shielding

Generally, it is more expensive to attain a certain neutron attenuation by using a small thickness of a dense material (e. g. iron, or heavy concrete) than by using a greater thickness of a fairly light material (e. g. sand). Therefore, whenever there are no space limitations and it is not necessary to have only a small thickness of shielding, light materials are used. Steel is used for certain shielding doors because they are more convenient than thick, cumbersome concrete doors.

1.6 Earthquake Design Procedure

1.6.1 Introduction

As the reference site is an active seismic zone, careful consideration of the effects of ground disturbances is necessary. The static method of analysis of the 1965 National Building Code of Canada is considered adequate for the conventional buildings, but for certain structures, notably the thermal neutron facility, the SOC foundations, and all underground buildings, it is recommended that a detailed dynamic analysis be carried out.

1.6.2 Design Criteria

Smith¹ has estimated past accelerations at Chalk River to have reached something in the order of .035 g. The acceleration of the rock suggested by the National Building Code, about 0.10 g, should be assumed whenever there is no danger of a nuclear incident occurring. However, for zone 3 conditions, it does not seem advisable to use an acceleration of less than 0.2 g for equipment items of major importance.²

1.6.3 Design Methods

1.6.3.1 Static Analysis

This method is described in the National Building Code. The stresses given by this analysis can be taken as the minimum to be used for design and are applicable only to conventional structures.

1.6.3.2 Dynamic Analysis

A dynamic analysis can be used for all structures which cannot be analysed sufficiently by a static method and involves the use of response spectra curves.

2. Accelerator

The accelerator building characteristics described hereunder apply only to the SOC; the characteristics of the alternative linear accelerator are outlined in section XIV. D of this report.

As stated in section IX. C. 1 the selection and design of the support structures for the linac injector, magnets and cavities require a great deal of consideration and study. The following description of these supports is purely tentative and applies only to the reference site.

¹ W.E.T. Smith, Dominion Observatory, private communication.

² Nuclear Reactors and Earthquakes, USAEC, Publication No. TID-7024

2.1 Pre-Injector Building

The building that will house the pre-injector system (see Fig. IX. 6) is formed in two parts - one containing the injectors and their support services and the other an annex containing a room for ion source testing equipment, control room and cable vault.

The main building, 115' long 42' wide and 44' high, is divided into 5 sections - two containing ion source equipment (2200 sf), symmetrically opposed about the centre-line of the linac injector and divided by the injector passage, a mechanical services area and electronics shop. The floors are at EL. 531'-6".

The mechanical services area (1100 sf) and loading bay (200 sf) are located at one end of the building, and the electronics shop (500 sf) at the other. The mechanical services area also provides services for stage-1 SOC and permits access to one of the RF galleries. A 5-ton overhead travelling crane covers these areas and the pre-injector rooms.

The building frame is constructed in structural steel supported on concrete spread footings. The roof is constructed with steel 'Q'-decking supported by steel trusses. The walls are built of reinforced concrete, the two end walls being utilized as buttresses to the retaining wall adjacent to stage-1 SOC building. In order to maintain dust proof conditions the walls and ceiling of the ion source chambers are lined with aluminum sheathing, the ceiling being so formed that it can be removed in sections for maintenance or repair. The floor is finished with an epoxy resin.

The annex projects from one side of the main pre-injector building, with a floor at or near ground level, containing a control room (1500 sf), ion source test room (400 sf), an office, and a basement. The basement contains an electric cable vault (1700 sf) and corridors providing shielded access to the main pre-injector building. This building is constructed of reinforced concrete with block walls and brick facing above grade.

The floor and roof are of reinforced concrete.

2.2 Stage-1 SOC

The vault containing the linac injector and stage-1 SOC (50 MeV) (see Fig. IX. 6) is separated from the pre-injector building by 17' of sand shielding. The adjacent reinforced concrete retaining walls of both structures are connected by tie walls for stability. The vault (92' long x 69' wide x 49' high) and its RF galleries have sand for a biological shield. The floor of the vault at EL. 522'-0", built in

reinforced concrete, is constructed separately from the foundations of both the linac and SOC and each of these has a separate foundation.

The barrel vault roof spans the 69'0" width of the building and supports the sand shielding above. Reinforced concrete beams provide the necessary restraint during and after construction. The reinforced concrete walls supporting the roof are supported on concrete strip footings. All interior surfaces are suitably coated with epoxy resin to reduce dusting.

A 25-ton overhead travelling crane runs the length of the vault.

The linac injector is supported on a braced steel framework on a reinforced concrete mat.

The foundation structure of the SOC is an arrangement of reinforced concrete caissons taken down to rock, topped by a circular reinforced concrete pile-cap finished at floor level. One pile is provided under each 32-ton magnet.

The components of the SOC are supported on steel braced frames bearing on a large circular rigid reinforced concrete disc, separated from the pile-cap by a specially designed isolation system (see Section IX. C.1).

RF equipment and DC power supply equipment for the magnets are contained in a single storey structure (1680 sf), floor EL. 534'-0", and a two storey structure (3752 sf) with lower floor at EL. 520'-6". All concrete surfaces are treated with epoxy to prevent dusting. The RF gallery and vault are separated by sand equivalent to 8' of heavy concrete. The equivalent of 11' of heavy concrete is provided between the vault and areas where continuous access is required.

A curved tunnel 11'-0" above vault floor level allows access for equipment on a trolley from the maintenance and assembly building. No special shielding is required because of the bend in the tunnel. All mechanical services are housed in the pre-injector building and a heavily shielded maze provides access to the SOC from this area.

2.3 Stage-2 SOC

The structure containing the components of stage-2 SOC (300 MeV) (see Figs. IX.7 and IX.8) is an annular vault (with a barrel roof of reinforced concrete), at a lower level than that of stage-1, and is also shielded with sand over and around it. The dimensions of the

building are as follows: external radius 60'-6", internal radius 10'-6", height from floor to springing line of the roof 55'-0", rise of arch of the roof 10'-0". Reinforced concrete tie beams span the vault at the springing. The floor is at EL. 509'-0".

The external walls of reinforced concrete are supported on spread footings and the internal walls on a circular slab. The floor is integrated with the internal and external wall footings.

As with stage 1, the foundations of the SOC rest on bedrock through a system of reinforced concrete caissons which puncture the floor slab of the vault and are completely separate from it. A continuous reinforced concrete pile-cap ring is superimposed on the caissons. A pair of caissons is provided under each 220-ton magnet.

The components of the SOC are supported on steel braced frames bearing on a large continuous rigid reinforced concrete ring beam separated from the pile-cap by an isolation system (see section IX. C. 1). All interior concrete surfaces are treated with epoxy resin to prevent dusting.

Equipment in the vault is handled by a 100-ton overhead travelling crane.

The RF and DC power supply equipment is housed in a gallery 17'-0" wide by 22' high (not shown to scale in Fib. IX. 8) at EL. 512'-0", which almost encircles the SOC vault.

All interior concrete surfaces are treated with epoxy resin. Sand shielding equivalent to 11' of heavy concrete is provided between the vault and the RF gallery, and 14' of heavy concrete between the vault (and the output beam tunnel) and areas of continuous access. Shielding between the gallery and input beam tunnel consists of structural heavy concrete and iron blocks and that between the gallery and output tunnel of massive heavy concrete.

The inner wall of the vault is 2'-0" thick of heavy concrete and shields the vacuum system contained inside. A bench mark to rock is also located at the centre of the structure. The central area, inaccessible during the machine's operation, is served by an elevator with access from the top of the mound formed by the sand shielding. A cable operated trolley down the slope to the maintenance and assembly building provides access and assists maintenance and repair.

Equipment access to the main vault is provided by a tunnel at EL. 533'-0", leading from a pit in the maintenance and assembly building, which leads into a platform located inside the vault on the same radial line as one of the magnets.

A steel shielding door at the vault end of the tunnel reduces activity but does not permit personnel to work near to it. A separate door is located at the other end of this tunnel to prevent access during the machine's operation.

A separate entry for personnel is provided along a separate passage incorporating a maze.

The beam tube from stage-1 SOC passes along a tunnel at EL. 536'-6" through the outer vault wall and across the vault of stage-2 SOC horizontally 10'-0" above the centre line of the machine. It is then bent by an achromatic magnet down through a half turn in a vertical plane, into the SOC. The beam leaves through the outer vault wall into another tunnel EL. 526'-6" at right angles to the inlet beam. All cooling and ventilating equipment for this stage is located in the maintenance and assembly building.

2.4 Stage 3 SOC

Similar to the previous stage, the vault of stage-3 SOC (1000 MeV) (see Figs. IX. 7 & IX. 8) is built at a higher elevation (floor 531'-6") and has internal dimensions external radius 93'-0", internal radius 43'-0" and height 55'-0".

Construction details are the same as for stage 2 building but the overhead crane has a capacity of sixty tons because the magnets are smaller (145-ton).

The equivalent of 12' of heavy concrete shields the RF gallery from the main vault, and the equivalent of 16' of heavy concrete shields areas of continuous access from the main vault. There is 4' of heavy concrete between the main vault and the vacuum pump room, so that immediate access to the pumps can be gained when the machine is stopped. A central elevator leads to the pump room, but does not travel to the bottom of the shaft where a bench mark to rock is situated. Sand shielding is used around all the walls and over the roof. Massive heavy concrete is used between the input tunnel and the RF gallery, and reinforced heavy concrete and iron is used between the output tunnel and the RF gallery.

The RF gallery, housing the RF and DC power supply equipment, is 26'-0" wide by 22'-0" high (not shown to scale in Fig. IX. 8), with an internal radius of 117'-0". The cross-section is rectangular and a row of columns supports the middle of the roof. The floor is at EL. 527'-0".

The input tunnel is horizontal and passes through a gap in the RF gallery and under the floor slab of the vault between the

caissons. Access to this section of the tunnel can be gained by lifting removable floor slabs. The beam is bent by an achromatic magnet through a half turn in a vertical plane, into the SOC.

The equipment-removal tunnel at EL. 553'-0" leads to the main floor of the maintenance and assembly building. A separate personnel entrance incorporating a maze is provided.

All mechanical services are located in the maintenance and assembly building.

3. Maintenance and Assembly Building

This is a building with a conventional structural steel super-structure, 100' long, 85' wide and 47' high (see Figs. IX.7 & IX.8). Three tunnels enter the building, one from each SOC vault. The tunnel from stage-3 enters at floor level EL. 553'-0", and those from stage-2 and stage 1 enter 20' below. A door is provided in front of each tunnel to prevent entry during operation. Foundations are conventional strip and spread footings, which are lower near access tunnels than elsewhere. The surrounding ground is made up to floor level, so a 12'-0" reinforced concrete retaining wall is required.

This wall is higher where the foundations are lower and where sand shielding from the SOC buildings abuts against the side of the building. The basement area formed by these retaining walls can be utilized for storage.

The maintenance and assembly area is 100' long by 60' wide and is serviced by a 100-ton overhead travelling crane. The mechanical services area is 100' long by 25' wide and is serviced by a 5-ton monorail. A loading bay and double door truck entrance is provided at the end of the building.

Dimensionally stable concrete pads are provided for the setting of the magnets.

4. Low Energy Experimental Facility

This is a fully air-conditioned laboratory (80' long by 40' wide), with a conventional structural steel superstructure. Where the sand shielding for the SOC vaults is adjacent to the walls, a reinforced concrete retaining wall is provided. Foundations for the retaining walls are strip footings, and those for the superstructure are spread footings.

5. Meson Experimental Facility

This building (see Figs. IX.9 & IX.10) designed for experimental use of secondary beams taken from the main 1000 MeV proton beam, is built adjacent to the high activity tunnel containing the main 1000 MeV beam (beam no. 1) and beam tunnel no. 2 (beam no. 2). The high activity tunnel lies at one end of the building and includes two hot cells in the corner nearest to the accelerator exit tunnel. Beam tunnel no. 2 is located along the centre of the building and at right angles to the high activity tunnel.

The meson building is divided into three 100' bays; the central bay, at the end of beam tunnel no. 2, is 180' long, the bay nearest to the thermal neutron facility is 337' long. Two 45' x 100' areas at the end of these bays are utilized for mechanical and electrical services equipment. The bay 202' long nearest to the accelerator exit tunnel is the only part of the meson building incorporated in the basic facility. The building superstructure is constructed in structural steel, the roof adjoins the high activity tunnel and beam tunnel No. 2 and is supported by steel trusses supported on steel columns spaced at 45' centres and founded on isolated concrete footings. The building will provide a clear work area for experiments.

Each bay is serviced by a 25-ton overhead travelling crane with a 5-ton auxiliary that can service the whole length of the building and is capable of handling beam channel and experimental shielding blocks.

The roof of the building consists of an insulated fire-proof steel deck supported on purlins and stringers formed into a grid smaller than the width of the steel sheets, so that in the event of an explosion, large sections of roof cannot fall back into the building and further damage experimental equipment. The roof will be sloped from the centre of each bay for drainage purposes. Large fans will be incorporated in the roof structure that will operate in unison with fast operating truck doors should quick purging of hydrogen from the building be required.³

The exterior walls of the building will be sheathed in insulated steel siding and provided with high level translucent panels for maximum utilization of natural light. Truck doors 16' x 20' are provided in the exterior walls for access to the experimental hall and to the mechanical and electrical service areas.

³ M. S. Livingston, report on accident to CEA, Proceedings, Vth International Conference on High Energy Accelerators, Frascati, 1965.

FIG. IX. 10 Meson Experimental Bldg. Sections.

The floor of the experimental building at EL. 545'-0" is a reinforced concrete slab constructed on a specially prepared sub-grade capable of supporting loads of 10,000 psf. The surface is treated with an epoxy resin to reduce dusting.

A network of trenches, linked to the service areas, is provided for mechanical and electrical services. These trenches are spaced at 45' centres and are 6' wide and 8' high, narrowing to a width of 4'-0" at experimental floor level. Special removable steel beams will be provided to span these trenches to support any arrangement of experimental shielding blocks.

The trenches will normally be covered with reinforced checker plating. Access to these trenches can be obtained from either the service area or from the experimental hall adjacent to the service area. These trenches are also linked by an underground passage to the thermal neutron facility, offices and laboratories.

An elevated observation gallery is provided around the building to permit movement from one experimental area to another and to assist in the planning of the layout of new experiments.

6. High Activity Beam Tunnel

The high activity beam tunnel (see Figs. IX.9 & IX.10) is located at the end of the meson experimental building between the accelerator exit tunnel and thermal neutron facility tunnel, and for the full machine will be built to contain a beam splitter and two targets (pion & muon).

The tunnel is 25' high, 20' wide and approximately 300' long. The walls and roof are of cellular reinforced concrete construction filled with sand 35' and 25' thick respectively. The latter thickness is sufficient to prevent skyshine but does not provide adequate personnel protection against radiation above the tunnel. Those sections of the wall through which the pion and muon channels pass are left free to receive concrete shielding blocks which can be handled by a travelling gantry crane supported on the walls of the tunnel at the roof level of the meson building. Each of these wall sections is provided with a removable roof. Any section of the wall can be broken out and new beam channels can be installed. The inside wall surface is lined with marble or graphite blocks 1' thick.

A special arrangement of heavy concrete and steel blocks is provided where the pion and muon channels leave the main tunnel. These are arranged to give sufficient shielding of the experimental hall.

Midway along the tunnel two secondary tunnels branch off - one at right angles into beam tunnel no. 2 of the meson experimental building, and the other at 45° into beam tunnel no. 3 leading to the resonance neutron and advanced power technology facilities.

In the basic facility, only the pion channel is provided, and the remainder of the high activity tunnel is built like the thermal neutron facility tunnel except that the reinforced concrete walls and roof supporting the sand shielding are formed in weatherproof pre-cast units which can be dismantled to permit expansion.

A remote controlled 10-ton overhead travelling crane is used to handle beam transport equipment including quadrupoles, targets, and beam splitter. It will also lift iron blocks used as local shielding around targets and the splitter.

A "Scorpion" type remote controlled manipulator mounted on a bridge utilizes the same crane rail system. The manipulator is provided to help adjustment or maintenance of any of the components of the beam transport ion optical system. Television cameras are mounted at 50' intervals along the tunnel and two cameras are located on the manipulator for the guidance of the operator.

Two trolleys are provided - one at the junction of the high activity tunnel and beam tunnel no. 2 and one at the hot cell to remove 'hot' pieces of equipment to the cells at the end of the high activity tunnel.

7. Beam Tunnel No. 2

This tunnel (Figs. IX.9 & XI.10) (not included in the basic facility), is located along the central bay of the meson experimental building and at right angles to the high activity beam tunnel. It is approximately 180' long and has the same cross-section as the latter tunnel. Beam no. 2 terminates in an underground beam dump at the end of the tunnel. The beam dump is basically a steel beam catcher made up of a steel tank about 6' diameter and 9' high holding steel plates around which cooling water is circulated. The room containing the beam dump at EL. 526'-0" has heavy concrete walls 10' thick to reduce radiation contamination of the surrounding soil. Access to this facility is provided from one of the galleries in the floor of the meson experimental building.

Sections of the cellular walls of beam tunnel no. 2, similar to the high activity tunnel, can be broken out and beam channels added at a later date when required.

Handling facilities will be provided similar to those of the high activity tunnel.

8. Hot Cells

Two hot cells are located at the accelerator end of the high activity tunnel (see Fig. IX. 9). Access to these hot cells from this tunnel is through three steel shielding doors which lead to an isolation room in front of the cells. Active equipment can be carried into either cell on a rail-mounted trolley. Shielding doors separate the isolation room from the hot cells. Another steel shielding door at the end of the isolation room permits access to the working area around the hot cells.

Each cell is 10' square and 15' high. The walls are 3' thick heavy concrete, and incorporate two shielding windows. To give total coverage of the cell floor area, each cell is provided with two master-slave manipulators and a 2-ton overhead travelling crane.

Only one cell is provided in the basic machine.

9. Beam Tunnel No. 3

The secondary proton beam to the advanced power technology and resonance neutron time-of-flight facility (see Fig. IX. 11) is transported through a tunnel made of reinforced concrete (not included in the basic facility).

The 8' wide 10' high tunnel has a 6' thick floor slab and is shielded by sand. This sand can be replaced by 8' thick heavy concrete units for future expansion of the meson experimental facility. At approximately 65' from the high activity tunnel the tunnel broadens to 25' to include a splitter similar to that in the main tunnel. This wider section of tunnel extends for a further 100' before branching to the advanced power technology and resonance neutron facility. Access to beam tunnel no. 3 is provided through a wall by a steel-shielded door.

The two branch tunnels (3a and 3b) are similar in construction. They are 8' wide and 10' high and are made of reinforced concrete and shielded with 12' of sand.

All these tunnels are serviced by a 10-ton monorail used to transport quadrupoles and local iron shielding blocks. A maze-type access tunnel is provided to the branch tunnel leading to the advanced power technology facility. A service tunnel joins the two facilities and is provided with a truck door to facilitate removal of equipment.

FIG. IX. 11 Beam Tunnel No. 3 - Plan & Section.

10. Advanced Power Technology

The facility is housed in a structural steel framed building 55' long, 40' wide, and 40' high (see Fig. IX. 11), similar in construction to the meson experimental building. It is serviced by a 20-ton overhead travelling crane and has a 16' x 20' truck door. In the centre of the building at the end of the branch tunnels is an area 15' square, surrounded by iron walls 6' thick and covered by a heavy concrete roof 8' thick. A pit 19' deep is provided in the floor of the building to contain experimental equipment.

11. Resonance Neutron Facility

This is a reinforced concrete box structure 20' long, 12' wide, and 12' high (see Fig. IX. 11). The walls and roof are 4' thick, covered by 12' of sand shielding. A 6' x 8' concrete beam stop is placed at the end of the structure in the beam path. Four beam tubes of various lengths pass through the structures at various points within an arc of 180° for time-of-flight experiments, with provision for additional tubes.

The time-of-flight tubes pass over open ground cut or filled as required. The tubes will be supported on piers on footings founded below the frost line. Where the tubes traverse a road, the road will be ramped and the tube passed through a culvert. The beam tubes will terminate in small experimental buildings.

12. Thermal Neutron Facility Tunnel

This tunnel between the high activity tunnel and thermal neutron facility is 350' long (in the full facility) (see Fig. IX. 12), 15' wide and 20' high. The reinforced concrete walls and roof are 18" thick and the floor slab is 3' thick. Shielding is provided by 15' of sand all around the tunnel. No remote handling equipment is required, but a 10-ton monorail will cover its length and switching devices will allow it to enter a maze on one side which provides entry from the outside. A concrete beam stop is placed at the end of the tunnel where the beam is bent upwards at 20° into the thermal neutron facility. That part of the high activity tunnel, which in the basic facility is replaced by an extension of the thermal neutron facility tunnel, is formed in easily dismantled pre-cast concrete units.

13. Thermal Neutron Facility

The thermal neutron building will house the thermal neutron target, experimental facilities, and auxiliary equipment (see Figs. IX. 13 & IX. 14). The building will occupy an area 230' x 180' (41,400 sf) and will be divided into two levels. The main floor will be at EL. 545'-0" and

FIG. IX. 12 Thermal Neutron Facility Tunnel Plan & Section.

FIG. IX. 13 Thermal Neutron Bldg. - Plans.

will contain the main target assembly, shielding, experimental facilities, local control room, offices, and storage area. The basement floor at EL. 513'-0" will contain the lead-bismuth circuit, moderator circuit, cobalt circuit, shielded cooling pumps and heat exchangers, maintenance facilities, locker rooms, and two hot cells.

The main experimental floor area is 180' x 180' with the shielded target assembly at the center (net area 31,000 sf). An area 50' x 180' (9000 sf) at the west end of the building is set aside for a local control room, (1250 sf), storage area and double door truck entrance (5250 sf), and offices (2500 sf). An area 80' square around the main target shield will take floor loadings up to 8000 psf, whilst the remainder of the experimental floor will be limited to 2000 psf.

The main building frame and roof will be structural steel and will be divided into three bays: two of 50'-0" span, each served by a 50-ton overhead travelling crane and a central bay over the target of 80'-0" span, serviced by a 30-ton overhead travelling crane. The central bay will extend over the storage area at the west end of the building to allow for easy movement of equipment between this storage area and the main target assembly in the centre of the building.

An isolated truck entrance will be provided at the south end of the storage area to allow movement of vehicles into and out of the building without causing drafts and large losses of heat which might disrupt experiments. Truck doors at the corners of the experimental floor will permit occasional movement of large pieces of equipment into the experimental area. A large removable slab in the floor of the storage area and a service elevator will permit transfer of equipment between the main floor and the non-active basement floor area. A 20' x 20' storage block for active apparatus is also provided in this storage area. Two further removable slabs are provided in the experimental floor for access to active basement areas.

The office wing at the main floor level will contain a number of offices for experimenters, shift supervisors, health surveyors, and a locker and shower room for personnel working on this floor.

The foundation structure is divided into two separate rafts, one of 75' diameter carrying the main target assembly and the other carrying the remainder of the building.

The basement area is divided into three separate sectors:

- a) The lead-bismuth area containing lead-bismuth pumps, maintenance area and heat exchangers.

- b) The heavy water area containing the heavy water moderator pumps and heat exchangers, the heavy water-cobalt pumps and handling equipment, and heavy water maintenance areas.
- c) The clean maintenance area containing mechanical, electrical, and instrument shops.

The floors, walls, and ceilings of all potentially active areas will be coated with epoxy resin to provide a smooth, impermeable surface which may be easily cleaned if it becomes contaminated. Radiation monitors are provided at all exits from active areas.

14. Main Control Centre - Offices & Laboratories

This building containing the main control centre, offices, and laboratories for the scientific and technical staff is described under Section IX. D. 2 (see Fig. IX. 17).

The building is a four-level structure with foundations and basement below grade constructed of reinforced concrete. The upper floors are framed in structural steel with pre-cast concrete panels and aluminum window walls. Interior walls will be formed with steel partitions as required. Future underground tunnels from the basement area will connect with the meson experimental and thermal neutron facilities.

The building is provided with all the necessary services and is air conditioned.

15. Auxiliary Buildings

15.1 Workshops

Small maintenance shop facilities are provided in each of the mechanical service areas to handle routine and radioactive work. In addition, one central workshop of approximately 12,000 square feet is provided for moderately sized machines. It contains mechanical, electrical, instrument, and carpenter shops to handle large work including assemblies and modifications. Two 20-ton cranes are provided.

There is a separate building of approximately 4000 sq. ft. for workshop stores with a monorail.

15.2 Gatehouse & Lunchroom

Two gatehouses are provided - one (400 sq. ft. in area) situated along the old Mattawa road on the boundary of CRNL property

at Balmer's Bay. The other gatehouse (3000 sq. ft.) is situated at the main entrance to the complex. A small 40' x 60' lunchroom is centrally located within the complex and has services for minor lunchbar facilities.

The construction of auxiliary buildings is very conventional. Buildings such as workshops, lunchroom, emergency and stand-by power station and turbine structures will be constructed of structural steel supported on concrete foundations with steel wall cladding. Buildings such as water and sewage treatment plants will be of reinforced concrete construction below grade.

D. SERVICES

1. Utilities and Auxiliary Services

Sections IX. D 1.1, 1.2, 1.3 and 1.4 deal with the electric power supply. Further details are given in another document¹.

1.1 Electric Loads

The most important load is the group of RF chains which represent about 80% of the total for the basic facility. The second largest load is drawn by the full meson facilities. Both above groups will use power mainly in the form of DC.

Most of the power will be purchased from the Hydro Electric Power Commission of Ontario (HEPCO). About 10 MW will be generated at the facility by the two 6.25 MVA generators of the target heat recovery system.

1.2 Electric Power Supply

The power requirement during construction is about 4 MVA. When stage-1 SOC is in full operation, the total power requirement is about 16 MVA. It is proposed that power be transmitted from the present CRNL power network over a 34.5 kV overhead transmission line to provide power for both construction and stage-1 SOC.

For stage-2 and stage-3 SOC a higher supply voltage is necessary. HEPCO will provide power by two 230 kV transmission circuits. (Fig. IX.15). The load at the 230 kV, 5000 MVA bus is:

- a) 130.3 MVA at 0.954 lagging power factor for the basic facility;
- b) 204.8 MVA at 0.927 lagging power factor for the full facilities.

The single line diagram of the facility conforms to HEPCO for requirements a) for maximum voltage dip during RF crow-bars and b) for power factor under normal operating conditions. The permissible harmonic level will be specified later by HEPCO.

For the basic facility, three main transformers will step down the voltage from 230 kV to 34.5 kV. For the full facility, one more main transformer is required. If one main transformer is lost, the remaining transformers plus the 34.5 kV line connected to the present CRNL power network will have sufficient capacity to provide full load power for the facility.

¹ T.A. Creaney et al, The Shawinigan Engineering Co. Ltd. ING, Site Layout & Services, Costs, Schedule & Alternate Linac, AECL document FSD/ING-61, 1966, Section IX. D(i).

Power will be distributed on three different voltage levels (short circuit levels in brackets):

- a) 34.5 kV (1500 MVA symmetrical),
- b) 4.16 kV (250 MVA symmetrical),
- c) 600 V (50 MVA asymmetrical).

1.3 AC Electric Power Distribution

No load is connected directly to the 34.5 kV system, which is mostly fed from the 230 kV system. The 34.5 kV switchgear is of the metal-clad design and located in the 230 kV outdoor switchyard (Fig. IX.16). The remainder of the required power will come from the present CRNL network, and from the generators of the thermal power station via two 34.5 kV - 4.16 kV transformers.

Distribution of power at the 34.5 kV level is achieved by an underground duct system.

From the 34.5 kV level, power is provided:

- a) through rectifier transformers for the three SOC stages and the meson facilities.
- b) through unit substations for the 600 V level (auxiliary services, individual loads of small power).

The 4.16 kV system is normally self-sufficient and provides power for motors of large size and for loads which require Class 3 power. All the latter loads are connected to 600 V. The 4.16 kV distribution system is located partly outdoors, in ducts.

The 600 V system receives power -

- a) from four unit substations fed from the 34.5 kV system (for the full facilities, five substations are required);
- b) from two 4.16 kV - 600 V substations located at the thermal power station (most of the emergency loads will normally receive power from this source);
- c) from the secondaries of the two 34.5 kV grounding transformers.

Almost the entire 600 V distribution system will be installed indoors.

1.4 Construction, Emergency and Standby Power Supplies

1.4.1 Construction Power Supply

See section IX. D. 1. 2.

FIG. IX. 16 Electrical Power Supply - 230 kV Outdoor Substation
with 34.5 kV Metal-clad Switchgear.

1.4.2 Emergency Power Supply

Emergency power is required if all the utility power fails, to enable the safe shutdown of the machine and to operate certain essential services. The estimated total emergency load is about 1000 kW.

Some of the loads that require emergency power are connected to the 600 V AC system under normal conditions. Power will be provided for them through two transformers rated 1 MVA each, from the 4.16 kV system of the thermal power station (Section IX. D. 1. 3).

During the first few seconds of a total power failure, the kinetic energy of flywheels will provide the required torque for certain essential motor loads. After a few seconds, the required 1000 kW is available from the four units of the emergency diesel power station. This power source may be rated Class 3. A very small portion of the emergency power supply (mostly lighting and instruments), will be normally supplied from small rectifiers connected to the two transformers mentioned above. On the failure of the AC power supply, these loads will be switched over to 125 V batteries. This power supply may be rated Class 1.

1.4.3 Standby Power Supplies

Standby power is required, - estimated load shown in brackets -

- a) during scheduled shutdowns (5 MW);
- b) during the buildup of the electric load when the purchase of the next main transformer is not justified (10 MW);
- c) during a total 230 kV power failure, when more power is required than can be provided by the diesel units (5 MW).
- d) when one main transformer out of four is lost (10 MW).

The above power requirements may be met by utilizing the power available from present CRNL facilities (Section IX. D. 1. 2).

Unfortunately, the above power source may fail at the same time as the 230 kV supply. Hence, as a reliable power source of about 5 MW is required at all times, an oil fired system is installed in conjunction with the turbine generator units at the thermal power station. This power source will be available in about five minutes. The extra capital cost is modest.

1.5 Cooling Water System

1.5.1 Introduction

ING will dissipate about 175 MW of heat when fully developed. Although means are being studied of recovering some of this energy, the cooling system must be capable of rejecting the full amount.

A reference site has been chosen which is 180 ft. above the level of the Ottawa River. Pumping large quantities of water at this pressure is clearly expensive, and so a study² has been carried out to determine the most economic cooling method, by comparing the cost of direct river water cooling with (a) lake cooling, and (b) cooling towers.

For the reference design, a cooling system using four forced draft cooling towers has been adopted but subsequent study suggests that a lower operating temperature of the machine components such as RF tubes and cavities may be required. This cannot be achieved with a cooling tower system but could be obtained from a river water cooling system.

1.5.2 Cost Comparison

	<u>Direct River</u>	<u>Cooling Towers</u>
Capital Cost	1, 811, 000	1, 495, 500
Running Cost (capitalized)	346, 400	330, 000
TOTAL	2, 157, 400	1, 825, 500

1.5.3 Conclusions

The above figures indicate that the capital cost of a cooling tower installation is less than that of pumphouse and piping for conveying river water to the ING site, and that the operating cost of the towers is slightly lower.

To keep the total cost as low as possible, the ING design study is based on the use of cooling towers.

1.6 Demineralized Water Systems

1.6.1 General

The rectifiers, RF amplifiers, magnets, cavities, and all experimental areas are served by separate closed loop demineralized

² ibid. Section IX. D. (i) 1.5

water cooling systems. To reduce the length of pipes the cooling equipment is grouped together in mechanical services rooms which are located as close as possible to the areas to be served. Service tunnels are used to penetrate the thick shielding walls. Where this is not possible the pipes are cast into the walls.

1.6.2 RF Cooling System

This loop consists of a head tank, main circulating pumps, emergency circulation pumps, heat exchangers, water purification equipment and interconnecting piping and valves.

The RF tubes require water of low conductivity. Part of the cooling water is therefore circulated continuously through a water purification loop, consisting of oxygen exchange resin beds, mixed bed demineralizers and micro-filters.

The inlet water temperature to the RF tubes will be 104°F, the outlet temperature 122°F. Since the RF tubes are very sensitive to over-heating, emergency cooling will be provided.

To maintain the purity of the water and to improve the life of the water purification equipment, all piping will be tin-lined. All other wetted surfaces will be of stainless steel.

1.6.3 Magnet Cooling System

The water for the magnet cooling system must have the same high resistivity as that in the RF cooling circuit. The magnet-cooling loop can therefore be branched off the RF cooling system. Main circulation pumps, heat exchangers, head tank and water purification equipment will be common for both systems. The cooling water temperature will be 104°F at the magnet inlet and 115°F at the outlet. To minimize the variation of the temperature from point to point in the magnet, a counter-flow system is used. All piping will be tin-lined and all wetted surfaces, other than in the magnets itself, will be of non-corrosive steel.

1.6.4 Cooling System for Cavities

This loop consists of a head tank, inhibitor injection unit, circulation pumps, heat exchangers, cartridge-type filters and interconnecting piping and valves. The system will be filled with demineralized water to which an inhibitor such as hydrazine has been added. The pH-value of the water will be controlled by adding inhibitor.

The whole cooling system, including the cooling channels on the cavities, will be made of carbon steel.

1.6.5 Cooling of Vacuum Pumps

The cooling water for the vacuum-roughing pumps will be tapped off the cavity cooling system after it has passed through the cartridge-type filters.

1.6.6 Temperature and Pressure Control

The water temperature in the cavity and magnet cooling system will be controlled within very close tolerances. The output temperature is sensed and a signal is generated, which, by a controller, regulates the cooling water flow through a flow control valve.

The same device is used to control the cooling water temperature through the RF tubes and through the RF transmission lines.

A control valve is installed in the raw water line at the heat exchanger outlet in order to maintain a nearly constant water temperature in the main inlet headers of the various cooling circuits. Its operation is controlled by a temperature sensing element in the line at the output of the circulating pumps.

Each cooling system has a pressure control valve in the main inlet header.

1.6.7 Location of Cooling Equipment

As mentioned earlier, the cooling equipment for the various cooling circuits will be grouped together in certain areas close to the equipment to be cooled.

Pumps, heat exchangers, head tanks and water purification equipment, for the cooling systems in the injector areas and in stage-1 will therefore be located in a room inside the pre-injector building. The equipment for the cooling systems in stages-2 and -3 will be located in the maintenance and assembly building.

1.6.8 Cooling System for Beam Transport

The focusing magnets, beam splitters and bending magnets along the main beam tube and along the experimental beam tubes are cooled by demineralized water which is circulated in a closed loop. The water will contain an inhibitor such as hydrazine.

The cooling equipment will be installed in rooms in the target area and in the meson building, as close to the main heat sources as possible.

1.6.9 Cooling System for Experimental Facilities

The cooling capacity of the beam transport cooling system will be designed to allow for taking off branches, for cooling experiments located in different areas.

Where larger cooling capacities are required, or where the cooling water is likely to become radioactive, a separate closed demineralized water loop will be used. The equipment will be grouped together in rooms in the thermal neutron target area or in the meson building.

1.6.10 Demineralized Water Make-up System

A central demineralized water make-up plant will be provided. This building will contain a combined potable water and demineralized water plant. The plant will be capable of producing 25 US gpm of potable water and 5 US gpm of demineralized water continuously. The raw water will be pumped from the river. There will be sufficient storage capacity to cope with a peak demand.

1.7 Heating and Ventilation Systems

1.7.1 General

The following buildings will be air conditioned: pre-injector building, stage-1, -2, and -3, beam transport tunnel, beam tunnel no. 2, beam tunnel no. 3, high activity tunnel, thermal facility tunnel, and office building.

The meson area, part of the target area, the maintenance and assembly building, and auxiliary buildings such as work shops, will be heated with wall mounted unit heaters and ventilated as required to dissipate internal heat gains.

For the reference site the heating and air-conditioning systems will be based on an outdoor temperature of -40° F in winter and 95° F in summer.

1.7.2 Air-conditioning Systems

The air-conditioning systems will be designed to dissipate internal heat gains and to maintain the all year round constant temperature which is specified for the different areas. The design will be based on 10% fresh air and 90% recirculated air.

Stand-by fans will be installed to ensure full operation of the systems at all times. The exhaust air from all systems will be routed to a common stack.

1.7.3 Radioactive Contaminated Areas

All radioactive contaminated areas such as hot cells, target cells, beam splitters and rooms which contain radioactive cooling equipment will be provided with an exhaust ventilation system to maintain a negative pressure of one inch of water gauge with respect to adjacent non-active areas in order to prevent contamination of those areas with radioactive air.

The exhaust rate will be large enough to prevent a build-up of radioactive gases. All air exhausted from the cells will be filtered with "absolute" type filters before it is released, together with the exhaust air from non-active areas, through a common stack.

The make-up air will be taken from adjacent non-radioactive areas, following the contamination zoning principal of maintaining an air flow from less active to more active areas. The air exhaust and make-up systems will be fitted with two fans, one operating, one stand-by, to ensure safe operation of the systems.

1.7.4 Design Conditions

1.7.4.1 Pre-Injector Area

This area will be air conditioned to dissipate internal heat gains. The air temperature will be maintained at a nominal 75° F dry bulb and will not fluctuate more than plus or minus 0.5° F.

The recirculation will be rated at 9 air changes per hour. Since the operating voltage of the pre-injector is very high, good dry air insulation is required and a dehumidification system will be provided to keep the relative humidity below 40%.

1.7.4.2 Stages -1, -2, and -3 SOC

Each of the three stages will be air conditioned to dissipate internal heat gains. The air temperature will be maintained at 75° F dry bulb and will not fluctuate more than plus or minus 0.5° F.

The recirculation system will be rated at 9 air changes per hour and the relative humidity will be kept below 60%.

1.7.4.3 Beam Transport Tunnels

The heat gains along the beam tunnel will be dissipated by an air conditioning system. A dry bulb temperature of 75 °F will be maintained in all areas. This temperature will not fluctuate more than plus or minus 1° F. The recirculation system will be rated at 9 air changes per hour and the relative humidity will be kept below 60%.

1.7.4.4 Meson Area

The meson area will not be air conditioned. Wall mounted unit heaters will be used to maintain a comfortable temperature in winter and a ventilation system will ensure sufficient fresh air supply to all parts of the building. The outdoor and recirculation air will be filtered to remove dust.

Areas near the meson channels which are likely to become radioactive will be shielded by heavy concrete blocks and will be connected into the air conditioning system of the high activity tunnel which discharges the air through "absolute" type filters via the stack as described earlier.

Provision will be made to install additional purge units in some parts of the building where hydrogen gas is likely to be present. In the event of a major escape of hydrogen gas the whole building can be purged by roof mounted fans in less than 5 minutes.

1.7.4.5 Thermal Neutron Facility

The thermal neutron facility will be divided into active and non-active sections. All non-active rooms such as work shops and corridors located in the basement will be air conditioned. The active areas will be heated and ventilated as described earlier.

The main experimental hall will be heated by wall mounted unit heaters and ventilated to supply fresh air to all parts of the building and to dissipate internal heat gains. Ventilation will be rated at 9 air changes per hour with 90% recirculated and 10% fresh air. The temperature will be set between 70° F and 75° F dry bulb. The outdoor air will be filtered before entering the building to remove dust. The exhaust air will be discharged together with the exhaust air from all other buildings through a common stack.

Parts of the main experimental hall can become slightly radioactive if the target tube has to be changed. A local emergency purge system will then be brought into operation to prevent spreading of radioactive contaminated particles. It will exhaust into one of the exhaust ducts of the ventilation system serving radioactive areas.

1.8 Sewage Treatment Plant

The sewage treatment plant will be located at the south end of the site. The unit will be designed for a daily capacity of 15,000 US gallons and consist basically of a tank subdivided into an aeration, a settling, and a chlorine contact section.

The plant will be guaranteed to reduce the influent BOD (Biochemical Oxygen Demand) by 85% minimum.

The treated effluent will be discharged into Maskinonge Lake.

1.9 Active Liquid Waste Disposal

1.9.1 General

A closed active drain tank and a closed active sump tank will be provided in the basement of all buildings where radioactive contamination of the water is likely to occur. The drain tank will be used if a cooling system has to be emptied for maintenance and the sump tank is to collect all radioactive leakage water from the cooling systems or radioactive effluents from the various laboratories. The water collected in the sump tank will be pumped periodically to decay tanks.

Since the reference site chosen for the ING project is very close to the Chalk River Nuclear Laboratories, it has been decided not to provide a local treatment plant for radioactive liquid wastes for ING but to use the already existing plant at Chalk River. Therefore only storage tanks will be installed at the ING site to let the radioactive effluents decay. After sufficient time of decay the liquid waste can be carried away by a shielded tank car and processed at the Chalk River treatment plant or it can be disposed of, if the radioactivity level is low enough, in the Ottawa River.

1.9.2 Decay Tanks and Active Liquid Storage Tanks

The radioactive liquid wastes originate mainly from two sources, leaks from cooling systems and drains from laboratories or hot cells. These waters will be stored in different tanks, depending on the level of radioactive contamination.

There will be four tanks, two of 10,000 gallons and 2 of 3,000 gallons. They will be grouped together in a water-proof concrete pit at the north end of the ING site.

1.9.3 Tritium Contamination

Special consideration must be given to the formation of tritium in the target area.

One way of lowering the level of tritium contamination in a cooling system is by diffusing continuously a small quantity of tritium contaminated water into the ventilation exhaust system and disposing of it, together with the exhaust air, through the stack. This method has been proposed for the Los Alamos Linear Accelerator.

If it is decided that tritium should not be discharged into the atmosphere, the tritium water could be routed to a decay tank and later processed in the existing liquid waste system.

1.10 Heat Recovery System

1.10.1 The Recovery of Energy From the ING Target

A great deal of the energy contained in the ING proton beam will appear as heat in the liquid metal target, and must be dissipated continuously. The lead-bismuth eutectic will be run at a sufficiently high temperature (approx. 850°F) to justify an examination of the economics of recovering this heat by raising steam to be used in a conventional turbo-generator.

A number of considerations will affect the final choice of system. For example, it may be necessary to devise a heat storage system which will maintain the eutectic at a high temperature after the beam has been shut off. Safety may preclude a high-pressure secondary coolant on the grounds that a heat exchanger leak could force the eutectic back into the evacuated beam tube. The present report is not concerned with detailed design and leaves these considerations to Chapters VII and X, but it has been shown³ that the extra cost of power generation equipment is very quickly recovered by the savings in power which it permits.

Two basic approaches were considered; the direct generation of steam in a eutectic-to-water heat exchanger, and the introduction of a closed intermediate circuit containing:-

- a) Pressurized water
- b) Sodium-potassium eutectic
- c) Mercury
- d) Organic fluids

³ T. A. Creaney et al., The Shawinigan Engineering Co. Ltd., ING, Site Layout & Service, Costs, Schedule & Alternate Linac FSD/ING-61, 1966.

1. 10. 2 Comparison of Systems

The results of calculations to find the power available and its costs are summarized in Table IX.D. 2.

TABLE IX.D. 2

	<u>Pressurized Water</u>	<u>NaK</u>	<u>H_g</u>	<u>Direct System</u>
Capital Cost of System	1, 839, 500	2, 900, 000	3, 425, 000	1, 975, 000
Power Available/kW	8, 505	9, 065	9, 050	9, 420
Capital Cost/kW net output	216	320	379	210
Power Cost $\$5.71 \times 10^{-3}$ /kWhr				

The direct steam generation recovery system is the most advantageous because of its high power output and its comparatively low costs, and is therefore incorporated in the reference design. Technical arguments in favour of an intermediate system are presented in Section VII. A. 3.

1. 10. 3 Stand-by Power

The estimated cost of \$210.00/kW for power produced by the direct steam generation system is only theoretical. The actual figure will be less since the heat recovery system can be used as an emergency stand-by system. The cost of the diesel-generators which would be needed if the heat recovery system were not installed must be taken into account.

The direct steam generation system comprises a Pb-Bi/ water-steam-generator, 2 turbo-generator sets each rated 6, 250 kVA, an oil-fired boiler, which can be connected to either turbine in case of power failure, feed-water preheaters, deaerator, condensate and feed-water pumps as well as interconnecting piping and valves.

The power needed for the whole plant in case of a major power system failure is estimated to be between 4, 000 and 5, 000 kW. This is about the rating of one steam turbine.

Hence, either one of the two turbines can be used to generate stand-by power. Only a boiler with the necessary auxiliary equipment, large enough to supply steam for one turbine, will be required

as additional equipment. To ensure full reliability of the stand-by system, the boiler must be kept on hot-stand-by at all times to allow for a short starting-up time (5 min.). This can be done by circulating hot feedwater through heating coils inside the boiler steam drum. This, however, will only be necessary during the summer months, since during the winter months the boiler will be used for heating purposes and will be hot. For this purpose a pressure reducing and a desuperheating station will be provided at the steam outlet of the boiler.

To arrive at a true price for the installation of the heat recovery system, a price for the stand-by diesel sets must be evaluated.

Two diesel-generators (completely installed, cooling systems and electrical switchgear included) having a total net output of 4710 kW would cost \$705,000. The building would cost \$100,000 for a total of \$805,000.

The net capital cost for the heat recovery system therefore is \$1,170,000.

The value of generated electricity can be taken as \$376,000/year. Therefore the heat recovery system will be paid off after:

$$\frac{1,100,000.}{376,000} = \text{approximately 3 years.}$$

1.10.4 Conclusions

Detailed design work is necessary to develop suitable heat exchangers but it is clear that a heat recovery system is economically justified. The same system is used as a source of stand-by power, utilizing an oil-fired boiler, in place of the diesel engines which would otherwise be required.

2. Support Laboratories and Facilities

Figure IX.17 shows a possible layout for a building to serve as the main office building for ING. It provides space for the Main Control Room for the accelerator and for Data Processing Centres as well as making adequate provision for offices, laboratories, libraries, conference rooms and services.

The following table, which uses a scale of 1" = 64' for the drawing, gives the distribution of space in the building. With an occupancy of 300 a provision of approximately 500 sq. ft. of gross space per person is made.

<u>Classification</u>	<u>Total Space</u> (in sq. ft)	<u>Number of Units</u>
Office	29,568	142
Secretarial Offices	2,240	17
Libraries	3,328	6
Labs	22,848	23
Conference & Committee Rooms	4,224	6
Auditorium	5,760	1
Service Rooms	12,672	8
Shops	2,432	3
Control Rooms	6,016	2
Computer Rooms	7,680	4
Stores	2,816	6
Wash & Locker Rooms	5,760	8
Projection Room	256	1
Dwg. Off. & Tracer's Off.	4,096	2
Central Registry	768	1
Photographic Lab	384	1
<hr/>		
Total "Used" Space	110,848	
Total "Gross" Space	147,456	
Percentage Utilization	75

NOT TO SCALE

FIG. IX. 17 Main Control Centre, Offices and Laboratories.

CHAPTER X

HAZARDS

(J. C. Brown)

A. SAFETY SYSTEMS	X.1
1. Equipment Safety	1
2. Personnel Safety	5
2.1 Access Classifications	5
2.2 Basic Personnel Security System	6
2.3 High Hazard Areas	6
2.4 Medium Hazard Areas	10
2.5 Low Hazard Areas	11
2.6 Radiation Level Data Handling	11
2.7 Remote Handling Equipment	11
B. RADIATION HAZARDS	13
1. Introduction	13
2. Hazards from Routine Operation	14
3. Hazards from Accidents	15
4. Failure of the Pb-Bi Circuit	18
5. Suggested Safeguards	19

X. HAZARDS

A. SAFETY SYSTEMS

1. Equipment Safety

Safety has been defined as "the condition of being free from harm or risk of harm to life and property"¹. As a consequence of the public interest and concern for safety in nuclear reactors, there has evolved a considerable technology on safety systems. All seek to embody the following design features^{2, 3} to varying degree:

- Fail safe designs
- Provision for monitoring and test circuits
- Redundancy in the form of identical parallel signal channels with coincident circuits for comparison between these channels
- Highly reliable components

In so large a system as ING where the beam power is in the same order as that of many reactors, considerable attention must be devoted to the design of a safety system. Since extensive computer control is proposed, (Sec. VI.5), the possibility of using alarm information derived from input signals by the monitoring computer will be tempting. Such data is essential to decision making in the regulation computer but its use in a safety system would violate the redundancy principle since the separate identical signals would have to pass through a single component even though the reliability characteristics of this component, the monitoring computer, may be extremely high. Fig. X.1 shows a compromise arrangement in which the safety channels are independent of the output alarm data from the control computer. The latter is used because it provides more information on the status of a given parameter than is available from the safety channel (two states - safe or unsafe). The safety channels have been separated into two groups, i.e. those providing the rapid shutdown required by beam faults and those providing a programmed shutdown when the time responses of the systems involved are sufficiently long as to permit a much slower reduction of beam power. A slow shutdown is desirable, to reduce the disturbance to the Hydro system when a large portion of the total load is dropped. Information handling would be provided by a safety-data handling system which would receive signals

¹ E.C. Wenzinger, et. al., Some Aspects of Reactor Safety Systems, proc. 12th Annual IEEE Nuclear Science Symposium (San Francisco) NS-13, (1) 426 (1965).

² F. Larin, et al., Nuclear Safety, 1, (1) (1959).

³ B.J. Garrick, et al., Some Aspects of Protective Systems in Nuclear Power Plants, IEEE trans. Nuclear Sci. NS-12 (6) 22 (1965).

FIG. X. 1 Arrangement for an SOC Accelerator Safety System.

from the safety channels and from the alarm outputs of the control computers. It would provide control data for the convenience of the operating staff and logging of all fault signals for fault investigations or for analyses of safety performance. The system should be fast-scanning and capable of identifying the time sequence relationships of a number of rapidly occurring events. Frequently, in the operating experience of the NRU reactor, the inability to determine the first sign of a safety shutdown has hampered the identification of its real cause and thereby complicated the correction of faulty equipment or operating practice⁴.

For equipment protection, the greatest need for rapid shutdown arises from a fault producing a complete loss of the beam. A 'worst case' was considered in which the fault is assumed to be instantaneous and the total beam energy is dissipated over a small area of the stainless steel beam-tube wall where it is most likely to be thinnest, i.e. in the sector magnets. The time required to raise the wall temperature to the melting point would be about 250 μ s. To protect personnel, the limit on shutdown time may be less, for example in the thermal target facility, where the beam transport tube passes through the experimental area, the shielding has been designed for a 40 hour work week immediately below the beam tube and to limit the radiation exposure on a beam-loss accident caused by failure of the 20° bending magnet, the permissible shutdown time may be as low as 50 μ s (Chapter VII). Only a small fraction of this time would be available for operation of the safety channels since allowance must be made for the operating times of a beam sensor and a device for shutting off the beam, for the transit time of the beam remaining in the machine, and for a suitable safety margin. Since there has been little need for such a short response time in reactor safety systems, a highly reliable fast-acting system has yet to be developed.

The use of relays, as in early reactor safety systems, is limited by reliability and speed of operation. To reduce the probability of failure, frequent testing can be applied,⁵ but with relays there is a practical limit to the amount of testing that can be tolerated since their life is a function of the number of operations. Nowadays there is a general trend to the use of solid state systems. Systems based on DC semiconductor techniques are not favoured for general use because they are not fail-safe against internal faults and therefore require periodic manual testing to ensure that they are working properly⁶. Systems employing

⁴ L.M. Watkins, Design Proposal for NRU Trip and Alarm Improvements, report ED-168 (1961).

⁵ G.A. O' Sullivan, A Comparison of Solid State and Relay Reactor Safety Systems, proc. 12th Annual IEEE Nuclear Science Symposium (San Francisco), NS-13 (1) 420 (1965).

⁶ S.V. Kasargod and K.R. Rao, Semiconductor Logic for Safety and Interlock Systems, report AEET/ ED/ SG-18 (1963).

pulse-coding techniques are generally used because their reliability can be ensured by dynamic self-checking circuitry⁷. Such circuits require the application of correct input data to produce a unique output signal that can exist only if all of the components are operating correctly. For this application, their disadvantage is a relatively slow response time. A possible solution may be a combination of DC techniques which possess the required speed, and automatic fast pulse-testing techniques.

To provide a quick indication that all or part of the beam has been lost, the beam may be measured directly or the radiation, that such a loss would produce, may be measured. It is desirable to have both methods available. The necessary sensors can be made by existing techniques.

Beam monitoring devices of suitable speed are now in use.⁸ If only one type of sensor is to be used throughout the machine for safety purposes, then one responding to changes in beam current would suffice. Faulty beam positioning or focussing will result, eventually, in a beam current loss. To be independent of changes in operating level, the outputs from the current-sensors must be normalized to the current at the input of the machine. The reference signal fed to each device must be appropriately delayed to reduce its sensitivity to fluctuations in the ion source output. Redundancy might be achieved by comparing the error signal from the first device with the signals from the next two downstream. In the beam transport section, beam sensors downstream of the beam splitters must be interlocked with the switching pattern so as to avoid false signals when a beam is not present.

Inside the accelerator vaults an array of detectors may be used to sense the change in radiation levels resulting from a partial or total beam loss. Their outputs could very likely be arranged so as to satisfy the safety requirement for redundancy and to avoid false shut-downs from equipment failures. For example, two high signals from any adjacent group of three detectors would shut off the beam. In an alternative arrangement, a long ion chamber similar to that employed in the Stanford Linear Accelerator⁹ could be fixed at a suitable elevation on the outer wall

⁷ I. Wilson, et al., Pulse Coding Techniques for Reactor Safety Logic Systems, proc. IAEA Conf. Nuclear Electronics (Bombay 1965).

⁸ L.A. Law and L. Holcomb, The Cambridge Electron Accelerator Beam Position Monitors, proc. First National IEEE Particle Accelerator Conference (Washington) NS-12 (3) 856 (1965).

⁹ L.H. Johnston, Instrumentation and Controls for the Stanford Linear Accelerator, proc. First National IEEE Particle Accelerator Conference (Washington) NS-12 (3) 44 (1965).

of the vault. This device is particularly suited for use in the beam transport tunnels where the use of individual sensors would be inefficient and costly. Triplication, however, would be impractical.

It does not appear likely that a fast beam shutdown can be achieved by shutting off the source although the method to be employed will most likely be backed-up by this approach. A reduction of the source to safe levels will require about 1 ms. A fast acting switch can be located between the source and the linac pre-accelerator. An electrostatic or magnetic switch, perhaps using energy stored in capacitor banks, appears to be well within current technology.

If the protection requirements for systems with long response times, e.g. process systems in the accelerator and thermal target facility, are assigned to a secondary safety system a programmed shutdown can be used. No special demands are anticipated and the methods used for reactor systems will be adequate.

2. Personnel Safety

When the accelerator is in operation, very high radiation hazards will exist around each acceleration stage, the beam transport tubes, the beam switching devices, the piping and equipment of certain circuits of the thermal target facility, and around the many experiments which will make use of small parts of the proton beam. The primary means for protecting personnel and the general public will be the permanent shielding but access to the machine is essential for repairs and replacements during shutdown conditions. Maintenance will be complicated by residual radiation from components activated by beam spillage. Therefore a protection system making use of equipment, interlocks, and operating procedures and practices, is required. Certain industrial hazards, e.g. high electrical voltages and high temperature liquid metals, will also exist and suitable safety measures for these must be included in the system.

2.1 Access Classifications

The system and the operating procedures to be used with it must be designed to provide for changes in the degree of security required, to suit four operating states as follows:

- BEAM ON IMMINENT
- BEAM ON
- BEAM TEMPORARILY OFF
- BEAM OFF

Three conditions have been defined as follows:¹⁰

Free access - no restrictions required on entering or leaving.

Restricted access - existing where there are no overall machine operation hazards but where residual radiation exists at significant levels such that it is prudent to restrict entry to certain personnel.

Controlled access - existing whenever the machine is in operation or when operation is imminent. For this, all protective interlocks are active.

The protection provided by the system and the operating procedures can be matched to the degree of hazard involved. For example, very tight controls and interlocks can be applied for controlled-access conditions. These can be relaxed appropriately when the condition changes to restricted or free access. The extent of the interlocking can be set automatically by the access condition prevailing in a given area of the machine. Operation of the machine should not be possible until all areas of the machine are secure, i.e. in their safest state.

2.2 Basic Personnel Security System

The basic personnel security system is described in terms of the degree of hazard existing in a given area.

2.3 High Hazard Areas

When the machine is in operation all high hazard areas such as the accelerator stage vaults, the beam transport tunnels, and certain pump and piping rooms require the controlled-access level of protection. Accidental entry must be prevented and intentional entry must be discouraged by several independent means. These features are outlined briefly in the following:

- a) Shielding Doors and Gates - must be closed and locked when the accelerator is in operation. Screened gates or air-tight doors are used in lieu of shielding doors where labyrinth type access shielding is employed. Keys for these are stored in key banks located next to the doors. Screened gates or hatch covers which have been used to seal off beam transport tunnels or other areas that are

¹⁰ R.R. Kassner and W. Livant, Personnel Security at the Brookhaven Alternating Gradient Synchrotron, proc. First National IEEE Particle Accelerator Conference (Washington) NS-12, (3), 689 (1965).

accessible only from within a high hazard area, are also locked so as to restrict the area which must be searched following an extended shutdown. The keys for these are also stored in the key bank at the main entrance to the vault or tunnel.

- b) A Local Key Bank - is located in a position where it can be readily seen by personnel approaching the door. The operating status of the accelerator is displayed by the illumination of one of four panels of a board which is part of the key bank. Keys to all doors served by the board are held captive in cylinders and cannot be released until a permissive signal is received from the control room. An emergency key, which will open any of the doors served by the key panel, is retained in a cylinder under a glass panel. The removal of this key causes a programmed shutdown and gives an alarm signal in the control room.
- c) Interlocking - is required to ensure that a beam cannot remain on when the security system has been violated. Accidental entry is prevented by requiring a permissive signal from the control room before a key can be removed from the key panel. To reduce the number of accidental trips, the release circuitry is normally inoperative when the accelerator is running and must be set deliberately by the security control operator in the control room when a shutdown state has been reached. Should a door be opened by any means and the accelerator remain in operation, a door limit switch will cause a programmed shutdown. When a door has been opened, the key will remain captive in the door cylinder until a permissive signal has been received from the control room. This step is part of the procedure required to restore normal security status. After removal of the key from the locked door, a similar permissive signal is required to restore the local keyboard to normal, thus resetting the security interlocks. By taking part in this operation, the security control operator in the control room is assured, to the best of his knowledge, that the hazard area is now unoccupied.

A key system similar to that employed on the Stanford linear accelerator¹¹ was considered and rejected. Here, a key is retained by each person entering the hazard area to give him assurance that the beam cannot be turned on as long as he is in the room. Key control has already proved to be difficult and hence other means of control are to be employed.

¹¹ K. B. Mallory, A Design Report on a Personnel Radiation Protection System, report SLAC TN-65-81 (1965).

- d) Emergency Exit - is provided by equipping each door with a method for operating it from the inside. If the area is 'secure', opening of the door will shutdown the accelerator and release the security interlocks. They can be reset only by a visit to the area and, following an inspection, the completion of the normal reset procedure.
- e) Emergency Shutdown Buttons - These are located at convenient points inside the high hazard area and each is marked by a bright red lamp. There will be enough to allow at least one set to be easily seen and reached from any point in the area protected. Should any buttons be pushed, the area must be searched and the security status must be restored.
- f) Visual Warnings - For the information of inexperienced personnel each high hazard area is marked by a bright red light located immediately above the access door. It may be coded to provide two pieces of information, e.g. a flashing light for 'beam-on' and a steady light for 'beam-off' conditions. A sign will be posted on the door stating that a flashing light indicates that entrance is forbidden, and that a steady light requires permission and an escort.

Inside the high hazard area, there must be visual warning of an impending start-up. A short period before start-up the security control operator in the central control room will change the status to 'controlled access' thereby permitting interlocks to be reset. One half of the main lighting in the area will flash until the doors are locked and the area is secure, and the flashing lights will then be switched off. Sufficient lighting will remain on in the area to permit movement to an emergency shutdown button or to the main access door.

- g) Audible Warnings - Announcements will be made on a public address system before each change in the accelerator operating status. An announcement that start-up is imminent will be made when the 'BEAM ON IMMINENT' status is selected. A short tone burst will be repeated every minute automatically, until start-up is begun and then an announcement of start-up will be made.
- h) Communications - A telephone will be placed close to each key bank for operating the security system and for communications during maintenance. Inside the high hazard area an emergency phone will be located next to each set of emergency shutdown buttons. All will be connected directly to a set of loudspeakers located in the control room so as to provide uninterrupted access to the control room during an emergency.

Within the high hazard area, portable headsets are used for construction, maintenance, and testing requirements. A suitable number of jacks are located in the work areas to permit connection with other areas of the accelerator through a central switchboard.

- i) Access Control Stations - To ensure the safety of personnel who enter a high hazard area, a control station will be set up at each entrance in use and will be manned continuously while personnel are in the area. The attendant will be responsible for maintaining a record of all persons entering or leaving the area and for ensuring that personnel are equipped with suitable monitoring instruments. Turnstiles or photo-electric counters may prove useful in maintaining an accurate count of personnel movements.
- j) Typical Operating Procedures - Effective operation of the security system cannot be achieved without formal operating procedures. These must be devised so as to maintain the intent of the design without unnecessary complication or unwieldiness. It is prudent therefore that procedures required for a short shutdown be more rigid in their control than those for long shutdowns. For the former, there will be strong pressure to keep the down time as short as possible and a thorough search of an area may not be practical or possible where very high local residual fields exist. Thus personnel security can be maintained only by keeping a careful record of all persons entering or leaving the area.

During an extended shutdown there is generally sufficient time to carry out searches of all insecure areas. For this reason, access controls can be relaxed by dropping the requirement for personnel accounting. When the 'beam-imminent' warning is given, usually 30 minutes in advance, an operations team must make a physical search of all insecure areas. Personnel still in the area will be cleared as quickly as the work can be completed. The team will then tour the area to check that all doors are secured and that no people are left inside. For example, a team of three or four people may be required to search the final-stage vault, using catwalks along the inner and outer walls, to ensure that people are not hidden on top of the cavities or magnets and to search the inner and outer floor areas to ensure that the spaces under accelerator components are clear. When this search is complete permissive signals can be obtained from the control room, to allow the door to be locked and the security interlocking to be reset.

- k) Provisions for Testing - Normally, in the BEAM OFF or BEAM TEMPORARILY OFF states, an interlock prevents operation of the ion source. Bypassing this interlock is essential to permit testing of sources and this will be possible only if a mechanical beam stop

has been inserted so that a beam cannot leave the ion source area and reach the pre-accelerator and first-stage vault.

When an accelerator stage door has been opened, the RF and magnet power supplies are switched off. The interlocks may be bypassed when it is necessary to test or make adjustments on either of these systems. Both however will be prevented from operating at the same time.

- 1) Beam Stops - It is desirable to operate the accelerator while work is being carried out in certain experimental wings. Although the normal switching patterns can be adjusted and interlocks can be inserted to prevent operation of the beam switch, a positive means of ensuring that a beam cannot enter the area is required. A suitable mechanical beam stop must be installed until the work is finished.

2.4 Medium Hazard Areas

Routine or special activities will require entry to areas in which the radiation is high enough to limit access to experienced personnel, for controlled periods. Doors or gates to these areas are normally locked. Keys for areas requiring frequent access will be retained in keybanks similar to those for the high hazard areas, the remainder will be stored in the control room. Generally, no interlocking is involved but security status is indicated in the control room and permissive signals must be obtained before removing or replacing keys. Area monitoring suitable for the radiation in the area¹² can be set to give warning when the levels exceed preset values. Audible alarm signals are interlocked with door operation to avoid a noise nuisance when the doors are closed. A remote indication for each monitor is available in the control room.

Additional protective measures may be necessary in the RF galleries where the radiation level may be as high as 50-100 mR/h (γ, n) if the shielding is adequate only for limited access (Chapter VI). Assuming modular RF equipment, relatively frequent access, for periods up to one or two hours, may be required for replacement of faulty assemblies during normal operations. Since the efficiency of an operating crew can be impaired by too rapid an accumulation of permissible exposure, a positive aid to exposure control is essential.

A means of providing delayed shutdown is proposed in which the delay is inversely proportional to the highest dose rate in the

¹² R. D. Hiebert, et al., Area Radiation Monitor System with Logarithmic Indication and Audio-Visual Warning, proc. First National IEEE Particle Accelerator Conference (Washington) NS-12 (3), 721, (1965).

area¹³. Interlocking would be arranged so that when the door is opened, the highest output of the area monitoring is connected to an integrator which will initiate a programmed shutdown when a preset dose has been accumulated.

If the work assignment is completed within the delay period, the delay circuitry can be reset by restoring the security status to normal. During shutdowns no radiation is present and free access conditions prevail.

2.5 Low Hazard Areas

Areas in which low radiation levels may be present, are equipped with alarming monitors if unrestricted access is required. Where more intense local hazards are present for short times, for example around active magnets in the magnet test and assembly shop, supplementary measures, including portable instruments, are required.

Surface areas immediately above the accelerator will be isolated from plant personnel by suitably marked wire fencing. Keys for locked gates will be retained in the central control room and normally will not be available during operation.

2.6 Radiation Level Data Handling

To provide safe and efficient operation, maintenance and operations must be carefully controlled. Adequate information on radiation hazards must be available to the central control room operations staff, for the authorization of work assignments. Such information need not be displayed but may be provided on demand. Continuous chart recording of area levels can very likely be replaced by periodic data logging. Automatic logging of alarm information can also be provided.

The type, size and possible features need to be studied along with the possibility of providing this service through the monitoring units of the control computers.

2.7 Remote Handling Equipment

Certain components in the high activity tunnel, e.g. meson targets, will become highly active during normal operation. The additional shielding which surrounds them will also become active in time

¹³ G.F. Wells and W.E. Lingar, An Accelerator Radiation Protection System, proc. First National IEEE Particle Accelerator Conference (Washington), NS-12 (3), 718 (1965).

and both the shielding and the target assembly will be a hazard when replacement is required. Remote handling equipment will be required, designed specially for such operations. Vacuum flange joints, cooling water connections, electrical connections etc., must be designed for use with this equipment. For some operations, remote viewing equipment, such as closed circuit television, may be required.

In recent years, considerable work has been devoted to this field both for high energy accelerators and for reactors^{14, 15} and a wealth of information is now available.

¹⁴ W. W. Salsig, 200 BeV Accelerator Handling Systems in Regions of High Residual Radioactivity, report UCRL-16236 (1965).

¹⁵ A Proposal for Increasing the Intensity of the Alternating-Gradient Synchrotron at the Brookhaven National Laboratory, report BNL-7956 (1964).

B. RADIATION HAZARDS

1. Introduction

A "Hazards Analysis" of the ING project has not been done. This section merely attempts to place in perspective the potential hazards created by ING and to point out some factors which must be considered in the design and siting of the plant. Unlike a reactor, there is no criticality hazard, yet there will be a substantial inventory of radioactive nuclides. A complete analysis cannot be made until a fairly detailed conceptual design has been worked out, a site has been chosen, and more information on the chemistry and metallurgy of the main target is available.

Danger to the public may result from routine operation or from accidents within the plant. During routine operation, some radiation, mostly high energy neutrons, will penetrate the shielding and if excessive it will become a hazard to the public primarily by atmospheric scattering (skyshine). An appropriate combination of shielding and exclusion area will be required. Some radioactivity will be released to the environment and adequate processing and control of effluents will be necessary.

The accelerator system would not be as large a source of possible hazard through accidental releases as the Thermal Neutron Facility would be. For example, loss of control of the beam coincident with failure of the emergency shutdown system would not result in excessive exposures of the public because the beam is contained in heavily shielded vaults and tunnels. On the other hand one can envisage severe accidents which could lead to the release of some of the radio-nuclides held in the thermal neutron facility. These are listed for illustration as follows:

- a) Loss of circulation of the Pb-Bi system of the thermal neutron target, coincident with failure of the emergency shutdown system - Until details of shutdown systems are known and the consequences considered, the plausibility and severity of such an accident cannot be assessed.
- b) Circumstances bringing about the dispersion of isotopes and fission products contained in commercial-isotope production facilities - Until the isotope production has been predicted and the methods and systems for irradiating the source materials have been worked out, plausible accidents cannot be formulated. It can be noted, however, that if a substantial fraction of the 1.2 grams of neutrons available per day were at any time being absorbed in highly irradiated plutonium to produce transuranic elements, the fission product inventory might be comparable with that in a reactor of 100 or more thermal MW.
- c) Failure of the emergency cooling system required for removal of the Pb-Bi decay heat - the consequences and severity of

this have not been investigated.

- d) Failure of the piping of the Pb-Bi system leading to airborne dispersion of some of the contained spallation and neutron capture products - Failure of the main target tube within the moderator tank is considered plausible because the predicted lifetime, under the intense irradiation, is short (See Chapter VII regarding special provisions for frequent replacement). Fortunately the thermal energy that would be available to stimulate such a dispersal is smaller than in a pressurized-water power reactor like NPD, by a factor of about 30.

Possible consequences of the last accident are considered in section X.B.3. Because many details of the Pb-Bi system are not yet worked out, a realistic assessment cannot be made but simplifying assumptions have been used to obtain some perspective and to indicate design features which will be desirable.

2. Hazards from Routine Operation

The maximum permissible exposure to the population to external radiation is 0.5 rem/yr but in practice a much lower value is used in choosing sites. One of the more significant sources of external radiation will be neutron skyshine. This has been estimated (Chapter VIII.B) on the assumption that the total cascade neutron source originates from a beam spill of about 0.1 μA per sector, in the third stage of the accelerator.

The flux at the boundary of the limited access above the machine, 100 ft on each side, was calculated as $2 \text{ n cm}^{-2} \text{ s}^{-1}$ and the dose equivalent for this is approximately 20 mrem for a 40-hour week.

Assuming that the $1/R$ skyshine spatial dependence will hold for much beyond 100 ft (Chapter VIII.B), the boundary for a minimum exclusion area for this source alone is at about 1000 ft. Before a realistic assessment of the requirements for such safeguards can be made, a better knowledge of the expected beam spill is required and other effluents will have to be considered, for example active noble gases, i.e. Argon-41, which may be generated in the accelerator vaults, beam transport tunnels, and the thermal neutron target structure.

It is too early to make a realistic appraisal of the internal radiation hazards which would result from continuing releases of radioactive nuclides such as iodine isotopes, and so there is no estimate of the special treatment that may be required.

Tritium will be produced in the moderator and the target material. Equilibrium concentrations in the moderator will be about 50 times the equilibrium level for the NRX reactor. Good system containment will be required. Except for large spills, the hazards to the public are not appreciably increased. The tritium in the Pb-Bi target is not expected to combine chemically and may be removed at its production rate by the target vacuum system. It will pass through the cold trap and would be exhausted by the effluent air stack as hydrogen gas unless it were deliberately combined with oxygen or trapped by active metal such as zirconium. Although the rate of 390 Ci/day does not exceed the maximum permissible continuing release, it is about 15 times larger than the average release from the NRX and NRU reactors. Policy may require the removal of the tritium from the non-condensable gases before they are discharged.

The target vacuum system may also remove iodine isotopes at their production rates. This is about 11 mCi s^{-1} for I-126. For an exclusion area within one kilometer from the target, with an average atmospheric diffusion factor, K_{avg} , of about $10^7 \text{ m}^2 \text{ s}^{-1}$, the maximum permissible continuing release is given by

$$Q = K_{\text{avg}} C$$

where Q = max. permissible release rate

C = max. permissible concentration

Since, for one-year old children, the maximum permissible concentration in air is $6.6 \times 10^{-11} \text{ Ci m}^{-3}$, the release rate is 0.7 mCi s^{-1} . This is for exposure by respirable air only; a lower rate is required if exposure from locally produced milk is to be included.

If pasture land is near the site, the release rate must be restricted to about 0.01% of the production rate. If there is no local pasture land a release rate as large as 5% of the production rate would be barely acceptable for the public, and might create a problem on the site itself, depending on the layout.

3. Hazards from Accidents

A significant hazard to the public would originate from an uncontrolled release of the fission, spallation, and neutron capture products in the Pb-Bi system of the thermal neutron facility. Estimates of the amount of some of the by-products at the end of a first full power year have

been calculated by Eastwood and Fraser^{16, 17}. In addition there will be substantial quantities of short lived intermediate products of biological significance.

The amounts of biologically-significant radio-active nuclides in the system at any given time is uncertain not only because the yields are uncertain, but also because:

- a) The upper part of the target tube, where the Pb-Bi flows down along the inner wall, will act as a degassing system. Gaseous and volatile by-products may be removed through the large vacuum line connected near the beam tube entrance. Condensables will be collected in a cold trap and the non-condensables will be exhausted by the vacuum pump to the active-effluent air stack.
- b) The amount of any product removed by the degassing action will depend on its solubility in the Pb-Bi system, but little is known about these solubilities.
- c) Some of the products may combine chemically, either with other products or with the target material.
- d) Some products may deposit on the cooler surfaces of the Pb-Bi system, e.g. heat exchanger primary surfaces, and be retained following a major accident.

Because of these uncertainties and for simplicity in assessing the system safeguards, the estimated nuclide inventory at the end of the first full power year is arbitrarily assumed to be available.

Watson has calculated the maximum permissible accidental releases for some of the significant nuclides, and from this, set a simple guide for containment¹⁸. The methods described by Barry¹⁹ have been used.

¹⁶ T.A. Eastwood, Private communication, (May 4, 1966)

¹⁷ J.S. Fraser, Private communication, (April 22, 1966)

¹⁸ L.C. Watson, Private communication, (June 10, 1966)

¹⁹ P.J. Barry, Maximum Permissible Concentrations of Radioactive Nuclides in Airborne Effluents from Nuclear Reactors, report AECL-1624, (1962)

The maximum permissible exposures (MPE) shown in Table X.B.1 were calculated for adults; for children, smaller exposures are allowed.

TABLE X.B.1

MAXIMUM PERMISSIBLE EXPOSURES TO ADULT POPULATION FOR
VARIOUS SIGNIFICANT RADIO-NUCLIDES

<u>Nuclide</u>	<u>Assumed MPD for adults rem</u>	<u>Sensitive Organ</u>	<u>MPE Ci sm⁻³</u>
Sr-90	1.5/yr	Bone	0.0036
Cd-109	25*	Liver	0.93
I-126	25*	Thyroid	0.066
Po-210	25*	Kidney	0.0086

* Lifetime doses

The contribution of related nuclides present in the system must also be considered. For example, the amounts of I-123, 124, 125, 128, 130, and 132 present must be considered in calculating the MPE for iodine.

For accidental releases at ground level and one kilometer from the source, Barry recommends that K_{min} , the factor for the atmospheric dilution in an effluent plume, be $10^4 \text{ m}^3 \text{ s}^{-1}$. The maximum acceptable release and the ratio, (maximum acceptable release/ inventory) for the four nuclides considered are shown in Table X.B.2.

The ratio, (release/ inventory) indicates the containment required. Watson suggests the containment should be good enough to prevent the release during an accident of one part in 10^5 for particulate aerosols and one part in 10^4 for gases (iodine) after arbitrarily allowing a factor of ten each for the presence of other nuclides giving additive doses to the sensitive organs.

TABLE X. B. 2

MAXIMUM PERMISSIBLE RELEASES FOR EXPOSURES TO ADULT POPULATION			
Nuclide	Max. Release Ci	One Year Inventory Ci	Ratio Release/Inventory
Sr-90	36	$\sim 1 \times 10^4$	$\sim 3 \times 10^{-3}$
Cd-109	9300	$\sim 1 \times 10^5$	$\sim 8 \times 10^{-2}$
I-126	600	$\sim 2 \times 10^4$	$\sim 4 \times 10^{-2}$
Po-210	86	$\sim 5 \times 10^5$ *	$\sim 2 \times 10^{-4}$

* Equilibrium amount

4. Failure of the Pb-Bi Circuit

If both the ING target tube and the moderator tube surrounding it were to fail, allowing the moderator to mix freely with the liquid-metal target material, the transient pressure rise could disperse substantial quantities of radio-nuclides.

If the failure of the two tubes occurred at the bottom of the moderator tank where the moderator pressure is about 35 - 40 lb in⁻² greater than that in the Pb-Bi system, heavy water at 140°F would be forced into the Pb-Bi (which is at about 840°F when the beam is at full power). If it is assumed that none of the water, steam, and liquid metal mixture enters the moderator tank, and because the lower part of the Pb-Bi system is closed and full, the mixture will be ejected upwards to fill the upper part of the target-tube structure. If the beam tube were ruptured just above the upper shield by the pressure transient, a mixture of finely divided Pb-Bi and steam could escape into the experimental hall.

Normally less than 2% of the Pb-Bi is in the target tube and if only this volume is intermixed initially with the heavy water, it would appear reasonable to assume that, at the most, all of the nuclides in this volume that are gases and up to one third of those that are solids, are released. Should however these escape from the building, the maximum acceptable releases will be exceeded. The pressure surge could force a large portion of the liquid metal-water mix through the target-tube vacuum line to the cold trap where it would vaporize the contents. If the trap has collected an appreciable amount of radio-nuclides, the amount of these (eg. iodines, Po-210) which might escape could be substantially larger.

After the failure, the circulating pump will continue to discharge liquid metal into the target tube until the coast-down head is insufficient or, if the system pressure interlocks have failed, until the pump cavitates with steam. Ten times more liquid metal than is normally

in the target tube, could be mixed with moderator and would add appreciably to the amount of radio-nuclides released to the atmosphere.

It is clear that for the postulated accident the thermal neutron facility building must provide good containment for the airborne material produced. The energy release causing the first pressure surge is relatively small. If all of the available heat in the Pb-Bi normally in the target tube is transferred to the heavy water, the steam produced will occupy about 1000 ft³ at atmospheric pressure. In the experimental hall this will develop a very small over-pressure which could be readily handled by a negative pressure ventilation system operating in a semi-airtight building at about -0.5 in H₂O. If all of the available heat, from the largest volume of target material that could be pumped into the failed target tube, were to produce steam that escaped into the experimental hall, the overpressure would be about ten times larger. The volume of exhaust air then to be handled by the filter and scrubbing equipment would be too large and better containment would be required.

5. Suggested Safeguards

A better knowledge of the chemistry of the target system and the target system design is required before siting requirements and system safeguards can be well determined. Some safeguards are already in the reference design; others which seem to be necessary are:

- a) A rupture disc (or equivalent) should be installed in the Pb-Bi return line.
- b) The basement Pb-Bi area has already been designed as a sealed area to restrict the movement of nuclide containments, e.g. polonium, during normal operations and maintenance. The design should be extended to handle accidents.
- c) Those parts of the beam tube and upper target structure which on rupture would release activity into the experimental hall should be strengthened to resist pressures produced by the maximum credible accident.
- d) A fast-acting valve should be installed in the beam tube to protect the tube in the beam transport tunnel.
- e) A self-closing fast-acting valve should be placed in the target tube vacuum line so as to prevent the uncontrolled flow of Pb-Bi into the cold trap.

OGI

INTENSE NEUTRON GENERATOR
LINEAR ACCELERATOR

CHAPTER XII

COMMERCIAL ISOTOPE PRODUCTION

(R. Courtemanche, D.L. Rowat)

A. PRODUCTION OF RADIOISOTOPES	XII. 1
1. Antimony-124	1
2. Isotopic Power Sources	2
3. Transplutonium Isotopes	5
4. Other Isotopes	5
5. Cobalt-60	6
B. ISOTOPE PRODUCTION FACILITIES	8
1. High Flux Facility	8
2. Intermediate Flux Facilities	8
3. Low Flux Facilities	9
4. Cobalt Blanket	9

XII. COMMERCIAL ISOTOPE PRODUCTION

A. PRODUCTION OF RADIOISOTOPES

The use of ING for producing radioisotopes is not incompatible with its primary purpose as a research facility. Indeed, preserving the high neutron flux is as important for isotope production as it is for research. Thus, if ING were built solely for the production of radioisotopes, it would be essential to minimize the amount of target material near the center of the moderator tank as otherwise there would be a serious depression of the thermal flux, and this in turn would lower the specific activities obtainable. To put it differently, if ING were loaded heavily with target materials, there would be a larger quantity of isotopes produced but they would be of lower quality, and ING would not be a much better facility than a reactor.

Any radioisotope which is produced in NRX and NRU could be produced advantageously in ING, and the higher neutron flux would result in either a higher specific activity or a shorter irradiation time. In general the length of the irradiation is not of prime importance, but the higher specific activity usually means a better product, it is then obvious that the isotopes which should be produced in ING are those which will gain significantly in specific activity¹.

Some of the isotopes that are considered for production in ING are discussed below.

1. Antimony-124

^{124}Sb is of special interest among the radioisotopes because it is the only practical one which can be used for making neutron sources with high yields. The radioactive antimony is put into a beryllium block, and the neutrons are produced by the (γ, n) reaction in beryllium. The yield that can thus be obtained is proportional to the specific activity of the source. Since the specific activity is itself roughly proportional to the flux in which the antimony has been irradiated, the ^{124}Sb produced in ING will be very suitable for this application.

Large quantities of ^{124}Sb will be required to meet the demand. In recent years, neutron activation analysis has expanded remarkably, as a result of the availability of electrostatic neutron generators, and it would have been only natural that industry, which is striving for automation, would have found numerous applications for the new technique.

¹ D. L. Rowat, Possible Isotope Production in the ING, proc. AECL Symp. The Generation of Intense Neutron Fluxes (Chalk River), report AECL-2177, paper 9 (1965).

This has not happened though, and the reason is simply that while neutron generators are very good laboratory tools, they are neither stable nor reliable enough for continuous use. Alpha-beryllium sources can hardly be considered for producing high neutron yields, because they are too expensive, and their handling and shipping pose rather difficult problems. Consequently, at Commercial Products, there is now a concerted effort to develop Sb-Be neutron sources to satisfy the industrial requirements. It will be remembered that, a few years ago, ^{60}Co was able to replace the accelerator for industrial gamma irradiation because of the inherent reliability of the isotopic neutron source. There is now every indication that Sb-Be will supplant the neutron generator whenever reliability is a prime requirement, as in industry.

With the ^{124}Sb produced in NRU, it is possible to provide thermal fluxes exceeding $10^9 \text{ n cm}^{-2} \text{ s}^{-1}$, which is comparable to those given by neutron generators, but with the advantage that Sb-Be does not give off neutrons above one MeV. With the ^{124}Sb that could be produced in ING, it is estimated that thermal fluxes of up to $10^{11} \text{ n cm}^{-2} \text{ s}^{-1}$ could be obtained, and this would make Sb-Be assemblies as good as thermal columns of reactors, both for the quality and the intensity of the flux. Such facilities would obviously be outstanding for commercial activation-analysis as well as for laboratory uses.

There is no doubt that ^{124}Sb will soon be the largest-selling isotope next to ^{60}Co . As said before, the ^{124}Sb produced in NRU already puts Sb-Be in a favorable competitive position relative to the electrostatic machine, and there should be a well established market by the time ING is built. When the ^{124}Sb from ING becomes available, its higher specific activity will put Commercial Products well ahead of the competition, because the Sb-Be neutron irradiation facility will only be surpassed by the much more expensive nuclear reactor.

2. Isotopic Power Sources

There is a fast-growing demand for high specific activity isotopes to be used as heat sources, and by the time ING is built the demand will probably exceed the supply^{2, 3}. At first only fission products were used, but it is now evident that, to satisfy specific needs, isotopes produced by simple neutron irradiation will be required.

Among the radioisotopes which can thus be produced, there are few beta emitters suitable for use as heat sources. Since high specific activity is a requirement, the radioactive isotopes should be

² G. T. Seaborg, Address to Atomic Industrial Forum, San Francisco (1964).

³ H. Taylor, Missiles and Rockets 16, (17), 12 (1965).

produced from an element which has only one stable isotope, as otherwise the presence of unwanted isotopes would decrease the specific activity. There are in fact only three satisfactory isotopes. ^{46}Sc gives off 14 W k Ci^{-1} and could reach a specific activity of 15000 Ci g^{-1} in ING, but its half life of 85 days is too short. ^{171}Tm could reach $1,000 \text{ Ci g}^{-1}$ in ING; its half life of 1.94 years is long enough for some applications, but its heat output is only 0.58 W k Ci^{-1} . ^{60}Co , the most satisfactory of the three, has the reasonably-long half life of 5.27 years and a heat output of 16 W k Ci^{-1} ; it could reach 800 Ci g^{-1} in the high flux of ING and would be relatively cheap to produce.

However, the beta emitters often have the disadvantage of giving off a large fraction of their energy in the form of gamma rays which are difficult to absorb. Such is the case with ^{46}Sc and ^{60}Co . As a result, heat is generated in a relatively large volume of absorber, and this reduces markedly the "effective" power density. And of course there is the additional disadvantage that heavy shielding is required.

Consequently, more importance is given to the alpha emitters. These have a higher heat output per curie, and since most of the energy is associated with the alpha particles, the heat is mostly produced locally. Another consequence is that the "gamma-to-heat" ratio is much less than that of beta emitters, which means that less shielding is required -- a very important consideration in space applications where the weight must be kept to a minimum.

^{238}Pu is one of the best alpha emitters for making power sources, with its 90-year half-life, its very low gamma output and its specific heat output of 33 W k Ci^{-1} . By 1980, it is estimated that 15 M Ci of ^{238}Pu will be needed⁴. The isotope is produced by the neutron irradiation of ^{237}Np , a by-product of uranium reactor fuel. If the ^{237}Np is irradiated in too high a flux, there may be a considerable waste of target, because the intermediate product ^{238}Np has a high fission cross section. Thus, in $2 \times 10^{14} \text{ n cm}^{-2} \text{ s}^{-1}$, 8% of the ^{238}Np - and hence of ^{238}Pu - is lost through fission, and in $2 \times 10^{15} \text{ n cm}^{-2} \text{ s}^{-1}$ the loss is increased to 46%. Nevertheless, the high flux of ING could be used profitably to produce large amounts of ^{238}Pu if the target were circulated in a loop so that ^{238}Np could decay outside the neutron flux. It might then also be possible to extract the ^{238}Pu as it is produced and so prevent its being destroyed by further neutron capture.

A possibly better source is ^{244}Cm ; it has the same characteristics as ^{238}Pu except that its shorter half life of 18 years, which is still sufficiently long, results in a specific activity and heat output five

⁴ E. J. Henelly and R. R. Hood, Radioisotope Production Capabilities of U.S. Power Reactors, DP-1015 (1965).

times as large as that of ^{238}Pu . Its production, however, is more costly, because it involves a double neutron capture, and because the target ^{242}Pu is mixed with other plutonium isotopes, two of which have large fission cross sections.

^{242}Cm is another good heat source, although its half life of 163 days limits its usefulness. It is much like ^{238}Pu and ^{244}Cm , except of course that its specific activity is much higher (40 times as high as that of ^{244}Cm). It is produced by the irradiation of ^{241}Am , an isotope which accumulates in the plutonium produced in natural uranium fuel rods. ^{242}Cm is doubly valuable, because its decay product is the long-lived ^{238}Pu which can be recovered when ^{242}Cm has decayed below a useful level, and because the remaining curium is rich in ^{244}Cm .

The target materials for producing ^{238}Pu , ^{244}Cm and ^{242}Cm could all be obtained from Canadian reactors, because these are fuelled with natural uranium. The high burnup in power reactors will be particularly favorable to the production of the heavier plutonium isotopes. Thus it is estimated that the ^{241}Pu and ^{242}Pu content of the plutonium produced in the Pickering reactors will be 6% and 2% respectively.

Another attractive heat source is ^{232}U . It has about the same half life as ^{238}Pu (74 years), but because it heads a family of shorter-lived isotopes, emitting a total of 6 alphas and 2 betas, its heat output is 10 times as much as that of ^{238}Pu . It has the disadvantage of emitting gamma rays, although its "gamma to heat" ratio is significantly less than that of ^{60}Co . The production of ^{232}U depends on the availability of protactinium (^{231}Pa) and ionium (^{230}Th) which are found in uranium ore but normally are not extracted. However, in view of the attractiveness of ^{232}U as a heat source (and also as a neutron source), the recovery of ^{231}Pa and ^{230}Th may be warranted.

There are two other isotopes which are suitable as power sources and which will accumulate as by-products of the operation of ING: tritium and polonium.

Tritium is of interest because of its long half life (12 years) and because it does not emit any gamma rays. In ING, it is estimated that tritium will accumulate at a rate of at least 300,000 curies per year, in the heavy water of the moderator tank.

Polonium (^{210}Po) is an alpha emitter which has practically the same characteristics as ^{242}Cm for its half life, specific heat and low gamma output. It will be produced in the lead-bismuth target of the moderator tank by the thermal neutron irradiation of ^{209}Bi . With the present target design, and assuming that there is no flux depression in the target, it is estimated that about 2 million curies or 450 grams will be produced per year. Since polonium is fairly volatile, a cold trap will be

needed to prevent the vapor from entering the proton beam tube. Furthermore, since polonium produces heat at the rate of 140 W g^{-1} which is all absorbed locally, it will have to be removed periodically from the cold trap. A substantial revenue could thus be derived from this inevitable by-product of the operation of ING.

3. Transplutonium Elements

A fairly obvious use for a high neutron flux is the production of transplutonium elements, because this involves multiple neutron captures. The interest in these elements is such that the USAEC have built a high flux reactor (HFIR) especially for producing them.

It was seen above that ^{244}Cm could be made, for use as a heat source. This isotope could also be used as the target material for producing the heavier elements such as californium, einsteinium, fermium, which so far have only been obtained in minute amounts. The highest flux of ING would be most useful for such an application.

The advantage of ING over other facilities can be shown by an example. The highest neutron flux available at the present is $5 \times 10^{15} \text{ n cm}^{-2} \text{ s}^{-1}$ in HFIR; near the center of ING and over a relatively large volume, the flux will be twice as high. If ^{244}Cm were irradiated to produce ^{254}Es , two kg of target would yield $0.1 \mu\text{g}$ in HFIR, and $100 \mu\text{g}$ in ING, that is 1000 times as much. The availability of the long-lived ^{254}Es could open up new possibilities, since this isotope could then be used as a target in accelerators, to produce new elements.

4. Other Isotopes

The short-lived isotopes will greatly benefit from the high flux of ING, because their specific activity is directly proportional to the irradiation flux. Thus, ^{64}Cu (12.8 hr), ^{90}Y (64.2 hr) and ^{99}Mo (67 hr), which are commercially used, are not presently produced by Commercial Products because the market is sufficiently far away that even sources produced in NRU will decay too much before reaching the customers¹. The availability of fluxes greater than $10^{15} \text{ n cm}^{-2} \text{ s}^{-1}$ should change the picture and open up new markets to Commercial Products.

^{46}Sc , a hard gamma emitter with a half life of 84 days, is an isotope which is often mentioned as a substitute for ^{60}Co in seasonal irradiators, i.e. irradiators which may be used only during the few months following the crop. Large quantities of high specific activity ^{46}Sc could be produced in relatively short times, and for this reason, this isotope could even be used as a temporary replacement for ^{60}Co in "permanent" irradiators, should a shortage of ^{60}Co occur.

There are long-lived isotopes, with negligible neutron capture cross sections, which could occasionally be produced in ING to satisfy an unexpected demand. Typical examples are ^{63}Ni (92 yr) and ^{14}C (5730 yr), which require long irradiations in NRU. Since the time of irradiation to produce a given amount of activity is inversely proportional to the irradiation flux, the availability of ING could allow Commercial Products to supply such isotopes at a short notice. It may also be pointed out that the ^{14}C produced in ING would be of better quality than that produced in lower fluxes, because the inactive carbon content would be substantially reduced.

The isotopes which are produced by a double neutron capture often can not be produced in NRU because too much of the intermediate product remains at the end of the irradiation. For example, ^{171}Tm , possibly the best low-energy gamma source, cannot be produced in NRU from natural ^{169}Tm : it could reach 180 Ci g^{-1} but the dominant activity would be the unwelcome ^{170}Tm (400 Ci g^{-1}). In the highest flux of ING, ^{171}Tm would reach 1000 Ci g^{-1} and would be almost free of ^{170}Tm (less than 10 Ci g^{-1} , depending on the length of irradiation).

There are some radionuclides which can reach reasonably high activities in NRU only when enriched isotopes are used as targets. Thus, natural nickel is a poor target for producing ^{63}Ni , because the natural element contains only 3.7% of ^{62}Ni . Similarly, ^{152}Gd , the target for producing ^{153}Gd , amounts to only 0.2% in natural gadolinium. Other examples of radioisotopes which are now produced from enriched targets are ^{75}Se , ^{85}Sr , ^{197}Hg . But the enriched isotopes are expensive and of limited availability. In many cases, the improvement in specific activity that would be obtained in ING would be such that there would be no need to use the enriched materials, or else these expensive targets could still be used, but would be utilized far more efficiently.

Another case of interest is that in which the desired radioisotope is produced by a neutron capture followed by the relatively slow decay of the intermediate product. If the desired radioisotope has a large neutron cross section, a significant fraction could be destroyed by a long irradiation, resulting sometimes in the production of an unwanted activity. A higher irradiation flux would be advantageous because it would permit reducing the irradiation time, so that a smaller fraction of the intermediate product would decay during the irradiation. A typical example is the production of ^{125}I from ^{124}Xe , where it is essential that the ^{126}I content be kept low¹.

5. Cobalt-60

^{60}Co is in a category by itself among the radioisotopes, because of the very large quantities that are used.

^{60}Co could be produced in the moderator tank of ING. The irradiation times would be shorter than in a reactor but the gain in specific activity would only be fractional¹. Since the specific activities required by the market can easily be obtained in power reactors, it is obvious that the high flux of ING should not be used for producing ^{60}Co , but rather to produce those high-specific-activity isotopes which can be produced nowhere else.

However, at the periphery of the tank where the neutron flux has dropped to a relatively low level, it will be possible to irradiate a large mass of cobalt in the form of a blanket which would form the inner layer of the shielding. This cobalt will have no adverse effect on the high flux in the tank, and it will effectively absorb the thermal neutrons which otherwise would produce a large amount of heat in the first layer of the iron shielding - in other words, it would act much like the J-rod annulus of NRX and NRU.

It appears that the yearly production of ^{60}Co could then be 5 to 10 M Ci, depending on the number of neutrons absorbed inside the tank. The specific activity would be 20 to 40 Ci g⁻¹ yr⁻¹, which would make this cobalt suitable for use in industrial irradiators. It should be noted that the cobalt thus produced would cost little, since for all practical purposes the neutrons at the periphery of the tank are considered as lost and have to be absorbed in the most practical way.

B. ISOTOPE PRODUCTION FACILITIES

It was stated before, that preserving the high flux in the ING moderator tank is as important for isotope production as it is for research, since it is a condition for producing very high specific activities. It is thus essential that the depression in the thermal neutron flux near the center be kept to a minimum. This in practice does not preclude the location of production facilities in the high flux region, because ING will only be justified by its real usefulness. The principle has been adopted that restrictions should be placed on the load permitted in the facilities rather than on their positions.

It will be seen that the isotope production facilities in ING are placed so as to cause little disturbance of the high flux region, and yet will still provide:

- a region of high flux (10^{16} n cm⁻² s⁻¹) close to the beryllium sleeve;
- a region of intermediate flux (2 to 5 x 10^{15} n cm⁻² s⁻¹) halfway between the center and the tank wall;
- a region of "low" flux (0.5 to 1 x 10^{15} n cm⁻² s⁻¹) just inside the tank wall;
- a region of very low flux in the tank wall, where the flux is low because of the heavy load and the resulting flux depression.

Only the main characteristics of the facilities are described here. A more detailed description has been given in Section VII. A.

1. High Flux Facility

The only production facility in the region of peak flux will be a "rabbit" with four irradiation positions (similar to that provided for research purposes - see section V - D). Only small amounts of target material will be permitted in this facility, not only to ensure that there will be little flux depression in the neighbouring region, but also to ensure that the effective flux in the targets will have a value close to that of the unperturbed flux, the aim being to produce the highest possible specific activities. The capacity of such a facility may seem small, but it must be remembered that 50 times as much activity will be produced per irradiation as in a similar rabbit in NRU.

2. Intermediate Flux Facilities

There will be two vertical thimbles passing in the 5×10^{15} n cm⁻² s⁻¹ region, and three in the 2×10^{15} n cm⁻² s⁻¹ region. These thimbles will have a diameter of 6 in and will be similar to those of NRU, in that they could be used for target rods, loop facilities, etc. as required. This means that these facilities can be adapted to the needs that will prevail at the time ING is built, and that they can be modified later if necessary.

The thimbles will extend the full length of the moderator tank, and the neutron flux will vary along their length. For the irradiation of target rods, the load can be varied according to the elevation in the rod so as to make the effective flux more uniform along the rod.

These facilities can be loaded more heavily than the "rabbit", as their effect on the region of peak flux is not expected to be serious, but it is likely that there will be a limitation on the load, imposed by the self-shielding that can be tolerated in the targets themselves, - and this will depend on the material being irradiated.

3. Low Flux Facilities

Just inside the tank wall, there will be 50 vertical rods that will be used for irradiating strings of capsules. These rods should not have any effect on the thermal flux at the center, and could thus be used for "mass" production. In particular, they would probably be ideal for the production of ^{124}Sb if the higher flux positions are needed for producing power sources.

In addition, there will be 6 tubes forming loops around the lead-bismuth target at the bottom of the tank, which would also serve to irradiate strings of capsules. These tubes should be loaded heavily: they will be too distant to have any effect on the thermal flux at the center, and they will reduce the number of neutrons that will escape through the bottom of the tank.

4. Cobalt Blanket

The wall of the moderator tank will be made of a double "blanket" of cobalt slugs. These slugs have a diameter and a height of 1/4 in. The reason for choosing a height equal to the diameter is to prevent the slugs from jamming inside the wall. The "standard slugs" which have been used by Commercial Products for over 10 years have a diameter of 1/4 in and a length of one in. It will thus be possible to use the short slugs from ING in all applications where the long ones have been used.

It is possible - and indeed probable - that the cobalt in the second layer of the blanket will never reach a "useful" activity. However, since one of the functions of the cobalt in the tank wall is to serve as a primary shield for the absorption of the thermal neutrons, the second layer will ensure that ING will not have to be shut down if the first layer is empty - for example, because of a shortage of slugs. It may be noted that it would always be possible to "boost" the specific activity in the outer layer by leaving the inner layer empty.

For practical reasons the blanket around the tank is divided into six vertical zones. It is likely that the specific activity required will be 50 Ci g^{-1} , which means that the length of irradiation will be about two years. The total activity would then be close to 15 M Ci. Obviously, Commercial Products would rather receive 6 shipments at regular intervals than one large shipment every two years. Furthermore since the specific activities required may vary, it is better that not all of the cobalt be irradiated for the same time.

CHAPTER XIII

POSSIBLE FUTURE ADDITIONS AND CONJOINT PROJECTS

A. VARIABLE ENERGY (B.G. Chidley)	XIII.1
B. STORAGE RING (J.W. Knowles, G.E. Lee-Whiting)	2
1. Introduction	2
2. Operation and Limitations	2
3. Required Performance	5
C. POWER/BREEDER TARGET (C.H. Millar)	8
D. ING & ELEMENTARY PARTICLE PHYSICS (J.D. Prentice, W.T. Sharp)	9
1. Introduction	9
2. ING as an Accelerator for Elementary-Particle Physics	9
3. ING as an Injector for a High-Energy Accelerator	10
4. Conclusions	11

XIII. POSSIBLE FUTURE ADDITIONS AND CONJOINT PROJECTS

A. VARIABLE ENERGY

For some experiments in physics research with energetic nucleons (Section V.A.4) it would be desirable to vary the energy of the proton beam continuously or in discrete steps of a few MeV. The SOC does not allow a continuous variation of energy, but it is possible to change the output energy in steps by extracting the beam at any desired orbit. This method would give energy steps of about 35 MeV which would be acceptable for most experiments. Although such a facility would not be generally welcome - because it would complicate performance of the accelerator and introduce grave problems of beam sharing and scheduling (all users would have to adapt to the energy changes dictated by one) - we consider it here as a possible addition that might, some day, find justification.

The SOC has one straight section with no cavity and this section could be used for extraction; its length in the third stage is 255 cm.

For radial extraction, a compact magnet with a field of 35-40 kG would be necessary. This field could be produced by a superconducting magnet, but there are development problems which seem beyond the state of the art in this field at the present time.

Tangential extraction could be accomplished by removing certain pole tips of the bending magnets and allowing the beam to continue in a straight line. This alternative is unattractive for two reasons: it would be very difficult to change the extraction energy, and an extraction path for each turn would have to be provided through the neighbouring cavities and yokes.

Vertical extraction along a path similar to the one used for injection is the most attractive alternative. A radial field of 17.5 kG is required and, although this is possible with conventional magnets, the restriction that the previous orbit should not be affected by the presence of this magnet would complicate the design.

An extractor restricted to energies between 350 MeV and 750 MeV would be easier to build than one working over the whole range of the third stage because the required magnetic field would be smaller and the turn spacing twice that at 1 GeV.

B. STORAGE RING

1. Introduction

The future addition of a proton storage ring placed in the beam transport between the accelerator output and thermal target facility would provide a means of converting the continuous (micro-structure only) beam into a pulsed beam. No detailed investigation of storage methods has been made as part of the present study. Various designs and sizes of ring with different storage capacities are possible. One such arrangement is shown schematically in Fig. XIII.1. The proton beam first passes through a "buncher" which adjusts the beam profile in both momentum and spatial co-ordinates to the requirements of the storage ring. The design of the buncher may present formidable problems at 1 GeV but, beyond recognizing that these can be solved in principle, no attempt will be made to specify the buncher design. The beam is next injected into the ring magnet where it is retained in an orbit and continuously stacked for a pre-determined length of time. The stacked beam is then ejected from the ring into the target in one revolution, a time short compared to the storage time.

Although rings have been constructed and proved successful for the storage of electrons^{1, 2} no storage rings have been built for protons. However, several proposals^{3, 4, 5} have been made for the storage of 25- and 300-GeV protons for colliding beam experiments.

2. Operation and Limitations

The maximum number of protons that can be stacked in a storage ring and the maximum storage time are subject to certain physical limitations. The most restrictive limitations seem to be the following:

¹ C. Bernardini, et al., A 250 MeV Electron-Positron Storage Ring: The "A d A", proc. Intl. Conf. High Energy Accelerators (Brookhaven National Laboratory) TID-7636, 256-261 (1961).

² G. K. O' Neill, Component Design and Testing for the Princeton-Stanford Colliding Beam Experiment, proc. Intl. Conf. High Energy Accelerators (Brookhaven National Laboratory) TID-7636, 247-255 (1961).

³ E. D. Courant, Storage Rings for Ultra-High Energies, report BNL-7091, 34 (1963).

⁴ A. Schoch, Nuclear Instr. Methods 11, 40 (1961).

⁵ B. de Raad, CERN report AR/INT/SG/62-6 (1962).

XIII. B

FIG. XIII. 1 A possible storage ring facility.

2.1 Available Phase Space

A theorem of dynamics⁶ says that the volume of phase space (phase space for a particle is described by three spatial and three momentum co-ordinates) occupied by a group of particles is a constant of their motion if the particles are subject only to conservative forces. In principle, only conservative forces are operative in the acceleration of protons and again in the bunching and storage of the proton beam in the magnetic ring. Thus any group of particles traversing the accelerator storage system occupies a fixed volume of phase space at any instant of time. The storing process is simply the coiling and stacking of a beam of constant phase-space density in a device of limited phase-space capacity. Although it is possible to conceive of a system that would have more than enough phase space, in principle, to meet the present application, it is not obvious that all of this phase space would be easily accessible in practice. This question is discussed further with reference to performance requirements in subsection 3 below.

2.2 Space-Charge Limitations

Even though adequate phase space may be available for the storage of 1-GeV protons, undesirable interactions between the particles can reduce the number that can be stored. For example, transverse de-focussing in the ring can occur because of Coulomb repulsion of the beam. This repulsion is compensated for by the self-magnetic focussing of the beam and the lens focussing of the confining magnetic field. The effect has been investigated theoretically for high-energy storage rings^{3, 7}. The same theory applied to a 1-GeV proton storage ring roughly of the size required for the present application suggests that this effect would be too small by about an order magnitude to interfere with storage, provided the beam is not neutralized by space charge. If it is partially neutralized by a stationary negative cloud the number of protons that can be stored is reduced. For example, if 25% of the particles are neutralized, storage capacity is reduced by a factor of 10. It is stated³ that neutralizing ions can probably be removed with clearing electrodes. Therefore, space charge probably will not present an insurmountable obstacle in the present application.

⁶ See H. Goldstein, Classical Mechanics, Addison-Wesley (1951); J. L. Synge and B. A. Griffith, Principles of Mechanics, McGraw-Hill (3rd. ed.) (1959).

⁷ J. D. Lawson, On the Possibility of Producing Relativistic Self-Constricted Ring Currents, AERE GP/M 196 (1957).

2.3 Mutual Coulomb Scattering

This effect will in time destroy the stacked beam. It is an important limiting factor of electron storage rings. The mean life of a stored electron beam can be predicted from theory based on this effect⁸. The same theory applied to a storage ring of 1-GeV protons, containing $\sim 10^{15}$ particles, predicts a mean life for the beam greater than two minutes. Thus the effect is unimportant for a ring that is dumped several times per second.

2.4 Gas Scattering

The effect of gas pressure on multiple gas scattering of protons has been calculated⁹ for 1-GeV particles orbiting in the Birmingham accelerator. These calculations, which also apply to a 1-GeV proton storage ring, predict that a gas pressure of less than 10^{-7} torr will cause gas scattering of $< 1:10^5$ during a storage time of a few milliseconds. The effect of gas scattering on single Coulomb scattering¹⁰ has been calculated and predicts a similar effect.

3. Required Performance

The relevant parameters of the storage ring for repetitive pulsing of neutron targets are the repetition rate and single-turn-ejection or 'dump' time. In the present application these parameters must be chosen to satisfy as closely as possible the requirements of experiments with both thermal and resonance neutrons (Section V.A. 3 and VII B). It will be assumed that the average current remains 65 mA regardless of the pulse characteristics of the ring.

For thermal-neutron time-of-flight experiments with incident neutron energies $> 10^{-2}$ eV it is convenient to choose a neutron burst time for the moderated neutrons of $5 \mu\text{s}$ (determined by a chopper phased to the bursts from the ring) and a scattered-neutron flight path of 2-4 m. The proton burst (determined by the dump time of the ring) is not an important consideration provided it is short compared to $5 \mu\text{s}$. In order to achieve a resolution of $\sim 1\%$ and, at the same time, avoid frame overlap for scattered neutrons of energies > 0.005 eV, the pulse repetition rate should be ≤ 500 Hz, although rates of ~ 1000 Hz could still be used for

⁸ C. Bernardini, et. al., Phys. Rev. Letters 10, 407 (1963).

⁹ N.M. Blachman and E.D. Courant, Phys. Rev. 74, 140 (1948).

¹⁰ G.K. O'Neill, Experimental Methods for Colliding Beams, proc. Intl. Conf. High Energy Accelerators and Instrumentation - CERN 1959, (Geneva) 23 (1959).

many experiments. From the point of view of ring design, a higher repetition rate is favoured because it means a smaller storage requirement. We have chosen 500 Hz as an acceptable compromise.

For resonance-neutron time-of-flight requirements, the repetition rate of the ring is not an important consideration but must not be much higher than ~ 1000 Hz if one applies the $v/4$ rule for frame overlap (see Section VII B). The time resolution for resonance-neutron time-of-flight spectroscopy depends on the width of the undermoderated neutron burst which will be a function of the storage-ring dump time. The dump time must therefore be kept as short as possible. Here again, a compromise is necessary because short dump times lead to rings of small diameter which provide restricted storage capacity and require strong magnetic fields. We chose a dump time of $0.15 \mu\text{s}$ although, from the experimental point of view, somewhat longer pulses would also be acceptable. The radius for 1-GeV protons is then 6.3 m and the average magnetic field is ~ 9 kG, a convenient strength for strong focussing magnets.

It follows from the above that for continuous operation at an input current of 65 mA with a repetition rate of 500 Hz, the ring must have a capacity for storing $\sim 8 \times 10^{14}$ protons in some 1.3×10^4 orbits. The peak output current in the $0.15\text{-}\mu\text{s}$ burst is ~ 850 A. An upper limit for the diameter of the stacked beam at the target is provided by the diameter of the target to be bombarded, viz. 20 cm, for a target of size equal to that of the thermal target described in Chapter VII.

No further attempt will be made here to detail the geometrical and electromagnetic properties of the ring except to emphasize that it must provide the necessary phase space to store the 1.3×10^4 orbits. This requirement places severe, but not obviously impossible, conditions on the design. To take a fictitious example, assume that the storage ring has the property that, during the process of injection and stacking nothing disturbs the momentum spread or micropulse structure of the beam and at one azimuth in the ring, all stacked orbits are parallel. To conserve phase space, the geometrical area of the stacked beam at that point would then be $\sim 1.3 \times 10^4$ times that of the input beam, which we assume is $\sim 1 \text{ cm}^2$. Such a thick beam would of course present serious difficulties of containment and its diameter would be about 6.5 times larger than that of the thermal-neutron target. There are, however, several ways in which the area of the stacked beam may, in principle, be reduced, e.g. by increasing the strong focussing at the ring, by injecting in such a way that all orbits are never parallel, and by using an injection system for filling the space between micropulses (a gain of a factor of ~ 8 in longitudinal phase space). It should also be noted that the phase-space distribution of the 1-cm^2 beam from the accelerator may be badly distorted in a way which prevents close-packed stacking. If this distortion could be reduced, say by a buncher of sophisticated design, the phase-space requirements would be

further alleviated. These considerations plus the rather obvious observation that one can always, if necessary, resort to multiple rings to increase the available storage or, as a last resort, relax the criteria for repetition rate and dump time, lead to the conclusion that a ring approaching the desired performance can probably be developed.

C. POWER/BREEDER TARGET

Target and blanket research in the original low-power nuclear power technology facility would be expected to lead to a firm design for a power/breeder target to operate with the full beam of high-energy protons. The construction of such a target together with its associated heat removal and electrical generating equipment, would be analogous in magnitude and objective to the construction of NPD in the Canadian power program. Whether it could make a significant contribution to the power program would depend on what fraction of the time the full beam could be diverted into it, what processing facilities were available for the extraction of ^{233}U , and what the demand for ^{233}U was. As an indication of the order of magnitude of its possible contribution, it is worth noting that while it would take about 100 MW to operate, ING could, without any multiplication in the target blanket, produce enough ^{233}U to generate 400-500 MW of power if burned in fully enriched reactors, or provide the make-up fissile material for 4000-5000 MW of CANDU-type reactors operating at an average conversion factor of 0.9.

D. ING AND ELEMENTARY-PARTICLE PHYSICS

1. Introduction

In this Section ING is considered from the standpoint of elementary-particle physics. In subsection 2 the present ING concept (65 mA of 1-GeV protons) is considered and in subsection 3 the possibility of using ING as an injector for a higher-energy accelerator. Conclusions are collected in sub-section 4.

2. ING as an Accelerator for Elementary-Particle Physics

Elementary-particle physics is concerned with the structure and interactions of the elementary particles (nucleons and other baryons, mesons, electrons etc.). Nuclear physics on the other hand is largely concerned with the structure of nuclei as many-nucleon systems. Elementary-particle physics is in a sense the most fundamental field of physics and it has been commonly regarded as the most removed from practical application. Today, however, it would be rash to predict that quarks, the presently hypothetical particles that may be regarded as building blocks from which the baryons are constructed, if discovered in nature would be of no significance for power. Elementary-particle (or 'high-energy') physics research has not been much pursued in Canada until recently¹¹. Several Canadian groups are now collaborating with others in experiments on U.S. accelerators, but the level of financial support for elementary-particle physics in Canada remains low compared with that for nuclear physics. ING would offer a high-intensity beam of protons of ten times the energy of the McGill cyclotron, the highest-energy accelerator at present in operation in Canada. It is then natural to ask if ING would meet Canadian aspirations in experimental particle-physics research.

The answer in brief is that the energy of ING is too low to meet all the needs of particle physics. Although, as discussed in sections V. A. 5 and V. A. 6, ING will provide unique beams of pions, muons and neutrinos, the proton energy is too low to yield a useful intensity of K-mesons. The threshold of K^+ production from protons incident on protons at rest is about 1.5 GeV, for K^- production it is about 2.5 GeV. Because of the momentum distribution of the nucleons in the nucleus, the K production is not zero below these energies, but at 1 GeV it is unlikely to be useful. To argue that K-mesons are essential for what seem to be the most significant areas of elementary-particle physics, an analogy with nuclear physics is helpful. Although a great deal can be learned from nuclear ground states, progress has been much more rapid since low-energy accelerators gave us access to low-lying excited states. At present we

¹¹ E. W. Vogt, et al., Phys. in Canada 21, 3 (1965).

have some understanding of the symmetries of the strong interactions. To understand the dynamics we probably need much more information about the low-lying excited states and that requires K-mesons or even higher energies. The negatively charged K-meson, the most easily produced particle with negative hypercharge, is of special importance for the production of the baryon resonances with hypercharge 0 and ± 1 . The recent excitement about charge conjugation symmetry in K-decay is a different reason why K-mesons are of special interest. We conclude then that it would be undesirable for Canadian elementary-particle physicists to concentrate their attention on ING; while the pion and muon beams from ING would attract some, other Canadian groups should continue on U.S. accelerators. ING should not be regarded as a machine for particle physics although the meson beams are a useful dividend. Given their choice of accelerator, elementary-particle physicists in Canada would choose a machine other than ING. It nevertheless remains desirable to make ING as useful as possible for elementary-particle physics without compromising the main aims of ING.

The attractiveness of ING for elementary-particle physics would be much increased if the proton energy were increased to 3 GeV with a corresponding decrease in proton intensity. The eloquent arguments of Lomon¹² for the importance of 'intermediate energy' physics seem to apply to proton energies of 3 GeV. Certainly a high-intensity accelerator of that energy would open new horizons in high-energy physics. However, the present calculations (Appendix VI.1) indicate an additional total cost (capital plus present value of five years of power) of \$20 million for a 2-GeV SOC compared with a 1-GeV SOC with the same neutron yield and the cost penalty for a linear accelerator seems comparable (Appendix VI.1). There are many uncertainties in the input for these calculations. Assuming the conclusions are unchanged by revised calculations, extension of ING to 2 GeV is probably not justified for particle physics. Even if the extra cost were available for particle physics, it seems probable that the money could be spent more fruitfully in other ways. A 3-GeV ING, if feasible, would be of much greater interest for particle physics and its potential value would increase rapidly with further increase in energy.

3. ING as an Injector for a Higher-Energy Accelerator

The ideal accelerator for Canadian particle physicists would probably be a high-intensity proton machine of energy at least 10 GeV, the energy being dependent on time on the time scale and intensity. Since ING would provide 65 mA of 1-GeV protons, it is natural to consider whether ING could eventually be used as an injector for such a machine. A SOC is at present being studied as a booster injector for Nimrod at the Rutherford Laboratory. We have discussed the question of using ING as an injector for a proton accelerator with a number of accelerator physicists.

¹² E. Lomon, Phys. in Canada 21, (6), 8 (1965).

The general opinion is that the possibility is promising, but detailed study would be required. For an AG machine, according to Russell¹³, it would seem best to use the full 65-mA current with a typical injection time of one milli-second per second. A major problem would be that of keeping the beam emittance sufficiently low. We have not examined these questions in detail. If there is serious interest in ING as an injector, a thorough study (perhaps 3-6 man-months) by accelerator physicists is required.

There are of course many problems apart from accelerator physics in considering ING as a part of a major high-energy-physics facility. Whether the cost can be justified depends on the state of particle physics in Canada and elsewhere and on many other considerations beyond the scope of this report. The U.S. criteria for siting major accelerators include a nearby major international airport and a nearby major university. Certainly transportation facilities to Chalk River are at present inadequate. The ING site layout (Chapter IX) includes sufficient space for possible extension to high energy. An organizational structure suitable for a National Laboratory would also be essential for a high-energy accelerator attached to ING.

If ING appears an attractive injector, there are other possibilities than to build a high-energy machine near ING. Thus an ING-like injector might be the Canadian contribution to an international accelerator to be built elsewhere. In any case increased Canadian experience in accelerator technology is likely to aid particle physics in the long run. ING would encourage nuclear physicists to work in the 100-1000 MeV energy range and some would eventually choose to work in high-energy physics. In the long run then ING would be of indirect interest to particle physics.

4. Conclusions

The presently envisaged proton energy of 1 GeV is too low to make ING an important accelerator for particle-physics research. A 3-GeV ING would be much more attractive. ING appears to be a promising injector for a high-energy proton accelerator but detailed study by accelerator physicists is required for a proper evaluation.

¹³ F.M. Russell, private communication, (1966).

CHAPTER XIV

LINEAR ACCELERATOR

(H.R. Schneider)*

A. INTRODUCTION	XIV. 1
B. LINAC STRUCTURES	2
1. Alvarez Structures	2
2. Waveguide Structures	4
C. RADIO FREQUENCY POWER SUPPLIES	13
1. Choice of Amplifier	13
2. Description of the Amplitron	14
2.1 Principle of Operation	14
2.2 The Amplitron as a Circuit Element	15
2.3 Amplitron Efficiency	18
2.4 The Super-Power CW Amplitron	20
2.5 200 MHz Amplitron Development	23
D. REFERENCE DESIGN	24
1. Choice of Parameters	24
1.1 Cost Minimization	24
1.2 Alvarez Section	25
1.3 Waveguide Section	26
2. Engineering Aspects	30
2.1 General Description of the Project	30
2.2 Alvarez Accelerator Section	30
2.3 Side-Coupled Waveguide Structure	32
2.4 Accelerator Support and Alignment	32
2.5 The RF System	35
2.6 Electrical Power Supplies	52
2.7 Cooling Water Systems	57
2.8 Mechanical Services	59
2.9 Shielding and Activation	60
2.10 Site and Buildings	60
2.11 Cost Estimates	(omitted) --
2.12 Schedule	66
2.13 The Engineering Advantages of a Linac	66

* with supporting contribution from the Shawinigan Engineering Co. Ltd.

XIV. LINEAR ACCELERATOR

A. INTRODUCTION

It was mentioned in section VI.A. that at the start of the ING study the type of accelerator was rapidly narrowed to a choice between a separated orbit cyclotron and a linear accelerator. The SOC was chosen as the first reference design because it promised to be more efficient in the conversion of electrical power to beam power and to have a lower capital cost.

This decision was based on the linear accelerator design for the Yale meson factory, an accelerator designed for pulsed operation producing 800 MeV protons with a peak beam current of 50 mA. The RF power that went into wall losses was expected to be about 86 MW peak. Even with reoptimization for CW operation, as required in ING, the losses still appeared to exceed 50 MW.

When the study of a meson facility for Los Alamos was started several years ago they took as their basis the work already done at Yale. It was soon found, however, that the Yale linac structure as then proposed had drawbacks. Firstly its efficiency was low and secondly it did not appear to be satisfactory for the large beam currents contemplated¹. A new study of accelerating structures, involving both computational and experimental work, was then started at Los Alamos. It resulted in the design of a structure about three times as efficient as the original Yale design.

When the results of this work became known during the latter part of 1965 a review was made of possible RF sources that could drive a CW linac. The Amplitron, considered for the SOC but dropped because a 50 MHz version was not in sight, looked promising in this application. The outstanding feature of the Amplitron is its high DC to RF conversion efficiency (85% is promised). The combination of Los Alamos accelerator structure and Amplitron driver puts this system in strong competition with the SOC as the ING accelerator.

To compare the linac and the SOC on the basis of cost and engineering feasibility it was necessary to produce a conceptual design of an ING linac. In this we have drawn freely on the work at Los Alamos and MURA.

Before discussing the linac design however, a brief description of linear accelerator structures will be given.

¹ L. Rosen, Review of Los Alamos Project, proc. AECL Symp. on Separated Orbit Cyclotrons and Their Uses in Neutron Generation (Chalk River, 1964), FSD/ING-30, 66 (1965).

B. LINAC STRUCTURES

1. Alvarez Structure

Basically this accelerator is a long cylindrical cavity in which an electromagnetic standing wave is established through some type of coupling (such as a loop) to a properly tuned radio frequency source. The particular mode of oscillation that is excited is designated TM_{010} . This mode has an alternating axial electric field which has its maximum value on the axis of the cylinder, dropping to zero at the wall, and circular magnetic field lines having zero intensity on the axis and rising to a maximum near the wall.

To accelerate an ion, it is injected into the cavity along the axis at a time when the electric field is in the direction of motion. Since the ion cannot traverse the entire length of the cavity during one half of an RF cycle it is necessary to put a series of electrostatic screens (copper tubes) along the axis. The spacings and lengths of the tubes are chosen so that the ion will be drifting through a tube, screened from the electric field, while the field is in the reverse direction. The length of each succeeding drift tube is increased so a particular ion (the synchronous particle) will arrive at each successive gap at the same relative phase. The principle of phase focussing² applies here as it does in the SOC.

Since longitudinal or phase stability implies radial instability³ some provision is necessary to counteract the radial defocussing forces due to the electromagnetic field. This is accomplished using the strong focussing principle⁴, the required quadrupole magnets being within the drift tubes.

In principle acceleration to any given energy is possible by making the cylindrical cavity long enough and/or increasing the electric field strength. Practical considerations, however, impose certain limitations. It is found that the cavity length should not exceed 20λ (λ is the wavelength corresponding to the resonant frequency) in order to limit excitation of spatial harmonics that would lead to a non-uniform field on the axis⁵. In the language of the accelerator designer, tank flattening becomes very difficult for cavities longer than 20λ .

² Chapter VI, Section A.

³ J. J. Livingood, Cyclic Particle Accelerators, Van Nostrand, 284 (1961).

⁴ *ibid*, p. 195.

⁵ G. W. Wheeler and S. Giordano, RF Structures for Linear Accelerators, *proc. 1st National IEEE Particle Accelerator Conf. (Washington)*, NS-12, (3) 110 (1965).

The maximum electric fields allowed in the accelerator are determined by one or other of two considerations.

- a) Sparking Limit: If the electric field is too high sparking occurs between adjacent drift tubes. The minimum field at which sparking occurs depends on factors that are not well understood. The frequency of the RF and the material and surface condition of the drift tubes all play a role. For a 200 MHz linac, 15 MV/m is considered a conservative maximum value for the electric field at the drift tube surfaces⁶.
- b) RF Losses: The RF power loss in the cavity walls and drift tubes varies as the square of the field strength. Either the cost of providing the power for the wall losses or the cost of heat removal can limit the field strength.

Alvarez linear accelerators built or proposed to operate near 200 MHz have cavity lengths less than 30 meters. The energy gain in this distance depends on many design factors but is generally 50 MeV or less. For higher energies more cavities are used. A proposed 200 MeV injector, for example, for the ZGS proton synchrotron would use eight cavities⁶.

A figure of merit for a linear accelerator structure is its shunt impedance, defined by,

$$ZT^2 \equiv \frac{(\Delta W)^2}{PL}$$

where ZT^2 is the effective shunt impedance including the effect of the transit time for the proton crossing the accelerating gap,

ΔW is the energy gain of a proton which is centred in the accelerating gap when the field is a maximum.

PL is the RF loss to the structure of length L .

For an Alvarez structure the shunt impedance falls as the unit cell length increases*. That is, the accelerator becomes less efficient as proton energy is increased. Economic considerations dictate that when proton energies beyond about 200 MeV ($\beta \gtrsim 0.5$) are required more efficient structures must be sought.

⁶ Title One Report and Cost Estimate for the 200 MeV Injector Proposal for the Zero Gradient Synchrotron, (Argonne National Laboratory, p. 34 (1965)).

* The unit cell length is the distance from the centre of one drift tube to the centre of the succeeding one. For the n^{th} accelerating cell this distance is equal to $\beta_n \lambda$ where $\beta_n (= v/c)$ is the average velocity of the synchronous particle in the n^{th} cell.

Since it can be shown that $ZT\alpha^2 f^{1/2}$, the obvious way to reduce the RF losses to the structure is by increasing the operating frequency.

Unfortunately other factors must also be taken into consideration when determining the operating frequency. Two of these are the finite beam size and the minimum drift-tube-quadrupole size necessary for radial focussing.

To accommodate the beam from the pre-accelerator it is general practice to use a 1 cm radius drift-tube bore-hole. With this as a fixed parameter then, increasing the operating frequency, i.e. reducing the accelerator tank diameter, implies a larger radial variation of the electric field across the bore hole. Particles travelling off axis will therefore experience a different acceleration from those on the axis, leading to a strong coupling of the longitudinal and radial oscillations of the beam.

An increase in the operating frequency also entails a decrease in cell lengths. At injection energies (usually less than 1 MeV) the drift tube lengths become too small for the incorporation of the high-gradient quadrupole magnets if the frequency is much above 200 MHz.

The frequency limitations become less severe as the proton energy increases. In fact at an energy of about 200 MeV transition to a higher frequency becomes attractive. The higher frequency must obviously be a multiple of the initial frequency. It has been shown⁷ from considerations of particle dynamics that following a proton linac at 200 MHz accelerating to 200 MeV we may use a linac at, at most, 800 MHz without losing part of the beam at the transition.

2. Waveguide Structures

A series of cylindrical pillbox cavities, as illustrated in Fig. XIV.1, resonant in the TM_{010} mode and driven by separate RF sources can function as an accelerator if the relative phases of the RF drivers are properly adjusted. Such accelerators have in fact been built for electrons^{8,9}.

⁷ G. W. Wheeler and T. W. Ludlam, The Effects of Phase and Field Errors on the Longitudinal Motion in a Long Proton Linac, proc. Yale Conf. on Proton Linear Accelerators (1963), TID-7691, 29 (1964).

⁸ H. L. Schultz and W. G. Wadey, Rev. Sci. Instr. 22, 383 (1951).

⁹ T. J. Boyd, et al., Rev. Sci. Instr. 36, 1401 (1965).

FIG. XIV. 1 "Pillbox" Cavity Linear Accelerator.

FIG. XIV. 2 Dispersion Curve for an Iris-loaded Waveguide.

To overcome the need for a multiplicity of RF sources and their phasing the accelerating cells can be made contiguous, with suitable RF coupling. A single RF source can then drive a number of cells.

In the simplest case coupling is achieved through the axial beam holes. This construction is the familiar iris loaded waveguide used in electron linacs¹⁰.

The electrical behaviour of the coupled cavities differs from that of a single cavity. The single TM_{010} mode is split by the coupling into N (where N is the number of cavities that are coupled) discrete modes, characterized by phase differences of $0, \pi/N, 2\pi/N, \dots, \pi$ radians between adjacent cells.

A typical plot of the mode frequency versus the phase shift between adjacent cells (usually denoted by βl) is shown in Fig. XIV.2¹¹.

The conventional choice of operating mode for a chain of coupled cavities is the π mode where the field in any two adjacent cavities at any instant of time are in opposite directions, as illustrated in Fig. XIV.3. It will be noted in Fig. XIV.2 that the $\omega, \beta l$ curve (the dispersion curve) has zero slope at the π mode so that the adjacent mode tends to be near the operating mode. Close mode spacing at the operating mode implies very tight tolerances must be maintained in the fabrication of the structure to insure that each cell has the same resonant frequency so that it will be possible to excite the desired π mode without excitation of the adjacent mode.

In the case we are considering the bandwidth of the structure, defined by

$$2 \left(\frac{\omega_0 - \omega_\pi}{\omega_0 + \omega_\pi} \right) \times 100\% \quad \text{may be used as a measure of the mode}$$

spacing.

The bandwidth of a possible iris loaded accelerator structure is around 1 - 2%⁵, which requires an extremely tight fabrication tolerance if this structure is to be used in the π mode.

¹⁰ A. L. Eldridge, et al., Design and Fabrication of the Accelerating Structure for the Stanford Two-Mile Accelerator, SLAC-7 (1962).

¹¹ A Proposal for a High Flux Meson Facility at Los Alamos, 434 (1965).

FIG. XIV. 3 π -mode Operation of a Chain of Coupled Cavities.

FIG. XIV. 4 Slotted Iris Structure.

The bandwidth can be increased by increasing the cell to cell coupling. Increasing the size of the beam hole does this but also reduces the shunt impedance. Alternatively magnetic coupling through slots in the iris can be used to increase the coupling. Such a structure, illustrated in Fig. XIV.4, has been studied extensively at Yale and BNL^{12, 13}. Typical parameters of a slotted iris structure proposed for the new AGS injector are given in Table XIV.B.1.

TABLE XIV.B. 1

TYPICAL PARAMETERS OF SLOTTED IRIS
STRUCTURE OF THE PROPOSED AGS INJECTOR

	At 187 MeV	At 500 MeV
Shunt Impedance	15.4	28.2 M Ω /m
Slot Angle	50°	50°
Bore Hole Diameter	2 in	1.75 in
Cavity Diameter	9.25 in	9.25 in
Bandwidth	8%	6%

Another method of magnetic slot coupling is accomplished as follows: four symmetrically placed indentations are made in the walls of the accelerating cavity, resulting in the circular magnetic field lines of the TM₀₁₀ mode being distorted so that they have radial components. Locating eight slots in the septum along these field lines then couples the electromagnetic energy from one cell to the next. This is known as the "clover-leaf structure" and is illustrated in Fig. XIV.5. To make the radial field the same on both sides of the slot in the π mode adjacent cavities are rotated 45°. The cloverleaf structure was originally proposed for accelerator use by Carne¹⁴ and has been studied in considerable detail at Los Alamos. Until very recently it was proposed as the structure for the high energy part of their meson facility linac¹¹.

¹² A Proposal for Increasing the Intensity of Alternating-Gradient Synchrotron at the Brookhaven National Laboratory, BNL 7956, (1964).

¹³ S. Giordano, Characteristics of Slotted Irises, proc. 1964 Linear Accelerator Conf. (Midwestern Universities Research Association), MURA-714, 60 (1964).

¹⁴ A. Carne, Crossbar and Cloverleaf Structures at Rutherford, proc. Yale Conf. on Proton Linear Accelerators, TID-7691, 104 (1963).

FIG. XIV. 5 Exploded View of the Cloverleaf Structure.

FIG. XIV. 6 Fields in a $\frac{\pi}{2}$ mode Structure.

Among the advantages claimed for the cloverleaf structure are the following¹¹:

- a) High efficiency as an accelerator.
The effective shunt impedance for a proton linac is $30 \text{ M } \Omega/\text{m}$ at 350 MeV.
- b) Loose tolerance requirements.
By designing the slots to have a resonant frequency near the operating frequency, large effective coupling coefficients can be achieved. Thus machining tolerances are relaxed.
- c) Freedom from spark breakdown in the coupling mechanism
There is little or no electric field in the coupling slot. High power tests to 1.6 times the design field for the LAMPF linac show no sparking¹⁵.

The structures considered so far have all been intended for π mode operation, since the highest shunt impedance is realized with this mode. π mode operation means, by definition, operation at a maximum or minimum of the dispersion curve where the mode spacing is small and the group velocity ($v_g = d\omega/d\beta$) is zero. The disadvantages of close mode spacing have already been pointed out. Zero group velocity means the structure is sensitive to beam loading which will alter phase and amplitudes of the electromagnetic fields in the accelerating cells.

The advantages of using the $\pi/2$ mode which is in the centre of the dispersion curve, where mode spacing and group velocity both have a maximum, have been pointed out¹⁶.

The field pattern, at a particular instant in a periodic structure excited in this mode, is indicated in Fig. XIV.6. Alternate cells have no fields in them other than those necessary to couple energy to succeeding cells to make up for losses. The shunt impedance for a structure excited in this mode is therefore approximately half that for the π mode structure. To overcome this loss in efficiency Giordano¹⁷ has studied a slotted iris structure in which the coupling cells are shorter than the

¹⁵ J.R. Parker, et al., High Power Test on a Cloverleaf Cavity, proc. First National IEEE Particle Accelerator Conf. (Washington), NS-12 (3) 156 (1965).

¹⁶ E. Knapp, 800 MeV RF Structures, proc. Linear Accelerator Conf. (Midwestern Universities Research Association) MURA-714, 31 (1964).

¹⁷ S. Giordano, Some New Radio Frequency Accelerating Structures, proc. First National IEEE Particle Accelerator Conf. (Washington) NS-12 (3), 213 (1965).

accelerating cells. With drift tube loading in the accelerating cell and a two inch beam hole, shunt impedances of $16 \text{ M } \Omega/\text{m}$ for $\beta = 0.5$ (150 MeV) and of $28 \text{ M } \Omega/\text{m}$ for $\beta = 0.8$ (650 MeV) were measured. These values are about the same as for the π mode slotted-iris structure, however, the $\pi/2$ mode structure is at least ten times less sensitive to tank tuning errors.

Another method of improving the π mode shunt impedance is illustrated in Fig. XIV.7. In this the coupling cells are completely removed from the beam line and put on the side of the structure. Fig. XIV.8 is a cutaway view of such a structure developed at Los Alamos¹⁸. Since the fields in the coupling cavities are small centre post loading can be used to reduce the cavity size without affecting the Q of the structure.

A 47-cell sheet copper model of the side coupled structure, built at LASL, has a shunt impedance in excess of $30 \text{ M } \Omega/\text{m}$ at $\beta = 0.68$ ¹⁸ (350 MeV). More recent models machined from OFHC copper forgings have shunt impedances close to $45 \text{ M } \Omega/\text{m}$ for $\beta = 0.76$ (500 MeV).

Because of the advantages, already listed, of the $\pi/2$ mode, the simple construction (simpler than the cloverleaf) and the high shunt impedance, the side coupled structure is now proposed for the high energy portion of the Los Alamos Meson Facility Linac.

The conceptual design of an ING linac uses this structure for acceleration of the protons from 165 MeV to the final energy of 975 MeV.

¹⁸ B. C. Knapp, et al., Resonantly Coupled Accelerating Structures for High Current Proton Linacs, *ibid* ref. 17, NS-12 (3) 159 (1965).

FIG. XIV. 7 Side-coupled π mode Structure.

FIG. XIV. 8 Los Alamos Side-coupled Structure.

C. RADIO FREQUENCY POWER SUPPLIES

1. Choice of Amplifier

The choice of the RF power supply to provide the 65 MW of beam power plus losses is a major design decision comparable to, or even more important, than the choice of the accelerating structure.

The prime requirements for the RF driver for an ING linac are:

- 1) High DC to RF conversion efficiency.
- 2) Reliable operation and long operating life. Failure of a driver in most cases would mean a shutdown of the accelerator.

In addition to reasons given in Chapter VI, CW operation of the linac is desirable in order to make the beam loading problem no more severe than necessary.

The RF power is required at two frequencies, 200 MHz and 800 MHz (nominal values).

Gridded tubes (triodes, tetrodes), klystrons, and crossed-field devices (travelling wave tubes, magnetrons, amplitrons) have all been built to operate at these frequencies. However, not all would be suitable for linac service.

The reference design of the linac outlined in section XIV. D suggests that the 200 MHz power should be supplied in 1.4 MW units and the 800 MHz power in 500 kW units.

The Coaxitron represents the present state of the art at 800 MHz for gridded tubes¹⁹. Its average output power of 75 kW is far short of what is required.

A 1.25 MW, 800 MHz CW klystron is said to be feasible²⁰ but has not been built. A klystron has the advantage of very high gain (30-50 db) which simplifies the intermediate power-amplifier requirements. Unfortunately its efficiency would probably not be better than 60%. Lifetimes

¹⁹ M. V. Hoover, Grid-Controlled Power Tubes in Particle-Accelerator Applications, ibid, NS-12, (3) 76 (1965).

²⁰ O. C. Lundstrom, Triodes and Klystrons at Ultra-High Frequency, ibid, NS-12, (3) 222 (1965).

of klystrons in accelerator service are not encouraging. At SLAC for example, where there are 240 klystrons driving the two mile electron linac, they expect a failure rate of 2-3 tubes a day. This is tolerable for an electron linac, where a tube failure does not require the accelerator to shut down, but not for a proton linac.

Of the crossed field devices the Amplitron* is the most promising. The largest unit built for service at 800 MHz delivers 100 kW CW. The development of a 500 kW unit is considered to be straightforward²¹. An efficiency of 74% was obtained in the early development stage of the 100 kW unit and 85% plate efficiency for a 500 kW unit is considered possible. The tube structure is rugged, having no fragile grid or thermionic cathode - both sources of tube failures in other devices. A water-cooled platinum secondary-emission-cathode is used. Reliability in accelerator service should be high.

The Amplitron is, however, unproven in accelerator operation. Experience in operating it into a narrow band load, such as a linac cavity, is limited.

Evaluation programs have been started on the Amplitron at Los Alamos and CRNL. Pending an adverse finding it will be specified as the RF source for the waveguide part of the ING linac reference design.

2. Description of the Amplitron†

2.1 Principle of Operation

The Amplitron is basically a travelling wave tube (TWT) amplifier, the essential features of which are a slow wave structure on which an electromagnetic wave is propagated and an electron beam with a velocity equal to the phase velocity of the electromagnetic wave. The electron beam travels close to the slow wave structure so that a strong interaction between the electromagnetic field and the beam occurs.

* Trademark: Raytheon Co.

²¹ Raytheon Technical Report MPO-023, The Amplitron and its Use in an RF System for a CW Proton Linear Accelerator, FSD/ING-50 (April, 1966).

† Most of this information is based on information in reference 21.

Figure XIV.9 is a schematic representation of a simple linear TWT, consisting of a helical slow wave structure and an axial electron beam. When the electrons enter the helix they interact with the axial electric field of the electromagnetic wave on the helix. This leads to velocity modulation of the beam and subsequent bunching. The bunched beam induces an RF voltage on the helix which, if the electron velocity is correct, will add to the existing voltage and result in tighter bunching. A rapid buildup of the electromagnetic field travelling along the structure occurs at the expense of electron beam energy. The travelling wave tube may thus be regarded as a linear accelerator operating in reverse.

In appearance the Amplitron resembles a magnetron more nearly than the linear TWT just described. The periodic circular anode which supports the slow RF wave travelling from input to output is concentric with the cathode. An axial magnetic field confines the electrons to approximately circular orbits in the interaction space between the anode and cathode. Figure XIV.10 is a schematic representation of the Amplitron structure.

The device does not have a collector but uses a reentrant electron beam, as in a magnetron. The non-reentrant RF structure distinguishes it from the magnetron.

The principle of operation of the Amplitron is similar to that of the TWT described. In it electrons emitted from the cathode follow spiral paths because of the crossed electric and magnetic fields. As the anode to cathode DC potential difference is increased the electrons' azimuthal velocity increases till it becomes equal to the phase velocity of the RF wave on the periodic anode structure. Then the electrons assemble in rotating spokes of space charge, the number of spokes depending on the mode of operation. In the interaction, the potential energy of the electrons is converted directly into microwave energy as they travel from the cathode to the anode via the spokes.

The RF currents thereby induced on the anode add in the direction of the output and cancel in the direction of the input, amplifying the drive signal.

2.2 The Amplitron as a Circuit Element

The Amplitron may be looked upon as a two terminal pair device with phase shift properties which are nearly reciprocal, but with amplification properties that are not. Figure XIV.11 illustrates these properties. If energy is fed into the input it appears amplified at the output, however energy fed into the output connection appears essentially unaffected in amplitude at the input connection.

FIG. XIV. 9 Helix type Travelling Wave Tube.

FIG. XIV. 10 Schematic of the Amplitron.

FIG. XIV. 11 Basic Circuit Properties of the Amplitron.

The input-output characteristics of a typical Amplitron are shown in Fig. XIV.12 for various values of DC input. For a given DC power input the RF power output is relatively independent of the RF power input. The 500 kW DC input curve, for example, shows that a ten-fold increase in drive power from 10 kW to 100 kW results in less than a fifty per cent increase in output power, i.e. the device behaves as a saturated amplifier. Departure from such behaviour occurs when the drive power is comparable to the output power.

As the drive power is reduced a point is reached where the input does not control the output frequency. The output then becomes noisy, poorly defined, and at some frequency other than the input. The transition region between controlled and uncontrolled output is well defined and narrow.

Because the input and output circuits of the Amplitron are not isolated the tube can act as a self-excited oscillator. For example, when operating into a narrow band load (such as a linac tank) the Amplitron sees a mismatch at frequencies different from the desired operating frequency. A spurious signal would be reflected back through the Amplitron without attenuation. If the impedance of the input line to the Amplitron is also mismatched for the spurious frequency and the distance between the input and output reflection planes is an integral number of wavelengths, then an oscillatory buildup of the spurious signal will occur. Proper design of input and output circuits incorporating appropriate filters can, however, prevent the oscillations.

2.3 Amplitron Efficiency

Crossed-field devices such as the magnetron or Amplitron have demonstrated over-all efficiencies considerably in excess of that obtained from other microwave tubes. The Amplitron in particular has demonstrated efficiencies of 75% at nominal 10 db gain. Specially designed Amplitrons have been run with over-all efficiencies as high as 90% and it is claimed to be within the realm of possibility to extend the same design principles to the super-power Amplitron.

The theoretical electronic efficiency derived from simple theory is given by,

$$\eta_e = [(2B/B_0 - 2)] / [(2B/B_0 - 1)]$$

where B is the applied magnetic field and B_0 is the magnitude of the magnetic field for grazing of the anode by electrons at the synchronous velocity. Simplifying assumptions made in obtaining this relation are:

FIG. XIV. 12 Typical Performance Chart for Amplitron.

- a) the device is mechanically ideal and electrically lossless,
- b) the electrons interact synchronously with the proper component of the RF field,
- c) the electrons reach the anode radius with zero radial velocity (and therefore do not collide with the vanes) and
- d) the cathode losses are negligible.

The theoretical efficiency, as a function of B/B_0 , is plotted in Fig. XIV.13. The dashed curve in this figure represents typical Amplitron performance as a function of B/B_0 . A third curve on the graph gives the results of measurements made on an experimental Amplitron designed for high B/B_0 ratio. As can be seen this tube had an efficiency of 90% at $B/B_0 = 8$. The drop in efficiency for higher B/B_0 is not understood.

2.4 The Super-Power CW Amplitron

The generation of large amounts of CW power with an Amplitron has been best demonstrated by the Raytheon QK 1224. This Amplitron, operating as S-band, has delivered over 400 kW of CW power.

Of more interest for the linac application is a new model operating at 805 MHz and delivering 100 kW of CW power. Figure XIV.14 is a photograph of this tube, which could be used as the basis of the development of the higher power version required for the linac.

The DC to RF conversion efficiency of these super-power Amplitrons is high. An efficiency of 74% has been measured for both tubes mentioned above and it is anticipated that 80 - 85% should be achieved by using a higher B/B_0 value and a higher anode voltage. Between two and seven percent of the DC input power goes into cathode loss through back bombardment current. In super-power tubes this current is large and energetic enough to allow the use of a cold secondary emission cathode. A water-cooled platinum cathode is used in the super-power Amplitrons. This in addition to simplifying construction, is expected to give a long service life (tens of thousands of hours).

The microwave, super-power Amplitrons have employed high pressure water cooling (~600 psi) for the anode vanes. Because of the larger structure at 800 MHz the anode power densities are decreased and large cooling channels can be provided so that 60 psi coolant will be sufficient. Thus problems of reliability associated with high pressure cooling do not exist for UHF tubes.

FIG. XIV.13 Typical Amplitron Efficiency as a Function of B/B_0

FIG. XIV. 14 The 100 kW, CW, 805 MHz Amplitron.

2.5 200 MHz Amplitron Development

The size of Amplitron structures is inversely proportional to the frequencies at which they are designed to operate. Hence scaling from existing microwave or UHF Amplitrons would give a very large device for operation at 200 MHz.

If, however, one uses lumped-element circuits in the slow-wave structure, it is possible to design Amplitrons having dimensions of the order of one tenth of their operating wavelength.

Work along this line, to produce a compact high power VHF-UHF Amplitron, has been carried out by the Raytheon Co. The anode structure of these tubes is supported by insulators and the slow-wave structure made up of coils forming inductances which are connected to the anode vanes. Experimental models of such structures have been built and in principle a 200 MHz 1.5 megawatt tube of this type with better than 80% efficiency could be developed.

Development work on the lumped element structure is at an early stage and at the present time long term stability of the anode support ceramics is not known. One is concerned with contamination of the ceramic by impurities in the coolant which passes through it and the possible deposition of vaporized metal. It is therefore considered somewhat premature to seriously consider now the lumped element Amplitron for accelerator service.

D. REFERENCE DESIGN

1. Choice of Parameters1.1 Cost Minimization

In the short time that the study of the linear accelerator has been in progress it has not been possible to carry out an independent design for the ING project. Instead we have used the basic linac designs developed at MURA and Los Alamos and tried to adapt and optimize them to give what is believed to be a reasonable picture of a linac that would work for ING.

To determine the length and accelerating gradients for the linac a cost minimization procedure is followed.

The cost formula for a linac may be written as,

$$C = C_p P + C_L L + C_f \quad (1)$$

where C_f = fixed costs,
 C_p = power dependent costs per unit of power,
 C_L = length dependent cost per unit length,
 L = accelerator length,
 P = total power to excite the accelerator to operating field gradients without a beam.

The cost of power supplied to the beam is a fixed cost and does not play a role in selection of the length or gradients of the accelerator.

Using the relations,

$$P = (E_0 L)^2 / ZL \quad (2)$$

and

$$\Delta W = E_0 L T \cos \phi \quad (3)$$

where E_0 is the accelerating field gradient,
 Z is the shunt impedance of the structure per unit length,
 T is the transit time factor,
 ϕ is the stable phase angle and
 ΔW is the proton energy gain,

(1) becomes

$$C = (C_p (\Delta W)^2 / Z T^2 L \cos^2 \phi) + C_L L + C_f. \quad (4)$$

Thus, apart from C_f the linac cost formula contains one term proportional to the accelerator length and another inversely proportional to the length.

The length that results in minimum cost is

$$L_{\text{opt}} = (C_p / C_L Z T^2 \cos^2 \phi)^{1/2} \Delta W. \quad (5)$$

Substituting (3) into (5) gives the value for the accelerating gradient that minimizes the cost, i.e.

$$E_o = (Z C_L / C_p)^{1/2}. \quad (6)$$

With this value for E_o the length costs equal the power costs for the accelerator.

Putting (5) into (4) gives the cost minimum,

$$C_{\text{min}} = 2 \Delta W (C_p C_L / Z T^2 \cos^2 \phi)^{1/2}.$$

The above relations can now be used to arrive at the conceptual design of the ING linac.

1.2 Alvarez Section

This part of the accelerator is based on a 100 mA 200 MeV linac designed at MURA²² for pulsed operation. The operating frequency is 200 MHz. In altering this design for CW operation the accelerating gradients have been reduced by the factor $\sqrt{(0.094/0.55)}$ which reflects the difference

²² B. Austin, et al., The Design of Proton Linear Accelerators for Energies up to 200 MeV, MURA-713 (1965).

in the value for C_p used in equation 6. For the ING linac the assumed value for C_p is 0.55 dollars per watt. This is made up of 0.35 dollars per watt for the capital cost of the RF equipment plus 0.20 dollars per RF watt for the present value of five years of power, (this cost is for AC power at Chalk River assuming 80% AC to RF conversion efficiency). The capital cost of the RF equipment is taken from the budgetary estimate for the cost of the 805 MHz linac RF system²³. We assume the 200 MHz unit costs are approximately the same.

Table XIV.D.1 summarizes the design parameters for the CW Alvarez linac. Acceleration is from 0.75 MeV to 165 MeV in thirteen cavities that vary in length from 6.45 meters to 18.0 meters. The gradients in the third to thirteenth cavities are half the values used in the MURA design (in view of the approximations and assumptions made to arrive at this design we seem justified in taking $\sqrt{(0.094/0.55)} \approx 1/2$). The accelerating gradients in the first two cavities are not optimized, but rather are kept at the same value as used by MURA, in order to circumvent beam blow-up problems that may arise in the low energy stages if the acceleration rates are too low.

1.3 Waveguide Section

For acceleration beyond 165 MeV the side coupled waveguide structure operating at approximately 800 MHz will be used. The shunt impedance of the structure increases with increasing proton velocity, approaching 60 M Ω /m as β approaches one. A proper optimization of the accelerator would take into account the variation of ZT^2 ; for the present however, an average value for ZT^2 of 40 M Ω /m will be assumed for the 165 MeV - 975 MeV waveguide part of the accelerator.

A length dependent cost of 12×10^3 dollars per meter, based on Los Alamos estimates for their LAMPF project, will be used in the design optimization. This cost is consistent with the costs of the Stanford Linear Accelerator. A synchronous phase angle of 26° ($\cos \phi = 0.9$) is assumed. Putting the foregoing values in equation (5) we find the average rate of acceleration for a cost minimum is,

$$\Delta W/L_{\text{opt}} = 0.84 \text{ MeV/m.}$$

Using equations (2) and (3) the RF wall losses in the structure are found to be 21.8 kW/m for a 0.84 MeV/m acceleration rate. The RF power required for a 65 mA beam is 54.6 kW/m, making the total RF power requirement 76.4 kW/m.

²³ Raytheon Co., private communication, (May, 1966).

TABLE XIV. D.1

ALVAREZ LINAC BASED ON MURA 100 mA 200 MeV DESIGN

Cavity No.	Length Meters	E in MeV	E Out MeV	Gradient MV/m	RF Power Losses		
					Wall MW	Beam (65 mA) MW	Total MW
1	6.45	.75	10.4	1.89	.77	.63	1.40
2	6.45	10.4	20.0	1.89	.77	.63	1.40
3	14.3	20.0	34.8	1.4	.42	.96	1.38
4	14.3	34.8	49.6	1.4	.42	.96	1.38
5	14.5	49.6	63.4	1.4	.47	.90	1.37
6	14.5	63.4	77.3	1.4	.47	.90	1.37
7	15.3	77.3	90.6	1.35	.50	.86	1.36
8	15.3	90.6	104.0	1.35	.50	.86	1.36
9	15.6	104.0	116.3	1.3	.50	.80	1.30
10	15.6	116.3	128.7	1.3	.50	.80	1.30
11	16.9	128.7	140.8	1.25	.53	.79	1.32
12	16.9	140.8	153.0	1.25	.53	.79	1.32
13	18.0	153.0	165.00	1.20	.54	.78	1.32

XIV. D

The RF drive will be provided by Amplitrons in units of 500 kW. Thus one Amplitron could drive 6.67 meters of the linac. The length of an individual accelerator tank is however limited by field flattening considerations to less than $20 \beta \lambda$, or approximately 3 meters at the injection end. With a power splitter one Amplitron can drive two 3 meter tanks. Since there is some advantage to power splitting in this way this arrangement will be used for the entire accelerator length.

In the design chosen the waveguide portion of the linac consists of a series of tanks 3.12 meters long, each having approximately 40 acceleration cells. A less crude calculation taking into account the variation of ZT^2 with β would result in a slight increase in the length of the tanks as the proton energy increased. The tank lengths should be chosen so that the full output power of the driver Amplitron is utilized.

The proton energy gain in one tank is 2.63 MeV. By using 308 tanks, which allows convenient splitting of the controls and services along the linac into eleven sectors, the final proton energy would be about 975 MeV. Table XIV.D.2 summarizes the parameters for the waveguide part of the accelerator, and Fig. XIV. 15 summarizes the Linac reference design.

TABLE XIV.D.2

WAVEGUIDE LINAC DESIGN PARAMETERS

Operating Frequency	800 MHz
Number of Tanks	308
Length of Tank	3.12 m
Inter Tank Space	1 m
Over-all Length of Section	1269 m
Input Energy	165 MeV
Output Energy	975 MeV
Power Dissipation in Tank Walls	68 kW/tank
Total RF Power per Tank (65 mA beam)	235 kW
RF Power Unit	500 kW (nominal) Amplitron (each unit drives two tanks)

FIG. XIV. 15 Block Diagram of ING Linac.

2. Engineering Aspects

2.1 General Description of the Project

The use is assumed of an injector stage of the Cockcroft-Walton type, together with its supporting services, similar to that used in the main ING study. The disposition of the 975 MeV beam after leaving the linear accelerator is also assumed similar.

The linear accelerator takes the proton beam from an energy of 0.75 MeV up to 975 MeV in a straight line some 4800 feet long. The first section, about 15% of the length, is of the Alvarez drift-tube type operating at 200 MHz, and accelerates the beam from the injection energy to 165 MeV. The remainder is a waveguide section operating at 800 MHz.

Physically the accelerator consists of a beam tunnel partly below grade and covered with soil for shielding (see Fig. XIV.29). To one side and at grade level runs an equipment gallery which houses the RF power equipment, cooling water pumps and general services. At intervals of about 460 feet the equipment gallery broadens out into a larger building containing switchgear, water treatment plant, air conditioning equipment and so on. The equipment gallery is connected to the beam tunnel by service corridors at frequent intervals for carrying pipes, cables and waveguides. All buildings are air conditioned and the accelerator temperature controlled.

2.2 Alvarez Accelerator Section

In the present reference design the mechanical design of the Alvarez section is copied from existing linacs. Each tank is built of copper-clad steel, rolled and welded into sections which bolt together. Inside the tank are drift tubes suspended on adjustable stems. Within each drift tube there are cooling channels, as precise temperature control is essential to keep the tank operating on frequency. Regulation to $\pm 0.25^\circ\text{F}$ is feasible and necessary. Further cooling channels are welded to the tank surface, as shown in Fig. XIV.16. Quadrupole magnets incorporated within the drift tubes are DC excited, requiring about 500 watts each. Accurate alignment of quadrupoles, both geometrically and magnetically, is essential.

The tanks are evacuated by two roughing pumps in series operating on each tank in turn. These are located in the equipment gallery and are valved off when the pressure is low enough to be picked up by the ion pumps mounted on the accelerator support structure. The pumping units may be portable.

Tank tuning may be either by altering the operating temperature or by the use of slug tuners attached to each tank.

FIG. XIV. 16 Conceptual Arrangement of Alvarez Section.

The RF power is fed into each tank by a drive loop at its mid-point. The connections are made with spring rings and the vacuum seals with metal gaskets.

2.3 Side-Coupled Waveguide Structure

This structure is fabricated from accurately machined copper forgings brazed together to form sections. No work has been done to determine the most economical method of manufacture, nor has a design specification been completed.

The waveguide is assumed to consist of 3-meter sections. Figure XIV.17, which is freely copied from the LAMPF design study¹⁵, shows a possible arrangement. The space of 1 meter between sections is occupied by a quadrupole triplet and an isolation valve.

Temperature control to $\pm 0.25^\circ\text{F}$ is required to keep the tanks at resonance and is provided by a high-flow-rate circulating water system. As with the Alvarez stage, vacuum is provided initially by roughing pumps located outside the beam tunnel and finally by ion pumps mounted on the accelerator itself.

Each tank is supported on four brackets which permit alignment adjustment.

Two tanks are driven by each Amplitron chain, the RF power being introduced into the centre point of each tank through an iris coupling which may be adjusted for the purpose of matching the impedance of the supply waveguide to the impedance of the tank. The operating frequency is 800 MHz (approx.).

2.4 Accelerator Support and Alignment

One of the largest single uncertainties in the design of a linac for ING is the best means of providing and maintaining accurate alignment of the cavities and magnets. It is not possible to guarantee that civil engineering structures will remain accurately aligned over such a long distance; the effects of settlement, ground movement, seasonal temperature changes, earth tremors etc. will inevitably cause movements. The best design philosophy is to arrange for realignment to be possible at any time, which is not difficult with a linear accelerator.

Alignment tolerances for the quadrupoles in the LAMPF linac have been analyzed, using beam dynamics computer programs developed at CRNL²⁴. The results, presented here for illustrative purposes only, are believed to be indicative of the magnitude of the tolerances that must be met in the ING linac alignment.

²⁴ B.G. Chidley, private communication (1966).

FIG. XIV. 17 Conceptual Arrangement of Waveguide Section.

<u>Type of Misalignment</u>	<u>Max. error</u>	<u>Sketch</u>
Random transverse error from centre line	$< 0.65 \text{ mm}$
Random transverse error from from previous quadrupole triplet	$< 0.72 \text{ mm}$
Constant transverse shift quadrupole triplets No. 20 to No. 90 from centre line	3.6 mm
Constant angular error per quadrupole triplet from previous triplet	$0.023^\circ/\text{cell}$ $2^\circ \text{ end to end}$	1
Constant transverse shift from previous quadrupole triplet	3.8 mm
Transverse shift quadrupole triplet No. 20 only	3.1 mm
Random rotation about an axis perpendicular to the beam line	$< 0.29^\circ$

Satisfactory alignment requires three things :

- a) Initial alignment to a high order of accuracy. This is a straightforward engineering problem.
- b) Detection and identification of a departure from the initial alignment. This will be indicated in the first instance by RF pickups monitoring the position and phase of the beam but it will also be desirable to have mechanical means of checking the movement.
- c) Means for re-aligning the machine. This the most difficult problem to define since its solution depends on the amount of induced activity to be expected in the beam tunnel. Standard optical methods may be used if direct physical contact with the cavities is permissible; if not, a fairly elaborate and expensive remote realignment procedure as in Stanford two-mile accelerator, may be needed.

An intermediate solution would be to provide in the first instance for manual realignment and also facilities for the addition of the necessary remotely-operated jacks, servo-mechanisms, television cameras

etc. if it turns out that frequent adjustments are in fact necessary and that activation is beginning to build up. It could well be found that most movement and settlement takes place in the first year or so and that this can be coped with manually.

No detailed study has been carried out on this problem and no elaborate remote equipment has been included in the present cost estimate.

2.5 The RF System

2.5.1 RF System for the Waveguide Section

2.5.1.1 General Description

The recommended RF system is shown in block diagram form in Fig. XIV.18. The system consists essentially of a 500 kW output Amplitron, a 36 kW driver Amplitron, and a 2 kW high gain klystron. The 500 kW output is divided equally by means of a magic tee, each arm feeding an accelerator tank through a filter. Each Amplitron will operate at 13 db gain and each tube design is optimized for its particular output power. The klystron drive power is low enough to allow the use of a varactor -type fast phase-shifter at its input.

Directional couplers at the output of each tube sense fast changes of reflected power due to RF arcs. This information is used to trigger a protect circuit in the DC power supply. Additional fault protection is provided by DC arc and high gas pressure sensing circuits.

A 20 db circulator located between the driver and output Amplitron provides a good match for the driver Amplitron under normal operating conditions and, in the event of an RF arc in the load, will take output power for the time required to turn the system off. An isolator between the klystron and driver Amplitron performs the same function.

A closed-loop phase correcting system, similar to that described in the Los Alamos report²⁵, will maintain system phase stability within $\pm 2^\circ$. A varactor type phase -shifter will be used to compensate for fast phase shifts that occur as a result of power supply ripple and changes in beam loading. A slow phase shifter will correct for system drifts and phase changes that occur when the output Amplitron power is increased from minimum to maximum. The phase reference is the common drive line. The phase in the tank is compared with the reference phase and the resulting error signal is used to control the phase shifters. The slow and fast phase shift controllers will respond only to the required rate of change.

²⁵ Ibid, reference 11, p. 472.

FIG. XIV. 18 RF System for Waveguide Section of the Linac.

Constant voltage is maintained in the accelerator tanks by comparing the voltage in each tank with a common reference level. Corrections must be made for fast changes in beam loading and slow drifts due to temperature and line voltage fluctuations. The slow changes can be corrected either by the DC power supply primary controller or by an adjustment of magnetic field with the electromagnets. The former is recommended in the system described. Fast variation of beam loading results in an extremely fast change in demand on the RF system. A series control device, with the necessary response characteristics, is used to control the output of the driver Amplitron and thus supply the change of RF output required.

The DC power supplies proposed here are individual units for each microwave tube. The controls can be arranged so that all supplies are operated from a central operating position.

The operating procedure is as follows: the klystron and then the driver Amplitron are slowly raised to full power. The RF energy will pass through the output Amplitron with very little attenuation and into the accelerator tanks. The output Amplitron power is raised slowly until 136 kW is reached (68 kW into each tank), the beam and the phase and amplitude correcting circuits are then turned on and the power is raised until the desired operating level is reached. For shutdown, the power can be decreased slowly or a fast turnoff method described later can be used.

A detailed description of the operation of the proposed RF system and its major components is provided in the following sections.

2.5.1.2 Amplifiers

(i) Output Amplitron

The 500 kW Amplitron will utilize two backward wave Amplitrons in cascade within a single vacuum envelope, as has been done for S-band super-power Amplitrons. By operating the second stage at 3 db gain the power dissipation is divided equally between the stages. The specifications for the output Amplitron are:

Frequency	805 MHz
CW power output	500 kW
Drive power	32 kW
Electronic bandwidth	$\pm 5\%$
Gain	13 db
Efficiency	85%
Anode voltage	35 kV

Anode current	15.7 A
Phase pushing	$0.5^\circ/1\% \Delta I_b$

Input and output to the slow wave structure will be coupled to conventional WR975 waveguide.

(ii) Driver Amplitron

This tube will be similar to conventional backward wave Amplitrons. Specifications for the driver Amplitron are:

Frequency	805 MHz
CW power output	36 kW
Drive power	1.8 kW
Electronic bandwidth	8%
Gain	13 db minimum
Efficiency	85%
Anode voltage	20 kV
Anode current	2.01 A

(iii) Klystron

To amplify the 50 mW RF signal from the common drive line to the 2 kW level a klystron such as the Eimac 4KM3000LR is proposed. This is a four cavity klystron designed to operate in the band 610 - 985 MHz and to deliver a minimum of 2 kW CW with a gain of at least 45 db.

2.5.1.3 Power Supplies

(i) Output Amplitron Power Supply

The 500 kW Amplitron power supply will be rated at 550 kW and will operate at 35 kV DC. Expected efficiency is 95%. Figure XIV.19 is a block diagram of the supply.

Input AC line voltage could be 13 kV*. A primary line controller of the Inductrol type will permit continuous control of the input voltage from 10% to 100%. It will also be used to control slow variations in the linac RF

* More recent studies indicate that 34.5 kV would be preferable.

XIV.D

FIG. XIV. 19 Output Amplitron Power Supply Block Diagram.

power level, as shown in the block diagram. A $\pm 1\%$ regulation of the power supply input voltage can be maintained by the controller. Full output Amplitron RF power range control will thus be provided to permit proper aging and turn-on procedures for the linac.

Twelve-phase solid-state rectification with series stacked and balanced Δ and Y outputs will be used. Primary and secondary RC despiking will minimize rectifier switching transients appearing on the AC line or on the RF waveform, in addition to protecting the rectifiers. The rectifiers will have a reverse avalanche voltage (Zener type) characteristic which protects them from voltage failures common to high voltage power supplies. A 100 kW power supply recently designed has this type of rectifier and can be successfully snapped on and off at full power.

A multisection LC filter will be used to reduce voltage ripple to 0.1% peak to peak from power line frequencies up to 100 kHz. A swinging choke will be employed to help maintain critical inductance over the large dynamic power range (and proportional current change) expected of the RF system. Sufficient capacitance will be provided for the maximum operating current.

A crowbar of the infinite range, high energy, vacuum gap type, described in the section on crowbar protection, will be used and will, in turn, be protected by a main line circuit breaker in the primary.

This power supply, along with the others proposed, will be designed to operate at a maximum ambient temperature of 50°C and 90% relative humidity. Component deratings, to provide the reliable life expected, will be as follows: capacitors -- 70%, resistors -- 50% power, semiconductors -- 50% power, all in accordance with their ratings for maximum operating temperature. Use of vacuum tubes will be minimized. Circuitry which would be subject to periodic replacement will be built as plug-in type modules whenever practical.

(ii) Driver Amplitron Power Supply

The driver Amplitron power supply is rated at 20 kV and 40.2 kW. The basic design is shown in the block diagram of Fig. XIV.20. The power supply will be snapped on at 80% of nominal operating voltage, taking into account $\pm 10\%$ line voltage variations, and will have boost transformers and a primary controller having approximately 40% of the input power handling capability. Slow speed line voltage compensation to $\pm 1\%$ for DC output voltage variations will be sensed and controlled as shown in the block diagram.

XIV. D

FIG. XIV. 20 Driver Amplitron Power Supply Block Diagram.

Twelve-phase solid-state rectification will be accomplished by series stacking balanced and rectified Δ and Y outputs. An LC filter is used to reduce the series control circuit range and thus to maximize its response. The basic design would hold $\pm 0.1\%$ voltage ripple at rated current with a balanced line.

The triggered spark gap will bypass arc energy by the series control circuit within 10 μ s after fault occurs.

(iii) Klystron Power Supply

The proposed klystron power supply block diagram is shown in Fig. XIV.21. It is basically a filtered three-phase full wave rectified power supply with solid-state rectifiers.

Snap-on and snap-off operation of the supply is possible since the 2 kW RF output can be easily dissipated without serious arcing problems. The proper sequence of voltage application and turn-off would be maintained. For CW operation the modulating anode will be strapped to ground and tube arc protection maintained by clamping the cathode to ground with a thyatron crowbar.

2.5.1.4 Magic Tee

The power from the output of the final amplifier is split into two equal branches by use of a magic tee also known as an E/H or hybrid junction tee. Refer to Fig. XIV.22 magic tee's have the qualities of bridge circuits. When a signal is fed into the shunt branch and both arms of the straight or colinear section are terminated in matched loads the power will divide between the two colinear arms. Because of the structural symmetry no net electrical vector will be developed across the entrance to the series branch and there will be no electrical coupling between the shunt and series branches. If the colinear arms are not terminated with matched loads, RF power will be reflected back to the junction from both terminations. Arrival of the reflected waves at the junction in phase results in power flow out of the shunt arm but not the series arm. A 180° phase difference between the waves at the junction results in power flow out of the series arm but not the shunt arm. With the series arm terminated with a matched load the latter characteristic can be used as a means of absorbing energy reflected from the accelerator and is discussed in more detail in section 2.5.1.8.

2.5.1.5 Filter

In section XIV.C.2.2 the need for a filter between the Amplitron and a narrow band load, such as the linac tank, was pointed out. Spurious oscillations can occur near the lower cut-off frequency of the

FIG. XIV. 21 Klystron Power Supply Block Diagram.

FIG. XIV. 22 Magic Tee Power Splitter.

Amplitron. It is the function of the filter to act as an energy absorber at these frequencies.

A drawing of a typical filter is shown in Fig. XIV.23. L_2 and L_3 are adjusted so that at position A there will be a short circuit at 800 MHz and an open circuit at the spurious frequency. Spurious energy, therefore, will pass through the filter and will be absorbed in its matched termination. 800 MHz energy will be transmitted to the accelerator tank. This type of filter must be located near the accelerator tank, a small number of $1/2$ wavelengths from the detuned short of the accelerator tank.

2.5.1.6 RF Amplitude Control

An approach for regulating the power level of the RF chain is shown in the block diagram in Fig. XIV.24.

Large RF power changes and control during run-up and aging are provided by the primary controller when directed by the discriminator output. The discriminator is adjustable and permits the series tube to operate at the minimum dynamic range for maximum efficiency.

Since the drive power for an Amplitron appears in the output a limited amount of fast amplitude control can be produced through a series regulator in the anode supply of the driver Amplitron. To compensate for a $\pm 1\%$ change in load at the accelerator tank (due to a variation in beam loading) a $\pm 20\%$ change in the driver output power is required.

A 10 μ s response time for the fast regulation is expected.

If further studies indicate that more fast regulation than provided for above is required a series regulator in the 500 kW Amplitron anode supply could be used. This would however lower the overall RF efficiency.

2.5.1.7 Phase Control

As the output power is raised the phase shift through the Amplitron increases. To compensate for this a slow phase shifter is incorporated in the input line of the RF chain. A ferromagnetic device will probably be used to cover a $\pm 90^\circ$ range.

Because of variations in beam loading fast phase shift compensation will also be required. Varactor diodes used as terminations in three or four-port networks such as 3 db hybrids, directional couplers, or circulators can provide continuous phase control. Phase modulation response to at least 10 MHz is possible with these devices. Fast phase shift compensation must also be done at low level, since the power handling capacity of the varactor devices is less than 1 watt.

FIG. XIV. 23 A Proposed Filter, showing Approximate Dimensions.

FIG. XIV. 24 R. F. Amplitude Control Block Diagram.

2.5.1.8 System Shutdown in the Event of a Fault

An accelerator malfunction that results in loss of control of the beam will require a fast shutdown of the beam and removal of the RF drive from the tanks. The latter can be accomplished by shifting the drive frequency up by a few percent, thus making the accelerator tanks appear as reactive loads at the end of the waveguide and hence reflecting the incident power. If the two arms from the hybrid tee feeding two tanks from a common Amplitron differ in length by $\lambda/4$ the reflected power from the tanks will arrive at the junction 180° out of phase and will be propagated in the series arm but not in the shunt arm. Power in the series arm is dissipated in the terminating (water) load.

The expected volt-ampere characteristics for the 500 kW Amplitron²⁶ indicate that the frequency shift will also result in reduced power output. Thus the power handling capabilities of the waster load can be relatively low.

In addition to providing for switch off of the accelerator in case of an emergency, while other slower acting protective devices remove the AC power, this system has the versatile capabilities of (a) removing RF power for an extended period without actuating other switches, (b) making it possible to restore normal full load conditions immediately to the accelerator, or (c) to cycle through some prescribed tune-up schedule without actuating any crowbars or contactors.

Further studies are necessary to determine whether the klystron in the RF chain has sufficient bandwidth for this shutdown method. If not use of a 2 kW CW travelling wave tube has been suggested²⁷. Such a tube is being developed as a driver or intermediate power amplifier for high power radar systems in the 700 - 1400 MHz range.

2.5.1.9 RF System Efficiency

The overall AC to RF efficiency of the system is equal to the power output (500 kW) divided by the total AC power input to the system. Assuming an efficiency of 85% for the Amplitrons and 45% for the klystron, the DC inputs are as follows:

Output Amplitron	550 kW
Driver Amplitron	40.2 kW
Klystron	4.4 kW
Total	594.6 kW

²⁶ Raytheon Report MPO-023; Vol. I, FSD/ING-50 (1966).

²⁷ Ibid, reference 26, Vol. II.

With a power supply efficiency of 95%, AC input power is 626 kW.

AC Power to DC Supplies	626 kW	
Klystron Heater Power	.155 kW	
Klystron Magnet Power	.850 kW	
Amplitron Magnet Power	1.500 kW	
Auxiliary 115 V AC Power	5.0 kW	
Total		633 kW

Overall AC to RF conversion is

$$\frac{500}{633} \approx 79\% .$$

2.5.1.10 Equipment Layout

Figure XIV.25 shows a proposed layout of equipment for an RF system. The equipment is contained in a module with approximate dimensions of 18 feet deep x 12 feet high x 30 feet wide. Each power supply cabinet contains all of the electronic circuits necessary for its particular amplifier stage. The phase shifting comparator and controllers are mounted in the klystron power supply cabinet. The rectifier transformers, rectifier and primary controller for the Amplitrons may be located outside. The advantages of this would be (a) to reduce the inside space requirements, (b) to reduce heat dissipation requirements and (c) to prevent the possibility of fires from mineral oil insulation or to eliminate the need to use expensive "Askarel" insulation. The rectifiers could be located in the same enclosure as the rectifier transformers - immersed in the same insulating oil.

The tube cabinets contain such components as detectors, directional couplers, transitions and electromagnets as well as the microwave tubes. The isolator, circulator, magic tee and terminating loads are located above the cabinets so that there is walking room throughout the module. The magic tee is located so that phasing to each tank is correct. All electrical and plumbing connections are of quick disconnect type so that the complete module can be easily removed and replaced by another identical one.

2.5.1.11 Elimination of Output Window

In future studies consideration will be given to the possibility of using an output Amplitron without an RF output window. RF windows are a problem common to all types of high power microwave tubes. A large percentage of the catastrophic failures that occur result from

FIG. XIV. 25 RF System Module.

cracking or melting of the output window and loss of vacuum. The elimination of the output window would greatly increase reliability and thus reduce the downtime of the accelerator.

With the Amplitron and accelerator sharing a common vacuum, it is necessary for all components inserted between the tube and accelerator to be vacuum-tight and to be constructed of materials compatible with a vacuum system. All waveguides, for instance, are made of OFHC copper and the ports of the filters and magic tee's to which loads are attached should have RF windows to prevent contamination of the system with power absorbing material. Loads are of the water cooled dry type or the irradiation chamber type to eliminate the possibility of filling the system with water. A suitable vacuum crush type seal is required between the waveguide and the RF input to the accelerator tank.

The Amplitron should be exhausted with an exhaust tubulation located near the input window in order to reduce the possibility of a plasma discharge across the input window when driver power is applied or when DC power is applied to the Amplitron.

To facilitate the aging process a cartridge type heater can be attached to the external anode structure. The heater would be used until a gas pressure of at least 10^{-6} mm Hg is obtained. It would be replaceable.

The Amplitron would be processed and tested in a similar manner at the factory, operating into a dummy load which would represent the load imposed by the accelerator tank. After testing, the tube would be filled with an inert gas at a moderate pressure in order to prevent contamination during shipment and handling at the site.

The platinum cathode is particularly adaptable to this type of operation because, not absorbing gas as does a thermionic type cathode, a long out-gassing procedure is not required.

2.5.2 RF System Alvarez Section

A study comparable to the 800 MHz system has not been done for the 200 MHz supply of the Alvarez accelerator.

The choice of a final amplifier for this part of the accelerator requires further investigation. It appears that either a klystron or Amplitron may be suitable but 200 MHz is lower than the frequencies at which these devices have been operated. Thus, from the RF system point of view, there is some incentive to operate the Alvarez accelerator at a higher frequency.

The possibility of using 400 MHz will be investigated.

2.6 Electrical Power Supplies

2.6.1 AC Load Requirements

The linac presents the following problem in electrical power distribution: about 18 MW of 200 MHz power to be evenly distributed along the first 600 ft and a further 77 MW of 800 MHz power along the remaining 4,200 ft.

The 18 MW load is divided into 13 units of 1.4 MW (nominal) each, i.e. one unit for each Alvarez tank. Thirteen rectifier substations supply this load. From the point of view of the AC supplies, there are 13 loads of about 1.9 MVA each at 0.9 lagging power factor (without capacitors) plus two loads of 20 kW each for the focussing magnets. Shunt capacitors are tentatively assumed both for harmonics filtering and for power factor improvement.

The waveguide part of the accelerator is powered by 154 RF chains each rated at 500 kW output. Each chain will be fed from a rectifier substation rated at 725 kVA. The power factor is again 0.9 lagging (without capacitors).

Power to the rectifier substations will be supplied at 34.5 kV using a double source feed for reliability. Each of the RF chains may be individually controlled by a load-break switch installed on the 34.5 kV side.

A breakdown of the AC load requirements for the basic 65 mA facility, including those listed above, is given in Table XIV.D.3. Load requirements for the full meson facility are given in Table XIV.D.4.

A comparison of Table XIV.D.3 with the comparable breakdown for the SOC²⁸, shows that the lighting load is larger for the linac because of the larger building areas involved. Also greater are the load requirements for the pressurized and purified water supply and for the cooling tower.

²⁸ T. A. Creaney, et al., The Shawinigan Engineering Co. Ltd., ING Site Layout and Services, Costs, Schedule and Alternative Linac, AECL Documents FSD/ING-61 (1966).

2.6.2 AC Power Distribution

Tables XIV. D. 3 and XIV. D. 4 show that the total power requirement, at the utilization level, for the basic 65 mA facility is 154.7 MVA which will increase to 216.8 MVA for the full meson facility. Apart from the 12.5 MVA supplied by generators at the thermal power plant (which is run on heat from the target) this power will be supplied to the facility from the Ontario Hydro grid at 230 kV. The power requirement at this point is 157 MVA increasing to 224 MVA for the full meson facility. The power is distributed at three voltages: 34.5 kV, 4.16 kV, and 600 volts. Figure XIV. 26 is a single line diagram of the distribution system. The system is essentially the same as the one for the SOC.

TABLE XIV. D. 3

AC LOAD REQUIREMENTS. BASIC 65 mA FACILITY

No.	Description	MW	Power Factor	MVA _r
1	65 mA Injector	0.20	0.95	j0.06
2	RF Supply for Alvarez and Waveguide Sections	119.50 *	0.952	j39.40
3	D-C Magnets	3.73	0.955	j1.16
4	Vacuum Pumps	0.99	0.95	j0.31
5-8	Experimental Areas	4.60	0.98	j0.94
9	Target Circulation	0.55	0.92	j0.22
10	Moderator Circulation	0.22	0.91	j0.09
11	Pressurized and Purified Water	3.96	0.90	j1.92
12	Cooling Tower	3.15	0.927	j1.27
13	Process Heating	0.67	1.00	-
14	Instrumentation	0.72	0.80	j0.46
15	Building Services	7.40	0.925	j3.10
		145.69		j48.93
Total: 154.7 MVA, composite power factor: 0.948 lag.				

* This load figure is for a 65 mA, 1015 MeV proton beam. Recent re-calculations of the optimum accelerating gradient have indicated it should be lower than originally specified. Without changing the physical layout or dimensions of the linac, the final proton energy, with the optimum gradient, is 975 MeV. This value has been used throughout this chapter. AC load calculations and costing are based on the earlier 1015 MeV design.

TABLE XIV. D. 4

AC LOAD REQUIREMENTS. BASIC 65 mA FACILITY
PLUS FULL MESON FACILITIES

No.	Description	MW	Power Factor	MVAr
1	65 mA Injector	0.20	0.95	j0.06
2	RF Supply for Alvarez and Waveguide Sections	119.50 *	0.952	j39.40
3	D-C Magnets	3.73	0.955	j1.16
4	Vacuum Pumps	0.99	0.95	j0.31
5-8	Experimental Areas	63.50	0.978	j13.20
9	Target Circulation	0.55	0.92	j0.22
10	Moderator Circulation	0.22	0.91	j0.09
11	Pressurized and Purified Water	4.02	0.90	j1.95
12	Cooling Tower	3.25	0.927	j1.31
13	Process Heating	0.67	1.0	-
14	Instrumentation	0.72	0.8	j0.46
15	Building Services	9.11	0.929	j3.66
		207.56		j61.82
Total: 216.8 MVA, composite power factor: 0.958 lag.				

* This load figure is for a 65 mA, 1015 MeV proton beam. Recent re-calculations of the optimum accelerating gradient have indicated it should be lower than originally specified. Without changing the physical layout or dimensions of the linac, the final proton energy, with the optimum gradient, is 975 MeV. This value has been used on the earlier 1015 MeV design.

2.7 Cooling Water Systems

2.7.1 General

All waste heat from the linear accelerator is rejected to cooling towers as shown in Fig. XIV.27. Three main units will dissipate the heat generated in the target area, the meson building, all experimental areas and in the main office building. The linac is divided into a convenient number of substations from which both electrical and mechanical services are distributed. Each of the 13 substations contain individual pumps, heat exchangers, water treatment plants and a roof mounted cooling tower to dissipate the heat generated in the cavities, RF tubes, magnets, and ventilation system.

Three grades of cooling water are used:

- a) Very pure, low conductivity demineralized water is used for cooling the large RF Amplitron tubes. These are very large cooling loads as most of the power losses occur in them. Low conductivity water is essential because of the high operating voltage.
- b) Purely demineralized water with inhibitor is used for cooling the accelerator cavities, focussing magnets, co-axial cables, and other equipment where corrosion control is important but high voltages are not encountered.

Chemically treated raw water is used on the secondary side of heat exchangers handling the purified water in (a) and (b) above and for various other duties such as building cooling systems, motor bearings, etc.

2.7.2 RF Power Supply

The tube manufacturers have provide the following specification for the cooling water to be used in the final amplitrons (500 kW size).

Specific resistance	0.5 megohms per cm
Oxygen content	15-20 ppm
Foreign matter particle size	less than 10^{-3} in
Pressure	60 psi
Flow per tube	47 gpm

FIG. XIV. 27 Typical Cooling Water Flow Diagram for one Waveguide Sector.

This water quality may be easily maintained by the deioniser columns shown in Fig. XIV.27. Each of the 11 sectors in the waveguide section has its own deioniser unit, serving the needs of 14 Amplitron chains. The total flow of deionised water in each sector will be 655 gpm, picking up 1750 kW in each sector.

The Alvarez section is divided into 2 sectors, each with a heat loss in the RF tubes of 200 kW. Hence each sector will require a cooling water flow of 830 gpm.

2.7.3 Cavity Cooling

The resonant frequency of all stages of the linac depends on the cavity dimensions and therefore will change if the dimensions change. A design figure has been chosen to maintain the temperature of cooling water flowing through the cavities to $\pm 0.25^\circ\text{F}$ of the set point, which will probably be 80°F in the Alvarez Section. The waveguide section will be fine-tuned by adjustment of the set point. A closed loop, recirculation system is used for cavity cooling. The output temperature is sensed, and a signal controls the input of water through a flow control valve.

Separate circuits are required for the quadrupole and drift tube cooling in the Alvarez section and for the quadrupole triplet magnets between each tank in the waveguide section.

Certain of the cavity cooling circuits may need electric heater elements to raise the cavity temperature to the resonance condition. This has not been decided yet.

2.8 Mechanical Services

The beam tunnel requires close temperature control and a design figure of $\pm 1^\circ\text{F}$ about the set point has been chosen. It would appear desirable to air condition the beam tunnel separately from the equipment gallery so that activated air and dust cannot reach rooms occupied by people.

The air conditioning requires to be broken down into 15 units corresponding to the 15 mechanical services control buildings, with a self-contained plant in each. It is not expected that refrigeration will be required, but the air conditioning system will be capable of both rejecting heat to the cooling water and of heating the buildings in cold weather.

The tunnel and equipment gallery will be divided by partitions, which do not require to be airtight, to form the 15 separate sections. At the high energy end special arrangements may be added at a later date if activation of the air becomes a problem.

2.9 Shielding and Activation

Shielding requirements vary with beam energy along the length of the accelerator. The radiation level in the equipment gallery is estimated to be below danger levels, even in the event of a complete beam spill.

The beam tunnel is of reinforced concrete construction sunk below grade and covered with earth fill. The total thickness from the roof of the tunnel to the earth surface varies from 15 ft at the low energy end to 32 ft at the exit end.

2.10 Site and Buildings

2.10.1 Site Layout

The same reference site is used for the linac as for the SOC reference design. The site plan is shown in Fig. XIV.28. For simplicity, the basic arrangement of the buildings beyond the accelerator is left unchanged except for a slight reorientation of the thermal neutron facility to allow the linac to be sited on the flattest portion of the reference site. The RF equipment gallery and mechanical equipment rooms are on the south side of the linac as this allows easier access between the central control building and the rest of the facilities. An access road along the south side of the linac facilitates maintenance of equipment in the RF equipment gallery and accelerator tunnel.

2.10.2 Beam Tunnel

The beam tunnel is of reinforced concrete having inside dimensions of 13' -0" wide by 15' -0" high, as shown in Fig. XIV.29. This structure is built in an open trench with the roof of the tunnel at the level of the existing grade. After completion of construction the excavation is backfilled with free draining material and this material is piled over the tunnel to provide radiation shielding. The shielding is 15' thick over the roof of the tunnel at the injector building graded to 32' at the entrance to the high activity tunnel.

Service tunnels at 37' -6" centres along the length of the beam tunnel carry mechanical and electrical services from the RF equipment gallery to the accelerator in the tunnel.

For ventilation the tunnel is divided into sectors each 460' long. An 8' -0" access tunnel connects each sector to a mechanical equipment room which houses maintenance facilities for the accelerating equipment. A service lift in each of these tunnels is provided for moving heavy equipment between the mechanical equipment room and the main beam tunnel. Each of the 460' sectors in the main tunnel is serviced by a 5-ton bridge crane, running along the tunnel.

FIG. XIV. 29 Beam Tunnel Plan and Sections.

2.10.3 Equipment Gallery

The equipment gallery is a structural steel building to house the RF and auxiliary equipment. It is a one storey structure 29 feet wide and 15 feet high. Service tunnels 30 feet long at 37' -6" centers along the north wall of the building connect it to the beam tunnel (see Fig. XIV.30). Most of the south wall of the building consists of a reinforced concrete retaining wall of variable height, necessary to prevent the sand shielding over the beam tunnel from encroaching on the equipment gallery.

The north wall of the building consists of sliding panels which facilitate maintenance of the RF equipment and allow a fork-lift truck to remove defective units without disrupting the rest of the RF equipment.

2.10.4 Mechanical Equipment and Control Buildings

The mechanical equipment rooms house the heat exchangers, pumps and ventilation equipment for each sector of the RF gallery and the accelerator tunnel. A service elevator connects each room to the access tunnel and the accelerator tunnel. A 5-ton overhead bridge crane services this building and truck doors are provided at one end of the building to allow for transfer of equipment.

The central control building houses the local controls for the accelerator and is located at the mid-point of the accelerator length. A basement area contains electrical power and control cables and the main floor level the control room, offices, and maintenance areas.

2.10.5 Injector Building

The injector building shown in Fig. XIV.31, houses the two injector machines, beam transport and auxiliary equipment. An electronics shop, control room and mechanical equipment room is contained in an area adjacent to the injector machine room. The floor of the injector machine room is approximately 40' below grade to allow for installation of the injectors at an elevation which will allow the beam to enter the accelerator tunnel without any vertical bending magnets.

Below grade, the walls of the building are of reinforced concrete and above grade structural steel superstructure and roof.

A 5-ton overhead bridge crane on a 60' span services the injector machine and staging area. Access is provided to the staging area by a service elevator from the RF equipment aisle.

FIG. XIV. 30 Beam Tunnel Plan.

FIG. XIV. 31 Injector Building Plan and Sections.

2.12 Schedule

The concept of the Critical Path Method (CPM) planning, scheduling and control will be used to direct management effort. Based on knowledge presently available, arrow diagrams have been prepared for the ING LINAC reference design. This information was used to prepare a logic bar-chart schedule.

The analysis shown in figure XIV.32 has resulted in a completion date of June 1st, 1973, for proton beam commissioning to 1 GeV at 65 mA.

2.13 The Engineering Advantages of a Linac

The following notes are some comments on the advantages of a linear accelerator over a cyclotron from the engineering point of view, following a parallel evaluation of the two systems over the past four months. Although this does not cover judgement of the economics or feasibility of beam production, it does appear that the engineering requirements set for the linac are far easier to achieve in practice than those set for the SOC.

a) Civil Engineering Aspects

The linac has a low ground loading, and so sets far less stringent restraints on site selection. It is almost essential that the heavy SOC structures should be set on bedrock.

The linac beam tube is supported by a mechanical structure which is easily adjustable in any direction. The linear accelerator is much more tolerant of settlement and movement of the civil structure because it can be so easily realigned. The SOC places very fine tolerances on the civil works, so that even unavoidable effects such as concrete shrinkage are a real cause for concern. The relative lightness of the linac beam tunnel also helps to minimize settlement.

The linac civil structure may be made uniform throughout its length, which greatly simplifies construction. A continuous overlapping construction programme may be developed so that the structure may be built quickly with a minimum labour force.

In the event of a major design change taking place during or after construction of a linac, it would not be an impossible task to shorten or lengthen the machine. Once construction begins on a SOC, its size is irrevocably fixed. Construction work could begin on a linac before all design details are completed, but this would not be true for a SOC.

b) Mechanical Aspects

For the greater part of its length a linear accelerator consists of a number of identical components. These components lend themselves to automatic production, with easy control of the close manufacturing tolerances necessary and with scope for reducing costs. The SOC components are all virtually "hand made" because of the variations between them.

A linear accelerator may be set up to a high order of accuracy by purely optical means. It may be checked for linearity at any time during its life with little difficulty, and the degree and the location of the misalignment may be identified. Even more important, the entire process of identifying and correcting a misalignment may, if desired, be carried out remotely using television and servo-actuated jacks.

It would almost certainly be impossible to align the beam tube of a SOC to the same order of accuracy. A spiral would have to be set out from a central reference point by radial and azimuthal measurements. The time necessary for full alignment of the machine is impossible to estimate at this time.

What is most alarming, however, is the situation that would arise if a fault or misalignment developed in a SOC which had become seriously activated. If in the course of time a portion of linac structure became highly active due to beam spill, one can envisage a repair being feasible, by sectioning off the affected part. The problem of access to the SOC would be very serious. In other words, activation (whose magnitude is not known, although it usually tends to be underestimated) could spoil the feasibility of a SOC, but could be tolerated in a linac.

CHAPTER XV

COMPETITIVE SYSTEMS

(L.G. Elliott, J. Mullin)

A. INTRODUCTION	XV.1
B. DISCUSSION	2
1. Very-High-Voltage Tandem Van de Graaff Accelerators	2
2. The Superconducting Linear Accelerator	4
3. The Protatron	5
4. The "Janes-Type" Accelerator or HIPAC	6
5. The Staticelerator	7
6. The Super-SOC	8
C. SUMMARY OF CONCLUSIONS	9

XV. COMPETITIVE SYSTEMS

A. INTRODUCTION

When the ING study began in late 1964, and selected for its reference accelerator the Separated Orbit Cyclotron (SOC), there was also initiated a parallel study of "possible means of producing high-energy (500 MeV - 2 GeV) high-current beams of protons for use in an ING target assembly".

Three principal avenues of investigation were followed:

- 1) A search for possible means of replacing RF acceleration by DC devices.
- 2) A search for very-high-efficiency RF systems produced by "emerging" technology (e.g. superconducting cavities).
- 3) An investigation of other means of producing high neutron fluxes (e.g. fusion).

This last approach was soon dropped and attention given in the main to DC devices and to RF systems other than the SOC. Literature searches were initiated and a number of systems investigated. The "conventional" linac, which appears to be the principal competitor with the SOC, is covered elsewhere in this document.

From the study, the following "ideas" or "devices" seemed the most promising (and the first of them would appear to be ideally suited to serve as an injector to either an SOC or a linac, whichever is finally selected as the accelerator for ING) :

- 1) A very-high-voltage tandem Van de Graaff accelerator
- 2) A superconducting linac
- 3) A "protatron" -- a type of "betatron for protons"
- 4) A "Janes type" accelerator, in which a cloud of electrons is used to set up a very high electric field gradient
- 5) A staticelerator, in which protons can be given increased potential energy without changing their velocity
- 6) A Super-SOC -- a variant of the SOC, suggested by F.M. Russell in January, 1966.

B. DISCUSSION

1. Very-High-Voltage Tandem Van de Graaff Accelerators

Throughout the investigations into 'Competitive Systems' there has been the hope that it would be possible to produce the required 65-mA beam of 1-GeV protons by simple DC acceleration, thereby avoiding (a) the inefficient, and hence expensive, process of converting DC power to RF power, and (b) the complex magnetic guiding fields of the SOC.

Consideration has been given to two possibilities:

- that all the acceleration be done by a DC device, or failing that,
- that DC be used to take the proton beam to some intermediate energy.

A DC accelerator of the type required for ING would be a very large extrapolation beyond the capabilities of the existing machines of this type, both in terms of voltage and current. The present-generation machine -- the MP Tandem -- will operate with a terminal potential of 12 MV and will use accelerating tubes that are expected to operate normally with a field gradient of 1.5 MV/m (gradients from the terminal, in the SF₆ insulating gas transverse to the beam path, will be of the order of 12 MV/m). Typical currents will be in the 10- μ A range.

It is worthy of note that while there are limits on the maximum voltage gradient attainable with present-day commercially available "inclined field" accelerating tubes, no limitation is believed to exist on the total voltage attainable^{1,2}. It might, therefore, be possible to build a 1-GeV accelerator for protons using existing technology, but this would be so large that its capital cost would be prohibitive.

Laboratory developments indicate that gradients of 8 MV/m can now be maintained on accelerating tubes³ and that, with a suitable

¹ J.G. Trump, Nuclear Instr. Methods 28, 10-15 (1964).

² K.H. Purser, et al., Properties of Inclined-Field Acceleration Tubes, Proc. MIT Symp. on Insulation of High Voltage in Vacuum, 317 (1964).

³ J.P. Shannon, et al., Insulation of High Voltage Across Solid Insulators in Vacuum, Proc. MIT Symp. Insulation of High Voltages in Vacuum, 281 (1964).

insulating gas, gradients of the order of 40 MV/m may be set up on a terminal⁴. Recent study of insulating materials has demonstrated that substances with dielectric strengths of the order of 500 MV/m are available^{5, 6, 7}, and so advances in insulator technology may soon be realized.

It is felt that the "inclined field" tube will be capable of operation at high current. The production of these high currents may well be feasible using the "axial magnetic generator" technique, proposed by Van de Graaff for the production of efficient high-voltage DC at high power levels, or by further developing the charging belts used at present. There is also a steady and encouraging development of the high-current negative-ion sources which would be required by a DC intense neutron generator. Ion sources of up to 5 mA of negative ions have already been constructed⁸.

It has been proposed that a two stage tandem, with a terminal potential of 350 MV on each of two terminals (the first negative, the second positive) might serve as the accelerator for ING. It is believed that such a machine would be practicable in size and acceptable in cost provided that the techniques referred to above were developed and applied. It seems clear however, that the time scale for the development and construction of such a large DC machine would be considerably longer than that for an SOC or linear accelerator.

⁴ A.S. Denholm, trans. IEEE Nuclear Sci, NS-12 (3) 780 (1965).

⁵ A.H. Sherbaugh and P.K. Watson, Conduction and Breakdown in Liquid Dielectrics, Progress in Dielectric 4, 223 (1962) Academic Press.

⁶ R.R. Charpentier, Disruptive Breakdown Measurements of Solid Materials in a Non-Uniform DC Field, proc. 33rd Annual NAS-NRC Conf. Electrical Insulation (Washington), paper 29 (1964).

⁷ B.L. Johnson, DC Breakdown of Thermoplastic Materials, publication NAS-NRC-1141, 1963 Annual Report on Conf. on Electrical Insulation.

⁸ K.W. Ehlers, trans. IEEE Nuclear Sci, NS-12 (3) 811 (1965).

It must be noted that the development of a tandem accelerator of intermediate voltage and high current - even of the order of 50 MV and 5 mA - would have great intrinsic interest, particularly in nuclear-structure studies using heavy-ion beams. With such a device the Coulomb barrier could be overcome for all nucleus-nucleus reactions, including the uranium-on-uranium reaction.

The value of a DC machine operating at high current and even rather modest voltage has been appreciated in connection with beam injection. It is suggested that a beam of protons in the 10 - 20 MeV range would be useful for injection into the basic machine.

It is proposed that strong support be given to development work on DC accelerators as mentioned above both because of their intrinsic usefulness and because of their value to the ING project.

2. The Superconducting Linear Accelerator

One disadvantage of linear accelerators is economic - the cost of the RF power required to establish the fields within their accelerating cavities. Since ohmic losses in the cavity walls are directly proportional to the surface resistance of these walls, any reduction of this resistance should lead to an increase in the efficiency of the machine.

It is proposed that superconducting cavities be used to make large reductions in cavity-wall surface resistance. If this is done, the economic advantage gained by reducing power losses must be weighed against the cost of providing enough refrigeration to maintain the cavity walls of the superconducting linac at temperatures of the order of 1°K.

The most successful work to date on superconducting cavities has been that at Stanford⁹, where the interest is in the acceleration of electrons. While the results obtained there are encouraging from the point of view of technical feasibility, it has yet to be demonstrated that, for the acceleration of protons, the superconducting device will give savings over a conventional linac. It is expected that savings will first be seen in electron machines where higher frequencies are employed than in proton devices, since the "advantage" of the superconducting devices can be shown to increase with frequency.

⁹ H.A. Schwettman, et al., Measurements at High Field Strengths on Superconducting Accelerator Cavities, proc. 5th Intl. Conf. on High Energy Accelerators, (Frascati, Italy, 1965) (Also appeared as Stanford Univ. Report HEPL-392).

The greatest single doubt about a superconducting linear accelerator lies in the stability of the beam. It is expected that the high current required for ING would generate unwanted modes which, if allowed to resonate, would destroy the integrity of the beam. No quantitative answers exist to the questions posed by this problem although it is expected that a superconducting cavity could be developed which would be capable of damping out these unwanted modes.

While superconducting devices have not been rejected as possible accelerators for this project, it remains to be shown that the above technical problem can be overcome and that they would be less costly than conventional linear accelerators, in the next few years. For these reasons the superconducting linear accelerators are not preferred in this proposal.

3. The Protatron

"Conventional" proposals for the production of high densities of protons depend on the use of a particle accelerator coupled to a magnetic storage ring. It has been suggested¹⁰ that an "induction accelerator" or "protatron" might achieve the same end-result in a single machine.

A protatron operates by using two separate magnetic fields - a flux-core magnet provides an accelerating field while a set of guide-field magnets provide the containment for charged particles orbiting in a toroid. It has been demonstrated that, for such a device, the energy losses are nearly independent of the circulating current, and hence the efficiency of the device increases with increasing particle current. Consideration of the scattering of the protons by Coulomb repulsion in a protatron indicates that the limiting number of protons which can be contained in the machine is of the order of 10^{17} . At this range of proton densities, the efficiency of the device - with an iron core - is expected to be in excess of 90%. In an air-cored device, comparable efficiency may be realized with lower proton densities, possibly of the order of 10^{14} .

It seems feasible that an efficient system for injecting large quantities of hydrogen ions into the protatron can be developed. It has been suggested that one practical way would be to use induction injection where injection is from an ion gun, mounted on the wall of the protatron, into an increasing magnetic field generated by an auxiliary toroidal winding.

¹⁰ J. W. Knowles, Acceleration and Storage of Protons in a Magnetic Induction Accelerator, report FSD/ING-45 (1966).

There are, however, many aspects of the protatron which have not as yet been thoroughly considered. For example, no method has been proposed for the efficient extraction of the beam. It is noted that an extracted proton beam is a requirement for a neutron generator of the type recommended in this proposal. Without an extracted beam it would not be feasible to provide many of the desired experimental facilities.

For the above reason, it does not appear that the protatron could be used as the basis of the proposed neutron generator.

4. The "Janes-Type" Accelerator or HIPAC

A report by G.S. Janes, et al.¹¹ has outlined a device - a "Heavy Ion Plasma Accelerator" - which, it is claimed, could add energy to ions of arbitrary atomic number by accelerating them in an electrostatic field inside a high-density electron cloud. It appears that a device of this type, designed to accelerate protons to 1 GeV, would be of practical size (a toroid of minor radius 1 m).

The potential well inside an electron cloud would serve both to trap and accelerate ions injected into it. In a toroidal HIPAC, the electron cloud could be maintained by generating a magnetic field parallel to the circular axis of the toroid, thereby constraining the electrons to orbit in a cycloidal path at a fixed distance from the circular axis.

It appears that the method of 'inductive charge injection' could be used to establish the electron cloud and it is felt that the subsequent injection of the ions to be accelerated may be feasible. However, beam extraction is impossible for positive ions in a HIPAC as proposed above (since the ions gain energy from a large negative potential) and so this accelerator is not suitable for use with the external neutron target required by this project.

It is interesting to observe that it is theoretically possible to operate a HIPAC in which a positron cloud is set up. By injecting negative hydrogen ions into such a device it could be made to operate in a tandem mode to produce beams of protons. However, to compensate for the neutralization of positrons by the electrons associated with the production of the necessary beam current, about 100 megacuries of a positron emitter would be required in the form of a thin source. It is suggested that this "positron-cloud HIPAC" could not be developed in the time scale desired.

¹¹ G.S. Janes, et al., On a New Type of Accelerator for Heavy Ions, Phys. Rev. 145, 925 (1966).

5. The Staticelerator

As indicated above in this Chapter, acceleration of the proton beam for ING by a DC potential is attractive, but it does not appear that a single terminal potential of sufficient magnitude is realizable in the necessary time scale. It does however, appear to be feasible to use a succession of terminals to provide the acceleration, using travelling-wave accelerator sections to introduce the charged-particle beam into successive terminals without loss of energy^{12, 13, 14}.

In essence, a staticelerator is a series of DC terminals linked by short linear accelerators; the linacs provide RF fields to cancel the DC fields during the time when the beam is being introduced into each terminal. The fact that the charged particles will travel with constant velocity through the linac sections would simplify the design of these sections.

The purpose of the staticelerator is to attain a high conversion efficiency of electric power to beam power. It is suggested that, by having the proton beam associated in the RF field with an electron cloud of equal charge, the net consumption of RF power will be small. The electron beam should give up as much power as is gained by the proton beam from the RF system. The proton beam power will then be derived efficiently by acceleration between subsequent DC terminals.

The principal technical and economic problems to be resolved in the staticelerator are as follows:

- From a technical point of view, it may prove to be difficult to use the proposed "two-beam" technique since the two beams would require to be focussed with precision along the length of the device.
- From an economic point of view one must contrast the capital costs of a conventional linac plus the operating cost of the associated RF power losses with the capital costs of both the linac sections and DC sections of a staticelerator (which will probably be longer than a conventional linac). It is not immediately apparent that the selection of a staticelerator would lead to a net saving.

¹² W.B. Lewis, Proton Acceleration for ING, Part 1, report DM-76 (July, 1964).

¹³ W.B. Lewis, Proton Acceleration for ING, Part 2, report DM-78 (Jan. 1965).

¹⁴ W.B. Lewis, Travelling Wave Accelerators and the Staticelerator, report FSD/ING-17, (August, 1965).

6. The Super-SOC

F.M. Russell, of the Rutherford High Energy Laboratory, has proposed a machine which bears some resemblance to a "rolled-up" staticelerator¹⁵. He contends that a separated orbit cyclotron could be built in which the RF cavities would be driven by power derived from an electron beam.

A typical cavity in the 'Super-SOC' would have the proton beam being accelerated in its inner region, close to the centre of the machine, while in the outer region of the cavity, electrons, travelling near the speed of light, would be decelerating, thus providing the power to drive the cavity.

The proposal suggests that the power consumed will be the DC power used in raising the electrons to a kinetic energy of approximately 5 MeV, and that electron beams would be provided to drive sets of eight cavities. To provide power sufficient to accelerate 65 mA of protons in twenty turns in a Super-SOC by 800 MeV, electron currents totalling 13 A are required at 4 to 4.5 MeV.

The technical difficulties in this machine which are absent in the SOC are related to the control of the electron beams. These beams would need to maintain the correct time-structure and be so phased as to be decelerated by the cavity fields. The possibility of beam blow-up, of the electron beam, in the last cavity through which it passes, has been raised and not disproved. This is linked to the choice of the lower-energy limit below which electrons have to be discarded, and which imposes immediately a limitation (~90%) on the efficiency.

The criticism of the device is mainly on the grounds of achievable efficiencies. The Super-SOC is proposed as a means of bypassing the inefficient process of converting DC power to RF power for the driving of cavities. However, in its suggested form, the Super-SOC presents two problems - those of generating DC power at 5 MV with high efficiency and of converting this power efficiently into beam power.

As with the staticelerator, so with the Super-SOC - there are complex technical problems to be solved before it can compete with the accelerators recommended in this proposal.

¹⁵ F.M. Russell, The Super-SOC, a Valveless Accelerator, Electronic Components, 133 (February, 1966).

C. SUMMARY OF CONCLUSIONS

The continuing study of competitive systems for use with ING has brought to light a number of interesting systems, all of which may eventually prove to be practicable for certain applications. It has, however, been noted that the main interest of the current study is the production of the next generation of neutron fluxes; accordingly the devices of most interest are those which show promise of making these fluxes attainable in the shortest time-scale.

Of the devices considered above, it is believed that a DC accelerator, operating at high-current and modest energy, could be developed as an injector for the main accelerator for this project.

Since it seems certain that the principal accelerator will utilize RF fields to bring about the acceleration of the proton beam to 1 GeV, a continuing interest has been registered in the development of superconducting cavities, since these may one day provide the means of increasing the efficiency of operation of whichever RF accelerator is selected for ING.