INGRID **MASTER**

**A Proposal for
An Intense Neutron Generator
for Radiation-Induced Damage Studies
in the CTR Materials Program**

OAK RIDGE NATIONAL LABORATORY

OPERATED BY UNION CARBIDE CORPORATION • FOR THE U.S. ATOMIC ENERGY COMMISSION

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
Price: Printed Copy \$7.75; Microfiche \$2.25

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Contract No. W-7405-eng-26

I N G R I D

AN INTENSE NEUTRON GENERATOR FOR RADIATION-INDUCED DAMAGE STUDIES
IN THE CTR MATERIALS PROGRAM

A PROPOSAL BY

OAK RIDGE NATIONAL LABORATORY

with

FERMILAB

M. J. Saltmarsh and R. E. Worsham

Editors

JANUARY 1976

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830

Operated by

UNION CARBIDE CORPORATION

for the

U. S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

CONTENTS

	<u>Page No.</u>
ACKNOWLEDGMENTS	vi
1. INTRODUCTION	1-1
<i>M. J. Saltmarsh</i>	
1.1. INGRID and Fusion Power	1-1
1.2. Design Options	1-2
1.3. Description of the Facility	1-4
1.4. Oak Ridge as a Site	1-9
2. THE NEED FOR A NEUTRON IRRADIATION FACILITY	2-1
<i>J. A. Horak, C. J. McHargue, and M. J. Saltmarsh</i>	
2.1. Bulk Radiation Effects in First-Wall Materials	2-2
2.2. First-Wall Surface Irradiation Effects	2-4
2.3. Nonstructural Materials Development	2-5
2.4. The Schedule for Fusion Powers	2-6
2.5. Summary of Source Requirements	2-7
3. CHARACTERISTICS OF THE NEUTRON SOURCE	3-1
<i>J. B. Roberto, M. J. Saltmarsh, and W. G. Wolfer</i>	
3.1. Choice of Target Material and Beam Energy	3-1
3.2. Neutron Flux Contours	3-3
3.3. Effect of Neutron Spectrum Shape on Damage Processes	3-6
3.3.1. Calculations of Damage as a Function of Neutron Energy	3-6
3.3.2. Experimental Damage Results and Correlations with Calculations	3-12
3.3.3. Assessment of a d-Li Neutron Spectrum for Producing CTR-Type Damage	3-14
3.4. Effect of Spatial Variations in Neutron Spectrum on Damage Processes	3-17
3.5. Effect of Beam Pulsing on Radiation Damage Processes	3-19
4. THE ACCELERATOR	4-1
<i>C. D. Curtis,* R. Goodwin,* D. Johnson,* G. M. Lee,* S. Ohnuma,* P. V. Livdahl,* J. O'Meara,* O. B. Morgan, C. W. Owen,* M. Palmer,* M. J. Saltmarsh, M. Shea,* L. C. Teng,* R. A. Winje,* and D. E. Young*</i>	
4.1. The Injector	4-2
4.1.1. The Ion Source	4-3
4.1.2. The High-Voltage Column	4-4
4.2. The Linac Design Parameters	4-7
4.2.1. Choice of Frequency and Injection Energy	4-7
4.2.2. First Cavity Parameters	4-10
4.2.3. Acceleration Rate	4-11
4.2.4. Transverse Focusing	4-11
4.2.5. Energy and Energy Spread of the Output Beam	4-12

	<u>Page No.</u>
4.3. The Radiofrequency System	4-14
4.3.1. Power Amplifier (PA)	4-15
4.3.2. Anode Power Supply	4-16
4.3.3. Intermediate Power Amplifier (IPA)	4-16
4.3.4. Low-Level Amplifier	4-17
4.3.5. Transmission Lines	4-17
4.3.6. Stabilization	4-17
4.3.7. Control System	4-18
4.4. Mechanical Details	4-18
4.5. The Control and Diagnostic System	4-20
4.6. High-Energy Beam Transport System	4-22
4.7. Shielding and Activation	4-24
4.7.1. Shielding	4-24
4.7.2. Activation	4-25
5. THE LITHIUM TARGET SYSTEM	5-1
<i>W. R. Huntley and S. L. Milora</i>	
5.1. Fluid Dynamics of the Lithium Jet	5-2
5.1.1. Stability of a Turbulent Lithium Jet	5-2
5.1.2. Distortion of Jet from Initial Rectangular Shape	5-6
5.1.3. Boiling of the Jet	5-7
5.2. Description of Lithium Circuit and Associated Systems	5-10
5.2.1. General Description of Lithium Circuit	5-10
5.2.2. Primary Lithium Pump	5-13
5.2.3. Auxiliary Systems for the Lithium Circuit	5-15
5.2.4. Lithium Bypass Purification and Sampling Systems	5-16
5.2.5. Intermediate Heat Exchanger and Dowtherm Circuit	5-18
5.2.6. Instrumentation	5-21
6. BUILDING, UTILITIES, AND EXPERIMENTAL FACILITIES	6-1
<i>R. E. Worsham and M. J. Saltmarsh</i>	
6.1. Building	6-1
6.2. Site	6-9
6.3. Electrical Substation and Transmission Line	6-9
6.4. Environmental Control --- Containment	6-9
6.5. Energy Conservation	6-12
6.6. Experimental Facilities	6-12
6.6.1. The Irradiation Cells	6-13
6.6.2. The Lithium Target System	6-16
6.6.3. The Hot Cell	6-18
7. PROJECT MANAGEMENT, SCHEDULE, AND COSTS	7-1
<i>M. J. Saltmarsh and R. E. Worsham</i>	
7.1. Management	7-1
7.2. Schedule	7-4
7.3. Construction Costs	7-7
7.4. Prototype Development	7-14
7.5. Operating Costs	7-15

Appendices

	<u>Page No.</u>
A. HIGH-EFFICIENCY BEAM BUNCHER SYSTEM	A-1
<i>L. C. Teng*</i>	
A.1. Beam Sectioning and Branching	A-1
A.2. Beam Recombining	A-2
A.3. Typical Buncher Parameters	A-3
B. CALCULATIONS OF NEUTRON SHIELDING FOR LINAC AND IRRADIATION CELLS	B-1
<i>M. J. Saltmarsh</i>	
B.1. Shielding for the Injector	B-1
B.2. Shielding for the First Linac Tank (First Cavity) . . .	B-4
B.3. Shielding for Higher Energy Cavities	B-4
B.4. Shielding for Irradiation Cells	B-8
C. CALCULATIONS OF RESIDUAL ACTIVATION IN FACILITY	C-1
<i>M. J. Saltmarsh</i>	
C.1. Deuteron Activation	C-1
C.1.1. Activation of the Copper Drift Tubes	C-1
C.1.2. Activation of the Lithium Target	C-4
C.2. Neutron Activation	C-4
C.2.1. Activation of the Linac Structure	C-4
C.2.2. Activation of the Concrete in the Linac Vault .	C-5
C.2.3. Activation of the Air in the Accelerator Vault	C-7
C.2.4. Activation of the Lithium Target Window	C-7
C.2.5. Activation of the Irradiation Cell Walls	C-8
C.2.6. Activation of the Helium Atmosphere in the Irradiation Cell	C-9
D. TURBULENCE DAMPING AND JET STABILIZATION BY MAGNETIC FIELDS .	D-1
<i>S. L. Milora</i>	
E. HYDRODYNAMIC SIMILARITY EXPERIMENTS WITH MERCURY	E-1
<i>S. L. Milora</i>	
F. CONSIDERATION OF ALTERNATE FLUIDS FOR INTERMEDIATE HEAT EXCHANGER COOLANT	F-1
<i>W. R. Huntley</i>	

Acknowledgements

We wish to express our gratitude to the many people who have helped in the preparation of this proposal by providing advice, performing calculations, and discussing problems. Invaluable contributions were made by staff members from the UCC-ND Engineering Division, the Fermilab Accelerator Division, and the ORNL Metals and Ceramics Division, Neutron Physics Division, Physics Division, Reactor Division, Solid State Division, and Thermonuclear Division.

Our thanks are also due for the encouragement provided by members of the ORNL INGRID Steering Committee: A. P. Fraas, C. J. McHargue, O. B. Morgan, D. F. Steiner, M. W. Rosenthal, and A. Zucker.

We have had several helpful discussions with the authors of the BNL proposal for an Accelerator-based Neutron Generator (BNL 20159), whose cooperation we greatly appreciate.

We are also indebted to Lorraine S. Abbott for her assistance in organizing and editing the report.

Finally, M. J. Saltmarsh would like to thank Sheila, who tolerated INGRID for four months.

1. INTRODUCTION

1.1 INGRID and Fusion Power

Commercial fusion power is one of the major long-term goals of the United States Energy Research and Development Agency.¹ There are many problems to be overcome in this search for a successful Controlled Thermonuclear Reactor design, both in areas of basic physics and in areas of technological development. In this latter category some of the major obstacles to be surmounted are associated with the need for structural materials which can tolerate the hostile radiation environment surrounding a fusion reactor core. The long lead time required for development of new alloys underscores the urgency of the necessary radiation damage studies, yet the CTR Materials Program is severely hampered by the lack of a suitably intense source of energetic neutrons.

In Chapter 2 arguments are presented defining the specifications required of a neutron source which can meet the immediate needs of the CTR Materials Program. These specifications are:

- (1) A continuous neutron flux $\geq 10^{14}$ neutrons $\cdot$ cm⁻² $\cdot$ sec⁻¹.
- (2) A usable experimental volume of several hundred cubic centimeters.
- (3) A neutron energy spectrum whose radiation damage effects will match those of a fusion spectrum.
- (4) The reliability to ensure a high plant duty factor for periods of several months of continuous operation.

INGRID, an Intense Neutron Generator for Radiation Induced Damage, is designed to satisfy these requirements. The facility could be operational approximately four years after authorization of the project. If sufficient capital funds were available at the beginning of FY-77, the total cost would be approximately \$60,000,000, plus \$3,700,000 for prototype development work.

1.2 Design Options

The only devices capable of continuous production of intense neutron fluxes are based either on fission reactors or on some combination of an accelerated ion beam and a target. Neutron sources based on fission reactors are relevant to the CTR Materials Program for the study of nickel-containing alloys. However, for other materials, e.g., refractory metals, the spectrum does not contain sufficient high-energy neutrons to produce the nuclear transmutation rates associated with fusion reactor neutrons. The choice of a suitable source therefore lies among the various accelerator-based facilities, which fall into three main categories:

- (1) Spallation sources, such as the LAMPF² beam stop area or the Canadian ING³ proposal, which use a high-energy proton beam and a heavy metal target.
- (2) d-T sources such as the upgraded RTNS⁴ or the gas-target INS⁵ projects.
- (3) Deuteron breakup, or stripping, sources, such as those presently in use at various cyclotron laboratories^{6,7} which use a moderately energetic deuteron beam and a low-Z target material.

The spallation source can be rejected on the basis of the neutron spectrum which is very different from that seen by the first wall of a fusion reactor. The d-T source can produce an energy spectrum which is quite similar to a fusion spectrum, but does not appear capable of providing the intensity or experimental volume required. The deuteron breakup source can however give a reasonably close match to a fusion neutron spectrum⁸ as well as meet the intensity and experimental volume criteria listed in the previous section. To achieve these source parameters requires a 20- to 40-MeV 100-mA deuteron beam to be incident over an area of a few square centimeters of a target made of some low-Z material such as lithium or beryllium.

The best accelerator for this purpose is an Alvarez-type linac, which is capable of accelerating large beam currents with very low beam losses. Low losses are vital in order to avoid activation of the accelerator components, which would cause serious and costly problems for routine maintenance and repair. Considerable experience has been accumulated with Alvarez linacs, with routine operation at instantaneous beam currents of 100 to 200 mA. For example, the Fermilab linac is capable of delivering beam 96.4% of the time scheduled. No major problems are expected in building a machine capable of CW operation. One might note that a performance comparable to that required for the INGRID facility was achieved over twenty years ago in the MTA project.⁹ The MkI injector was run with 100 mA of 10.5-MeV protons at a duty factor of 20%, while the A48 machine accelerated 30 mA of 7.5-MeV deuterons with a 100% duty factor, the current being limited by heat deposition on the target.¹⁰

The choice of target material is equally straightforward. Most existing facilities use beryllium, but the high beam power of the proposed device (4 MW) makes it doubtful that any system based on a solid target could be built to dissipate the heat generated by the beam. Lithium, in the form of a liquid jet, is the natural alternative. Not only is the neutron yield similar to that from beryllium, but lithium also has ideal thermophysical properties for this application. Furthermore, the extensive experience which has been accumulated with liquid-metal loops in various reactor systems is directly applicable to the target design.

With the accelerator-target combination chosen to satisfy the experimental volume, intensity, and spectral criteria, the remaining design choices center around the need to attain reliable long-term operation of the facility. The resultant design philosophy has been to avoid complexity wherever possible in the accelerator and target systems, a policy which led to the decision not to incorporate simultaneous acceleration of positive and negative beams as is done at LAMPF. At first sight the acceleration of two independent beams seems to offer two

facilities for the price of one; however, the following disadvantages seem to outweigh the potential benefits:

- (1) The d^- beam intensity would be much lower than that for the d^+ beam so that no significant increase in the total irradiation volume would be obtained. If lower neutron intensities were required, a large volume would be available from the d^+ beam.
- (2) Higher beam losses will occur due to the increased difficulty of tuning the accelerator. Even losses $\sim 0.01\%$ at the higher energy end of the accelerator can result in significant activation of accelerator components with subsequent difficulties for maintenance and repair operations.
- (3) There would be a significant increase in the complexity of the low-energy beam transport system, the rf system and the lithium target circuits, with a probable attendant loss of reliability.
- (4) The incremental cost involved in the extra injector, transport systems, targets and irradiation cells would be roughly \$10,000,000.

1.3 Description of the Facility

INGRID is based on a 100-mA deuteron beam interacting with a liquid-lithium target to produce an intense flux of neutrons inside a heavily shielded irradiation cell.

The major components of the facility will be:

- a) The injector, comprising an ion source and a 350-keV accelerating column, capable of producing 200 mA of d^+ ions.
- b) A 40-m-long linear accelerator operating at a frequency of 60 MHz, which will accelerate 100 mA of the 350-keV injected beam to an energy of 20 to 40 MeV, variable in steps of approximately 4 MeV.

- c) A liquid-lithium system which will provide the jet target in one of two irradiation cells and dissipate the 4 MW of beam power.
- d) Two shielded irradiation cells with provision for several independent assemblies of instrumented specimens, and the necessary equipment for controlling the physical and chemical environment of the specimens.
- e) Hot cells, remote handling equipment, shops, laboratory space and other experimental support facilities.

The main features of the completed facility are shown in the plan view of Fig. 1.1. Concrete shielding surrounds the injector, linear accelerator, high-energy beam transport system, irradiation cells, lithium

Fig. 1.1. Plan view of INGRID facility.

target system, hot cell facilities and hot storage areas. A structure along one side of the linac tunnel houses the rf system and mechanical equipment for the accelerator. A fenced area on the opposite side of the linac contains the local electrical distribution system and the rf power supplies. A large high bay area served by a 50-ton crane encloses the irradiation cells, hot cell facilities and the experimental staging areas. Hot storage space and components of the lithium system are located below moveable shielding which forms part of the staging area floor. The structure adjoining the high bay area houses the offices, laboratories, and shops. The experimenters' control room and the linac control are located above the linac tunnel overlooking the experimental staging area and irradiation cells.

Figure 1.2 shows an artist's conception of the building, with the injector located at the extreme left. Figure 1.3 is a cutaway view of the high bay area as seen from the direction of the experimenters' control room. Valve boxes which house external equipment serving the probes leading into the irradiation cells can be seen at various locations around the cell shielding.

The total floor area of the buildings is 40,600 sq ft, including 11,500 sq ft for the accelerator and associated equipment, 11,500 sq ft for the experimental staging area, and 17,700 sq ft for offices, control rooms, laboratory space and other experimental support areas.

Fig. 1.2. Artist's conception of INGRID building.

Fig. 1.3. Cutaway view of high bay area in INGRID building.

1.4 Oak Ridge as a Site

The successful construction and operation of a facility such as INGRID will require the involvement of an unusually wide range of disciplines. This is a task which is ideally suited to a multission laboratory like ORNL.

Some of the areas of expertise which exist at ORNL and which are pertinent to this project are listed below:

1. The Thermonuclear Division has a long and continuing tradition in the development of high current ion sources. This includes those studies most relevant to the injector design for INGRID, which were done as part of the DCX-2 program over ten years ago.¹¹
2. Because of more than twenty years of experience in liquid metal technology, ORNL has engineering staff well qualified for the design and construction of the lithium target system.
3. The large irradiation effects programs in the Metals and Ceramics and Solid State Divisions, which include the largest bulk radiation effects program funded by DCTR, provide an invaluable source of information on the design of the experimental areas and support facilities.
4. ORNL has considerable experience in the building and operation of accelerators, such as the ORIC, and in reactor irradiation facilities such as the ORR and HFIR. Both scientific and engineering expertise is available in these areas.
5. The Neutron Physics Division has done extensive shielding calculations for accelerators (e.g., Fermilab) and reactor facilities.
6. The large thermonuclear program at ORNL is available to provide direct guidance on the direction of the research.

7. Large support groups are available in engineering, hot cell operation, instrumentation, etc.
8. ORNL has already had considerable success in directing the use of accelerators and accelerator expertise to the needs of the materials programs. Examples are the heavy ion irradiation facility based on the Oak Ridge CN Van de Graaff¹² which is used for swelling studies for the LMFBR and CTR programs; the neutron sputtering experiments⁷ and fission-fusion damage correlation work¹³ based on the d-Be neutron source on the ORIC: and the extensive helium injection program, also on the ORIC, designed to explore the effect of high helium production rates in CTR first wall materials.

ORNL's resources for this project are inadequate in one respect: no major linear accelerator design has been done at Oak Ridge. To overcome this limitation, we have been consulting with a group from Fermilab. We propose to continue this collaboration, giving Fermilab the technical responsibility for the design of the accelerator part of the facility, overall responsibility being retained by ORNL. This mutually beneficial arrangement will give ORNL access to the talents of a major accelerator group, while providing Fermilab with an opportunity to contribute directly to ERDA's main mission, i.e., energy research and development. A more detailed discussion of the proposed management of this collaboration is given in Chapter 8.

REFERENCES

1. "A National Plan for Energy Research, Development and Demonstration: Creating Energy Choices for the Future," USERDA Report ERDA-48 Vol. I, p. S6 (June 1975).
2. W. Green, "LAMPF as a Neutron Radiation Damage Facility: Uses, Access, Limitations, and Problems," Proceedings of the International Conference on Radiation Test Facilities for the CTR Surface and Materials Program, Argonne National Laboratory, July 1975 (to be published).

3. G. A. Bartholomew, J. C. D. Milton and E. W. Vogt, "An Intense Neutron Generator Based on a Proton Accelerator," AECL-2059 (1964).
4. J. C. Davis, J. D. Anderson, R. Booth, C. M. Logan and J. E. Asher, "Livermore Neutron Source Design Concepts," Proceedings of the International Conference on Radiation Test Facilities for the CTR Surface and Materials Program, Argonne National Laboratory, July 1975 (to be published).
5. Dale D. Armstrong, C. Robert Emigh, Karl L. Meier, Earl A. Meyer and J. David Schneider, "An Intense Neutron Source Facility for the Fusion Energy Program," LA-UR-72-1262 (1975); also presented at the International Conference (see ref. 2).
6. L. H. Jenkins, T. S. Noggle, R. E. Reed, M. J. Saltmarsh and G. J. Smith, Appl. Phys. Lett. 26, 426 (1975).
7. A. d-Be source is under development at the University of California (Davis) (T. Cahill, private communication).
8. "Proposal for an Accelerator-based Neutron Generator," (ed.) P. Grand, BNL 20159, July 1975.
9. R. G. Hewlett and F. Duncan, "The Atomic Shield 1947-1952," p. 425, Pennsylvania State Press (1967).
10. P. V. Livdahl, private communication.
11. O. B. Morgan, G. G. Kelley and R. C. Davis, Rev. Sci. Inst. 38, 467 (1967).
12. M. B. Lewis, F. K. McGowan, C. H. Johnson and M. J. Saltmarsh, "The Oak Ridge CN Van de Graaff as a Facility for Heavy Ion Radiation Damage Studies," presented at the ASTM Symposium on Experimental Methods for Charged Particle Irradiations, Gatlinburg, Tennessee, October 1975.
13. J. B. Roberto, J. Narayan and M. J. Saltmarsh, "15 MeV Neutron Damage in Cu and Nb," Proceedings of the International Conference on Radiation Effects and Tritium Technology for Fusion Reactors, Gatlinburg, Tennessee (October 1975).

2. THE NEED FOR A NEUTRON IRRADIATION FACILITY

The ultimate objective of the ERDA-DCTR programs is the economical, reliable, and safe generation of power from fusion reactors. To meet this goal the components of a fusion reactor must provide several years of operation before they are replaced, and it is the responsibility of the DCTR Materials Program to develop the materials required for these components.

Many of the most severe materials problems arise as a result of the intense neutron flux associated with a fusion plasma, so that a large fraction of the materials development effort must be devoted to the study of neutron irradiation effects. Current fusion reactor design concepts employ first-wall neutron loadings of 1 to 3 MW/m² (refs. 1-5). The lower figure of 1 MW/m² corresponds to a neutron flux ($E > 0.1$ MeV) of $\sim 2.8 \times 10^{14}$ neutrons/cm²-sec, of which 30% is at a neutron energy of ~ 14 MeV. While total neutron fluxes of this value are not uncommon in fission reactors, the high-energy component in a fusion reactor spectrum will result in nuclear transmutation rates which are, with one exception, far higher than those experienced in fission reactors, as can be seen from the estimates given in Table 2.1. The exception is the irradiation of nickel-containing alloys in a mixed thermal/fast flux fission reactor. With such a spectrum, high helium generation rates can be achieved from the two-step process $^{58}\text{Ni}(n,\gamma)^{59}\text{Ni}$ followed by $^{59}\text{Ni}(n,\alpha)^{56}\text{Fe}$. Much base-line data can therefore be obtained using fission reactors to simulate fusion conditions for stainless steels or other nickel-containing alloys. However, these data must ultimately be correlated with information obtained using sources of high-energy neutrons. For other materials, such as the refractory metals or low-Z materials, no fission reactor spectrum is suitable, and energetic neutron sources must be used to produce the correct displacement-to-transmutation ratio.

Table 2.1. Calculated displacement and gas generation rates^a
for fusion and fission neutron sources

(All rates $\times 10^{-7}$)

Material		CTR (1 MW/m ²)	EBR-II ^b	HFIR ^c
316 SS	Displacement rate, dpa/sec	3.1	11	11
	He generation, appm/sec	64	1.5	660 ^d
	H generation, appm/sec	170	85	141
Vanadium	Displacement rate, dpa/sec	3.7	13	12
	He generation, appm/sec	18	0.1	0.2
	H generation, appm/sec	33	5	9
Niobium	Displacement rate, dpa/sec	2.3	7	6
	He generation, appm/sec	8	0.3	0.6
	H generation, appm/sec	25	2	.4

^aAll values except the HFIR-He value for 316 SS taken from G. L. Kulcinski, D. G. Doran, and M. A. Abdou (to be published).

^bCore center, Row 2 spectrum.

^cHFIR-PTP position, reactor midplane.

^dExperimental value, averaged over one year.

In this chapter we shall discuss some of the more important areas requiring neutron irradiation studies and the time-scale in which these studies must be made. From this information the characteristics of a suitable neutron source can be defined.

2.1 Bulk Radiation Effects in First-Wall Materials

For a fusion reactor the most crucial materials problems are associated with the first wall. The chief properties required of the first wall are resistance to fracture, creep, and swelling. For example, a fracture of the first wall would introduce the reactor coolant, lithium or helium, into the plasma region of the reactor and immediately quench the plasma to a temperature too low to sustain the fusion reaction. The

reactor would then be unavailable until the fracture was repaired. This repair could be a long and expensive operation.

To develop radiation-resistant first-wall materials, various physical properties must be measured as a function of a number of experimental parameters. The most important of these are given in Table 2.2. The range of the experimental parameters of interest to the CTR program is far greater than in the corresponding fission reactor program, primarily because the design options and technology requirements for fusion reactors are still not well defined. Furthermore, the cyclic mode of operation of most proposed fusion devices implies that fatigue properties will be more important to their successful operation. The welded regions of a CTR first wall will experience the same environment as the matrix material, so that radiation effects on weldments must be investigated. Thus the test matrices for first-wall materials development will be large, so that many hundreds of samples must be irradiated simultaneously.

Table 2.2. Properties and parameters required for fusion reactor bulk radiation effects

Properties	Parameters
Ductility Uniform and total elongation Stresses Yield and fracture Creep Rate Time to rupture Strain at rupture Fatigue Rate of cycling Stress per cycle Strain at failure Cycles to failure Swelling	as a function of
	Temperature Fluence Flux Composition Microstructure Stress Chemical environment

Since the temperature of irradiation and stress state during irradiation are two important parameters that can affect the mode of deformation and fracture of reactor structural materials, it is essential that some of the irradiation experiments be instrumented for temperature and stress control during irradiation. This requires that electrical heaters, gas gaps, bellows and strain sensing and transmitting devices be in the irradiation capsule. Furthermore, most bulk radiation effects of interest are significant only at high fluences ($\sim 10^{21}$ neutrons/cm²), while end-of-life damage studies will require fluences $\sim 10^{22}$ neutrons/cm²·sec. A neutron source must therefore provide a large experimental volume with a flux $\sim 10^{14}$ neutrons/cm²·sec if a sufficient number of samples are to be irradiated in a reasonable length of time. Comparison with the LMFBR materials program would suggest that the available volume should be measured in hundreds of cubic centimeters even if the source will be used primarily to correlate data from fission irradiations and other simulation techniques.

2.2 First-Wall Surface Irradiation Effects

The surface behavior of the inside of the first wall will be extremely important. Loss of atoms from the inside surface of the first wall must be minimized because the presence of high atomic number impurity atoms in the plasma can alter the physics of the fusion process and may determine whether or not the plasma achieves and sustains ignition. Measurements will be required of the surface erosion during irradiation with fusion neutrons, especially at the operating temperature of a fusion reactor first wall. Although surface studies are presently being done with neutron fluxes $\sim 10^{12}$ neutrons/cm²·sec, higher fluxes will be required in the future. However, the number of properties to be investigated and the range of experimental parameters to be varied are considerably less than those associated with the bulk radiation effects program. Furthermore, the fluence requirements are generally more modest. Thus, the experimental volume needed in the high flux regions will be small compared to that required for bulk irradiation effects work.

2.3 Nonstructural Materials Development

Some reactor design concepts employ a plasma protective material between the first wall and the plasma.³⁻⁵ These materials will be subjected to neutron fluxes comparable to those at the first wall, and information will be required on their mechanical and dimensional integrity after irradiation to high neutron fluences. In addition, neutron erosion of the surfaces must be investigated to ensure that the plasma is not poisoned by ejected atoms. In the case of the insulators, the effect of neutron irradiation on their electrical properties must be assessed.

In most fusion reactor designs the tritium breeding ratio is enhanced by (1) the inclusion of a neutron multiplier, composed of a beryllium alloy or compound, or (2) a graphite moderator-reflector. Under neutron irradiation and elevated temperatures, such materials will be subject to swelling, embrittlement and dimensional anisotropy effects which must be investigated.

Another component of a CTR for which radiation effects information is required is the superconducting magnet system. The magnets will be shielded to minimize the heat load from radiation on the superconducting magnet; this would also minimize radiation damage to the magnet. However, even at the low neutron fluxes that will exist at the magnet, the effects of the radiation on the superconducting magnet materials must be obtained. The changes in the electrical properties of the superconducting material, the stabilizing matrix and electrical insulators must be determined as a function of neutron fluence. Also, the annealing treatment required for the recovery of the preirradiation electrical properties must be established.

A volume of several liters at a flux $\sim 10^{11}$ neutrons/cm²·sec would accommodate the irradiation of entire magnet sections, which several magnet developers insist is required before we proceed too far on one magnet concept or system.

2.4 The Schedule for Fusion Power

Experience with new technologies has shown that several years are usually required to define the specific parameters which control the behavior of a material under combinations of temperature, stress, or radiation environment not previously encountered. Indeed, three to five years may be a normal period to qualify an established alloy for a new application. This qualification requires information on heat-to-heat variation in properties and sufficient data such that statistical methods can be applied for design purposes. In instances requiring an entirely new alloy, intervals of one to two decades are not unusual to progress from a definition of desired properties to a "standard" material.

It is likely that components of the Experimental Power Reactors (and possibly the first Demonstration Reactor) will be constructed from today's conventional alloys or from slight modifications of them. The materials community would be hard pressed to develop a new alloy system for the Demonstration Reactor; in fact, a vigorous program would be required to develop new alloys for the early commercial plants.

Figure 2.1 shows the schedule for the development of the TOKAMAK type reactor which was presented in the DCTR TOKAMAK Fusion Reactor Research and Development Plan of February 1975,⁶ together with the materials decision points.⁷ An irradiation facility available in the early 1980's could be used to verify the fission reactor data which would have been obtained for EPR-I materials and would have a significant impact on the selection of materials for EPR-II and DEMO-I. Any delay would reduce this impact, particularly in respect to the EPR-II.

Fig. 2.1. Schedule for development of TOKAMAK-type reactor.

2.5 Summary of Source Requirements

From the preceding discussion the specifications required of a neutron source for CTR materials development may be deduced. They are:

- (1) A neutron flux $\sim 10^{14}$ neutrons/cm²·sec, which would provide accelerated testing for EPR-I and EPR-II and real time testing for the Demonstration Reactor.
- (2) An experimental volume of several hundred cubic centimeters at this flux to permit many instrumented samples to be irradiated simultaneously, and a volume of several liters at fluxes $\sim 10^{11}$ neutrons/cm²·sec to allow irradiation of large magnet sections.
- (3) A neutron spectrum whose radiation damage effects will match those of a fusion spectrum.
- (4) The reliability needed for many months of continuous operation.
- (5) The earliest possible operational date.

REFERENCES

1. "Oak Ridge TOKAMAK Experimental Power Reactor Study Reference Design," ORNL-TM-5042 (to be published).
2. "Experimental Power Reactor Conceptual Design Study, 12-Month Progress Report for the Period July 1, 1974 Through June 30, 1975," GA-A13534 (July 1975).
3. "TOKAMAK Experimental Power Reactor Studies," ANL/CTR-72-2 (June 1975).
4. "A Fusion Power Plant," MATT-1050, PPPL (August 1974).
5. A. P. Fraas, "Conceptual Design of the Blanket and Shield Region and Related System for a Full Scale Toroidal Fusion Reactor," ORNL-3096 (May 1973).
6. "TOKAMAK Study - 1974 Fusion Reactor Research and Development Plan," draft of April 1, 1975, DCTR, USERDA.

7. K. M. Zwilsky, "Presentation of DCTR Development and Technology Materials Program to Fourth Meeting of the Fusion Power Coordinating Committee," Oak Ridge National Laboratory, September 23, 1974.

3. CHARACTERISTICS OF THE NEUTRON SOURCE

On the basis of the discussion in Chapter 2, the major characteristics required of the neutron source for CTR radiation damage studies can be stated to be:

- (1) An intensity $\sim 10^{14}$ neutrons $\cdot$ cm $^{-2}\cdot$ sec $^{-1}$, which is on the order of that expected to be incident on the first wall of a CTR based on current concepts.
- (2) An experimental volume $\sim 10^3$ cm ^{3} , large enough to accommodate many samples.
- (3) An energy spectrum that will produce radiation damage effects similar to those produced by a fusion neutron spectrum.

Any device which can be built with present-day technology will necessitate some compromise in these requirements. Sources based on the d-T reaction^{1,2} could meet the spectral requirements but not the intensity or experimental volume conditions. Spallation sources³ or reactors such as EBR-II could provide the intensity and experimental volume but would have drastically different energy spectra. Only sources based on the deuteron breakup (i.e., stripping) reaction can come close to meeting all these conditions. As has been stated previously, the specific stripping reaction selected for this machine is the d-Li reaction at a deuteron energy of 40 MeV. In this chapter we show how this choice was made and what neutron fluxes may be expected. We also describe the differences between a d-Li source and a CTR first-wall spectrum and the effect of these on the damage studies. In addition, the effect of the beam time structure is discussed.

3.1 Choice of Target Material and Beam Energy

The deuteron stripping reaction has been used for many years to provide beams of energetic neutrons. The d-Be reaction was utilized at cyclotrons at the University of Washington and at Berkeley for radiation damage studies associated with the Manhattan Project,^{4,5} and more recently

deuteron stripping sources have been used for CTR-related work, both here at ORNL^{6,7} and at the University of California (Davis).⁸

Recent measurements of the 0-deg neutron yields for a number of targets bombarded by deuterons have been reported by Meulders et al.⁹ Some of their results are shown in Fig. 3.1, together with data obtained at ORNL for lithium and beryllium bombarded with 40-MeV deuterons. Figure 3.1 shows that the greatest neutron yields are associated with high deuteron energies and low-Z targets. Beryllium has been a good choice of target material for deuteron accelerators in the past, but the intensities required for the facility we propose imply beam power densities that will be too high to dissipate in solid targets. Our choice of lithium was a natural alternative. It gives approximately the same yield as beryllium and also has ideal thermophysical properties for use as a windowless liquid target.

Fig. 3.1. Neutron yields ($E_n > 4$ MeV) from thick targets bombarded by deuterons. (Note: the lines drawn through the data points are only to guide the eye.)

In selecting the deuteron energy, a compromise was made between maximizing the neutron yield and simulating the neutron fusion energy spectrum. The work of Parkin and Goland^{10,11} indicates that the best match to a fusion spectrum occurs for deuteron energies somewhat lower than the 40-MeV maximum chosen, but since the deuteron beam energy will be variable (in 4-MeV steps) these lower energies will be available. At the same time the significantly higher neutron intensities which will undoubtedly be required for many of the studies can be produced with the higher energies. In any case, the shape of the fusion spectrum is not yet well defined, depending not only on what region of a CTR is being investigated but also on the reactor design. Moreover, as will be pointed out in Section 3.3 below, we will not be able to exactly match the CTR spectrum at any deuteron energy, and the spectrum that will most nearly produce the damage that would be produced by a CTR spectrum will vary from material to material. Thus having a machine in which the deuteron energy is variable will be a real advantage.

3.2 Neutron Flux Contours

The ORNL experiments with a lithium target and a 40-MeV deuteron beam included measurements of the neutron spectra at various angles from the incident beam, and on the basis of these results the neutron intensities within the experimental volume can be predicted.

The neutron spectra from measurements at angles of 0, 5, 10, 15, and 20 deg are plotted in Fig. 3.2. These data show that the neutron yield for energies $E_n \geq 4$ MeV drops to half of the 0-deg value at an angle of approximately 11 deg. In the irradiation cell the flux contours downstream of the target will depend upon the size and divergence of the beam spot at the target position, particularly in the high-intensity regions. For the purpose of illustration, we considered the beam to be circular in cross section, to have a gaussian intensity profile 2 cm in diameter (fwhm), and to have negligible divergence. The measured angular distribution was extrapolated beyond 20 deg by fitting the 0- to 20-deg data with the function

$$Y(\theta) = Y(0^\circ)/[1 + (\theta/\theta_0)^2] ,$$

where $Y(\theta)$ is the yield at an angle θ and $\theta_0 = 10.7$ deg. This function has no theoretical significance, but was used for analytical convenience. The precise form of the extrapolation beyond 20 deg has little effect on the flux contours in the interesting region. The effective source of the neutrons was assumed to be at the center of the lithium target.

Fig. 3.2. Energy spectra of neutrons emitted at various angles from a lithium target bombarded with 40-MeV deuterons. (Note: the lines drawn through the data points are only to guide the eye; data points for 5- and 15-deg curves have been omitted for clarity.)

Flux contours calculated for a 100-mA beam using the above assumptions are shown in Fig. 3.3, and corresponding experimental volumes for specific flux levels are given in Table 3.1. By altering the focusing of the beam on the target, some increase may be made in the volumes for the highest flux levels (i.e., $\gtrsim 10^{15}$ neutrons $\cdot$ cm ^{2} $\cdot$ sec $^{-1}$), but no significant improvement can be achieved for fluxes $\sim 10^{14}$ neutrons $\cdot$ cm $^{-2}$ $\cdot$ sec $^{-1}$.

Fig. 3.3. Neutron flux contours produced by a 2-cm-diam 100-mA 40-MeV deuteron beam incident on a lithium target. (In units of neutrons $\cdot$ cm $^{-2}$ $\cdot$ sec $^{-1}$.)

Table 3.1. Experimental volumes for various neutron flux levels

Neutron flux (for $E_n > 4$ MeV) (neutrons $\cdot$ cm $^{-2}$ $\cdot$ sec $^{-1}$)	Volume (cm ^{3})
$\geq 10^{15}$	5
$\geq 3 \times 10^{14}$	80
$\geq 10^{14}$	400
$\geq 0.5 \times 10^{14}$	1200

Experimental access to the roughly cylindrical irradiation region is excellent. Probes and instrumentation can be introduced from all sides, where the neutron intensities decrease rapidly, without materially affecting the intensities in the high-flux regions. Not only can the experimental volume be used efficiently, but the irradiation of auxiliary equipment can be minimized.

3.3 Effect of Neutron Spectrum Shape on Damage Processes

The d-Li neutron spectrum differs from a calculated first-wall fusion reactor spectrum in a number of ways, most dramatically at high energies.* These differences are apparent in Fig. 3.4, in which the d-Li spectrum ($E_d = 40$ MeV) is compared with a neutron spectrum recently calculated¹² for the first wall of an experimental fusion power reactor (EPR). The interpretation of radiation effects produced by a d-Li source in terms of those produced by a CTR source requires an understanding of the effects of these differences on the two most important parameters for radiation damage studies — the energies of the atomic recoils and the rate of transmutation. The influence of the high-energy tail of the d-Li neutron spectrum is of particular concern.

3.3.1 Calculations of Damage as a Function of Neutron Energy

When an incident neutron interacts with a target nucleus in a solid, momentum and energy are transferred to the target atom which can then recoil through the solid, producing electronic excitations and atomic displacements. These atomic displacements, along with any transmutations which may occur as a result of the nuclear interaction, are fundamental

---

*The "pure" 14-MeV neutron spectrum is also quite different from the first-wall spectrum. In practice, the d-Li source is more flexible, since the spectrum can be shifted by changing the deuteron energy.

Fig. 3.4. Comparison of d-Li and d-Be neutron spectra with EPR first-wall neutron spectrum.

to all subsequent radiation effects. In this discussion, we will concentrate on these fundamental damage-related phenomena.

The damage effectiveness of a particular neutron spectrum for producing displacements and transmutations depends on the interaction cross sections for the various nuclear reactions that can occur over the relevant energy range. These neutron cross sections are generally unknown above 15 MeV, which makes interpretation of radiation effects produced by a

d-Li source difficult. However, cross sections considered to be quite reliable can be generated theoretically, with results such as those shown for niobium in Fig. 3.5. These calculations¹³ were performed using sophisticated nuclear models which consider both elastic-scattering interactions and nonelastic interactions from which a neutron, proton, or alpha particle is the first particle to be emitted. For those cases for which comparisons are possible, agreement with experimental cross sections has been good. [Note the increasing importance of (n,p) and (n, α) type reactions with neutron energy, indicating that transmutations and helium gas production increase at the higher energies.]

Fig. 3.5. Calculated neutron cross sections for niobium ($E < 32$ MeV).

The energy distribution of the primary recoil atoms can also be calculated using nuclear models. These recoil spectra are directly related to the production of atomic displacements, and, as pointed out above, the extent to which a simulation source reproduces a CTR recoil distribution is an important consideration. The results of calculations of primary recoil spectra¹⁴ in niobium for elastic and inelastic neutron scatterings are shown in Figs. 3.6 and 3.7. The elastic scattering, which is isotropic at lower energies, becomes strongly peaked in the forward direction as the neutron energy is increased. This tends to reduce the damage contribution from elastic scattering at high energies by lowering the average recoil energy. The inelastic recoil distribution is broadly peaked at one-fourth the maximum recoil energy. This peak position corresponds kinematically to the maximum possible inelasticity, and the peak sharpness can be seen to increase with neutron energy.

Fig. 3.6. Energy distribution of niobium primary recoil atoms due to neutron elastic scatterings.

Fig. 3.7. Energy distribution of niobium primary recoil atoms due to neutron inelastic (n,n') scatterings.

The dependence of displacement damage on neutron energy is best described by the damage energy,¹⁵ which is the average primary recoil energy corrected for electronic losses both from the primary recoils and from subsequent secondary recoils. The damage energy is a direct measure of the amount of recoil energy available for producing atomic displacements. When multiplied by the appropriate neutron cross section, the damage energy yields the specific damage energy, a convenient quantity for comparing damage energies for different materials at different neutron energies.

Specific damage energies for niobium and copper as a function of incident neutron energy are plotted in Figs. 3.8 and 3.9 respectively. These curves are based on a Lindhard¹⁶ model for electronic losses using cross-section and recoil data similar to those shown in Figs. 3.5-3.7. The curves exhibit a general increase in specific damage energy with

Fig. 3.8. Specific damage energies for niobium as a function of neutron energy.

Fig. 3.9. Specific damage energy for copper as a function of neutron energy.

incident neutron energy and reflect the greater importance of nonelastic scatterings over elastic scatterings at higher energies. In particular, the calculations indicate that the specific damage energy varies somewhat smoothly with neutron energy, with no unusual behavior even at the highest energies.

3.3.2 Experimental Damage Results and Correlation with Calculations

The calculations described above for copper and niobium have been correlated with damage measurements⁷ made at the Oak Ridge Isochronous Cyclotron (ORIC) using as a source the high-energy neutrons generated by a 40-MeV deuteron beam incident on a thick beryllium target. As shown in Fig. 3.4, the d-Be neutron spectrum is very similar to a d-Li neutron spectrum, indicating that the d-Be source is an excellent prototype for the d-Li machine. In the experiment single crystals of copper and niobium were irradiated at room temperature to fluences of approximately 2×10^{17} neutrons/cm².

The loop-type defects resulting from these irradiations were characterized using x-ray diffuse scattering and transmission electron microscopy. These high-energy neutron results were compared with fission reactor irradiations of comparable damage energy using identically prepared crystals from the same source material.

The overall results suggest general similarities between the high-energy and fission-neutron irradiations. These similarities can be seen in the electron micrograph pair shown for niobium in Fig. 3.10 and in the loop size distributions shown for niobium in Fig. 3.11. The loop size distributions for both copper and niobium were integrated to yield retained point defect densities. When adjusted for differences in fluence, these point defect densities are an experimental measure of the damage effectiveness of d-Be neutrons as compared with fission neutrons. Ratios of the damage effectiveness of d-Be neutrons to fission neutrons are shown in Table 3.2 for both the experimental work and the theoretical calculations described in the preceding section. The theory and experiment

Fission neutron irradiation:
 $5 \times 10^{17}/\text{cm}^2$.

d-Be neutron (~ 15 MeV) irradiation:
 $1.8 \times 10^{17}/\text{cm}^2$.

Fig. 3.10. Electron micrograph pair for niobium. The arrow corresponds to the diffraction vector $[330]$ and is 0.2 microns long.

Fig. 3.11. Loop size distributions for niobium irradiated by d-Be neutrons and by fission neutrons.

are in good agreement for both copper and niobium and indicate that an average d-Be neutron is about three times more damage effective than an average fission neutron in these materials.

Table 3.2. Damage effectiveness of Be(d,n) neutrons ($E_d = 40$ MeV) as compared with fission neutrons

Material	Ratio: $\text{damage}_{\text{d-Be}} / \text{damage}_{\text{fiss}}$	
	Experiment, retained damage	Calculations, damage energy
Copper	3.7	3.4
Niobium	2.5	2.6

These results demonstrate that we can interpret low-dose radiation effects produced by neutrons from a deuteron breakup source and that no unusual effects from the source spectrum were apparent from these irradiations.

3.3.3 Assessment of a d-Li Neutron Spectrum for Producing CTR-Type Damage

In the above discussions, we have presented the results of experimental and theoretical studies which demonstrate the usefulness of a deuteron-breakup neutron source for high-energy radiation effects research. However, the relevant question is whether or not we can simulate CTR radiation effects with such a source. We address ourselves to this question in the following, bearing in mind that the important simulation parameters are recoil energy distributions and transmutations.

The production of helium in structural components of a fusion reactor is generally considered to be the most serious transmutation effect. The helium production cross sections are not well known, but, based on the above calculations, we have estimated helium production in copper and niobium for various neutron spectra. These estimates are shown in Table 3.3 for an EPR first-wall neutron spectrum, for a pure 14-MeV neutron spectrum, and for a d-Li neutron spectrum at emission angles of 0, 10,

Table 3.3. Helium production cross sections and related specific damage energies in copper and niobium for various neutron sources

Material	Source	Helium production cross section, $\langle\sigma(n,\alpha)\rangle$ (mb)	Specific damage energy, $\langle\sigma E_D\rangle$ (eV·cm ² x 10 ⁻²⁰)	Ratio: $\langle\sigma E_D\rangle/\langle\sigma(n,\alpha)\rangle$ (eV x 10 ⁷)
Copper	EPR	11.1	11.5	1.0
	14 MeV	39.6	28.1	0.7
	d-Li, ^a 0 deg	49.5	29.7	0.6
	d-Li, 10 deg	38.2	26.4	0.7
	d-Li, 20 deg	26.6	23.0	0.9
	d-Li mod. with iron ^b	44.2	27.2	0.6
	d-Li mod. with carbon ^b	42.6	27.2	0.6
Niobium	EPR	2.2	10.5	4.8
	14 MeV	7.7	24.4	3.1
	d-Li, 0 deg	12.6	22.2	1.8
	d-Li, 10 deg	9.7	20.6	2.1
	d-Li, 20 deg	6.9	18.2	2.6
	d-Li mod. with iron ^b	11.2	20.5	1.8
	d-Li mod. with carbon	11.0	20.7	1.9

^aDeuteron energy = 40 MeV.

^bSee Fig. 3.13.

and 20 deg (deuteron energy of 40 MeV). The helium production cross sections for the d-Li and 14-MeV sources are somewhat higher than those for the EPR source, the differences between the d-Li and 14-MeV sources being quite small.

We have also calculated primary recoil energy distributions for EPR, d-Li and 14-MeV neutrons incident on niobium and copper. The 0-deg results for niobium are shown in Fig. 3.12. As expected, the recoil distributions shown for the d-Li and 14-MeV sources include significantly more high-energy recoils than does the recoil distribution for the EPR source. This is a result of the much harder neutron energy distribution characteristic of the simulation sources and could be alleviated by moderating some of the high-energy neutrons.

Fig. 3.12. Comparison of primary recoil energy distributions for niobium produced by d-Li, 14-MeV and EPR neutron sources (0 deg).

The specific damage energies calculated for the recoil spectra are included in Table 3.3. They show that the damage effectiveness of 14-MeV and d-Li neutrons is two to three times greater than that of EPR neutrons. A flux of 10^{14} neutrons $\cdot$ cm $^{-2}$ $\cdot$ sec $^{-1}$ from the d-Li source would be equivalent to a fusion spectrum flux of 2.8×10^{14} neutrons $\cdot$ cm $^{-2}$ $\cdot$ sec $^{-1}$, which corresponds to a wall loading of 1 MW/m ^{2} .

The absolute values of helium production and displacement damage produced by a simulation source are probably not nearly so important as their ratio. These ratios are shown for copper and niobium in Table 3.3 for the d-Li, 14-MeV and EPR sources. The ratios for the d-Li and 14-MeV sources are probably close enough to the ratio for the EPR source for either to be used as a simulation source, although a closer match could be achieved for the d-Li source if desired.^{10,11}

We expect the general trends shown above for copper and niobium to hold true for most materials. We can conclude that a d-Li neutron source would be effective for producing CTR-type radiation effects, certainly as effective as a 14-MeV source and definitely more flexible. When experimental volumes and neutron fluxes are also considered, the d-Li source is far superior to any other.

3.4 Effect of Spatial Variations in Neutron Spectrum on Damage Processes

The above discussion on the effect of the neutron spectrum shape on radiation damage effects has centered on the neutron energy spectrum produced by a d-Li source at 0 deg from the incident beam. This spectrum will not be constant throughout the experimental volume since spatial variations in the spectral shape will be introduced by two effects. First, the energy spectrum changes as a function of the scattering angle as we have seen in Fig. 3.2. Second, the spectrum is affected by the presence of samples placed in the neutron beam.

The changes due to the presence of samples has been estimated using the idealized geometry shown in Fig. 3.13. The neutrons were considered to originate at the point S and then to pass through the samples, represented by an absorber of thickness t . The average neutron flux over the 1-cm-diam region A was then computed using the neutron transport code ANISN. Three cases were considered: (1) no absorber, (2) a carbon absorber 10 cm thick, and (3) an iron absorber 5 cm thick. The results are shown in Fig. 3.14, normalized to the yield from a 100-mA 40-MeV deuteron beam.

We have used the displacement-to-helium-production ratio to evaluate these spectral variations, and the results are included in Table 3.3. Both effects tend to increase the ratio, thus improving the correspondence between the EPR and 40-MeV d-Li spectra. The greatest change, due to the angular variations, will result in a spatial dependence of the ratio defined largely by the beam geometry. The ratio will not be materially altered by the presence of the sample material. However, there can be a substantial reduction in neutron intensity due to the presence of samples, and when several sample sets are being run simultaneously the experiments will not be independent of one another. Changes in absolute intensity can be adequately monitored with dosimetry foils, however, as the spectral variations are not very severe.

Fig. 3.13. Geometry used for calculating the effect of samples on the neutron energy spectrum.

Fig. 3.14. Modification of d-Li neutron spectrum by carbon and iron samples placed in the beam.

3.5 Effect of Beam Pulsing on Radiation Damage Processes

The deuteron beam incident on the lithium target will be pulsed at a frequency of 60 MHz. As a result, the neutrons produced at the source will be emitted in bursts separated by 16.7 nsec, each burst being about 5 nsec long. This deviation from the effectively steady-state condition in a CTR could affect the radiation damage processes by introducing fluctuations in the concentrations of vacancies and interstitials produced in the lattice. In order to determine whether the pulsing presented a problem, the migration times for vacancies and interstitials (τ_v and τ_i) in a nickel sample were estimated as follows.

From Einstein's relation,

$$\langle x^2 \rangle = D\tau ,$$

where $\langle x^2 \rangle$ is the mean square displacement of the defect in time τ , and D is its diffusion coefficient. Plots of D_v and D_i for nickel (taken from ref. 15) are shown in Fig. 3.15 as a function of T_m/T , where T_m is the absolute melting point and T is the temperature. In the temperature range of interest, that is, $3 > T_m/T > 1.7$, the interstitial diffusion coefficient D_i varies from 10^{-5} to 10^{-4} cm²/sec, and the vacancy diffusion coefficient D_v varies from 10^{-13} to 10^{-7} cm²/sec. (Most alloys will show similar variations of D_v and D_i as a function of T_m/T .)

If the sink density is L cm⁻², then the mean square displacement for reaching a sink will be

$$\langle x^2 \rangle \approx \frac{1}{L}.$$

Thus

$$\tau_i = 1/LD_i,$$

$$\tau_v = 1/LD_v.$$

As sink densities in irradiated materials are typically $\sim 10^{10}$ cm⁻², one finds

$$10^{-6} \text{ sec} < \tau_i < 10^{-5} \text{ sec}$$

and

$$10^{-3} \text{ sec} < \tau_v < 10^3 \text{ sec},$$

so that the shortest migration times, 10^{-6} sec for interstitials, is at least 50 times larger than the beam pulse separation. Thus, one can conclude that the pulsed nature of the beam will not noticeably affect the radiation damage processes.

Fig. 3.15. Interstitial and vacancy diffusion coefficients for nickel as a function of temperature.

References

1. J. C. Davis, J. D. Anderson, R. Booth, C. M. Logan, and J. E. Asher, "Livermore Neutron Source Design Concepts," Proceedings of the International Conference on Radiation Test Facilities for the CTR Surface and Materials Program, Argonne National Laboratory, July 1975 (to be published).
2. Dale D. Armstrong, C. Robert Emigh, Karl L. Meier, Earl A. Meyer, and J. David Schneider, "An Intense Neutron Source Facility for the Fusion Energy Program," LA-UR-72-1262 (1975); also to be included in Ref. 1.
3. G. A. Bartholomew, J. C. D. Milton, and E. W. Vogt, "An Intense Neutron Generator Based on a Proton Accelerator," AECL-2059 (1964).
4. F. Seitz, Physics Today 5, 6 (1952).
5. A. B. Martin, S. B. Austermann, R. R. Eggleston, J. F. McGee, and M. Tarpinian, Bull. Am. Phys. Soc. 25(6), 21 (1950).
6. L. H. Jenkins, T. S. Noggle, R. E. Reed, M. J. Saltmarsh, and G. J. Smith, Appl. Phys. Lett. 26, 426 (1975).
7. J. B. Roberto, J. Narayan and M. J. Saltmarsh, "15 MeV Neutron Damage in Cu and Nb," in Proceedings of the International Conference on Radiation Effects and Tritium Technology for Fusion Reactors, Gatlinburg, Tennessee, October 1975.
8. T. Cahill, private communication.
9. J. P. Meulders, P. Leleux, P. C. Macy, and C. Pirart, Phys. Med. Biol. 20 235 (1975).
10. Don M. Parkin and Allen M. Goland, "The Calculation of Radiation Effects as a Function of Incident Neutron Spectrum: LA-UR-75-989 (1975).
11. P. Grand (Ed.) "Proposal for an Accelerator-based Neutron Generator" BNL 20159, July 1975.
12. T. A. Gabriel, private communication.
13. C. Y. Fu and E. G. Perey, to be published.
14. J. B. Roberto and M. T. Robinson, to be published.
15. M. T. Robinson in "Nuclear Fusion Reactors," p. 364, Brit. Nucl. Energy Society (1970).

16. J. Lindhard, V. Nielsen, M. Scharff, and P. V. Thomsen, Kgl. Danske. Videnskab. Selskab, Mat.-Fys. Medd. 33 (1963).
17. "Vacancies and Interstitials in Metals," p. 38, (eds.) A. Seeger, D. Schumacher, W. Schilling, and J. Diehl, North Holland, Amsterdam (1970).

4. THE ACCELERATOR

It is proposed that a 40-MeV standing wave linear accelerator (Alvarez-type) be used for the acceleration of the deuterons. The linac is a natural choice for this application because of its proven capability for delivering high-intensity beams which can be easily extracted from the accelerator. The fact that the beam can be injected, accelerated, and extracted with only minimal losses at low energy is important in keeping the radioactivity levels in the accelerator low enough so that components do not suffer radiation damage and servicing of accelerator components can be easily performed.

The basic capability of the linac has been demonstrated by the operating performance of the linac injectors for higher energy proton synchrotrons, such as those at Brookhaven, Fermilab, CERN, Argonne, and elsewhere. Peak beam intensities in excess of 100 mA are routine, and good reliability has been demonstrated. Although these synchrotron injectors have not been required to run at a 100% duty factor, there is no fundamental reason that such operation cannot be achieved if sufficient rf power and cooling are provided. In fact, the A-48, a 7.5-MeV 30-mA deuteron linac, was successfully run with a 100% duty factor over 20 years ago as part of the MTA project.¹ The experience with proton linacs is readily applied to the design of a deuteron linac.

The design of the linac proposed here is based primarily on designs for the existing proton linacs at Brookhaven, Fermilab, and Los Alamos. It has been guided also by the operational experience acquired, principally at Fermilab, so that the expected performance will be realistic and reliable. Because of the extensive design data available for these linacs at their operating frequency of 201.25 MHz, it is possible to arrive at fairly accurate design parameters by scaling to our design frequency of 60 MHz. Some extrapolation to the lower injection energy of the deuterons ($\beta = 0.02$ at 350 keV) is also required. Although this scaling process is sufficiently accurate for an initial design study, a

final design and optimization of the structure would require the use of digital computer programs² which have been developed for this purpose.

The main characteristics of the linac are given in Table 4.1, together with some of the expected beam characteristics.

Table 4.1. Basic design features of the linac

Injection energy	350 keV
Final energy	Up to 39.4 MeV, variable in steps of ~ 4 MeV
Beam current	100 mA to 150 mA
Duty factor	100% (CW)
Time structure of the beam	~ 5 -nsec pulses separated by 17 nsec
Energy spread (FWHM)	200 keV to 800 keV (depending on mode of operation)
Transverse emittance (90% of beam, normalized)	2π mm-mr from the source, 3.5π mm-mr at injection, $\sim 10 \pi$ mm-mr at 39 MeV
Number of accelerating cavities	10
Number of cells	79
Cavity diameter	3.00 m and 3.15 m
Total linac length (including drift space between cavities)	$39.92 \text{ m} + 5.91 \text{ m} = 45.83 \text{ m}$
Total rf power (for 100-mA beam)	6.55 MW
Average acceleration rate	0.98 MeV/m
Synchronous phase angle	-30 to -40 deg
Injection capture efficiency	65% with conventional buncher, 95% with special bunching option

4.1 The Injector

The injector system may be conveniently discussed in terms of the three major components: the ion source, which produces the d^+ ions; the high-voltage column, which accelerates the deuteron beam to an energy of 350 keV; and the low-energy beam transport system, which matches the deuteron beam to the longitudinal and transverse phase acceptance of the linac.

4.1.1 The Ion Source

The design beam current for the linac is 100 mA. This implies a d^+ beam of 155 mA since a single-gap buncher will deliver about 65% of the dc beam from the injector into the phase acceptance of the linac. If we assume an ion beam which is 80% atomic, and allow for modest beam losses, we then require a total ion current from the source of ~ 250 mA. The best choice of source is probably a single-aperture duoplasmatron. State-of-the-art pulsed duoplasmatron ion sources are capable of delivering the required 250 mA with high-quality beams.³⁻⁵ For example, the Fermilab column can deliver an approximately parallel pulsed low-duty-cycle 230-mA beam from a duoplasmatron utilizing a large plasma expansion cup. The normalized emittance of this system is 0.2π cm-mrad for 90% of the beam or 0.6π cm-mrad for $\sim 99\%$ of the beam.

The information most relevant to CW operation of this type of ion source comes from the development of the 600-keV 350-mA CW injector system for the DCX-2 plasma physics experiment at ORNL.⁶ Incorporating the essential cooling requirements developed for the DCX-2 system to obtain CW operation capability from more modern source designs is one obvious solution for the required injector. One significant source of new information is the rapidly advancing ion source and pulsed low-to-medium-energy hydrogen beam technology for thermonuclear research.⁷⁻⁹ These systems now deliver 20 to 50 A of beam at 20 to 40 keV for 10 to 750 msec with up to 10% duty cycle. They are being developed^{10,11} to satisfy even more demanding thermonuclear research requirements by extending the energy to 100 or 200 keV and by increasing the pulse length until they are ultimately capable of CW operation. An important byproduct of these programs has been the development of ion beam computer codes that agree with experiment and can be used as a guide in future multiparameter experiments. In the near future the planned development of the accelerator for the LLL RTNS project^{12,13} should also provide new and pertinent information. Experiments are in progress to modify a low divergent zero duty cycle source for CW operation. The

goal of this program is a ~ 380 -keV deuterium beam of several hundred mA, although the beam emittance requirements¹² are probably not as stringent as for our design.

4.1.2 The High-Voltage Column

Most of the design problems for the 350-keV accelerating column are associated with the need for reliable and stable operation over very long periods. Again, experience from the DCX-2 and intense neutral beam programs is particularly relevant. This experience indicates that to achieve electrical stability during high-power CW operation, the following features may be required:

- (1) A high-gradient one- or two-stage column, with a minimum electrode surface area in the high-gradient electric fields.
- (2) Electrodes designed to eliminate potential PIG discharge regions.
- (3) X-ray shielding within the electrodes.
- (4) The use of an electronic switch (modulator) as an interface between the ion source and high-voltage supply to eliminate most high-voltage power supply interruptions and destructive fault currents into the source elements.

A Pierce extraction geometry is not desirable because of the first requirement listed above. In any case the Pierce effect will not be attained in the proposed design because of the shortness of the extraction gap compared to the beam diameter, the nonuniformity of the current density profile, and the lack of control of the shape of the plasma emission surface.

4.1.3 The Low-Energy Beam Transport System

Transport of the beam from the column to the linac will be in a straight line about 4.5 m long. There are a number of options available for

matching the beam to the linac. These revolve around various chopper and buncher schemes. The simplest of these, which we initially propose, comprises three triplets for focusing plus a single-gap buncher (see Fig. 4.1). Nearly all the molecular deuterium ions will be lost in the transport line. Without a chopper, 30 to 40% of the dc deuteron beam will be lost in the linac. Most of these will be lost very early at low energy but some will be lost after they have been accelerated to a few MeV, resulting in an increased neutron yield from d-d reactions. Although the radiation level from these seems quite manageable (see Section 4.7), a 1-m-long section following the first triplet will accommodate a chopper that will remove all the beam not accepted by the linac.

Fig. 4.1. Beam transport line.

As a possible improvement in the transport line, to be held in reserve for the present, we consider use of an unusual bunching scheme, described in detail in Appendix A. It will permit at least 95% of the beam to be captured by the linac and will stop the remainder in the transport system. The basic idea is to cut the beam into 360-deg sections and to send alternate sections through two different buncher cavities operating at half the linac frequency. The resulting phase length of the bunches is well within the phase acceptance of the linac. The system offers the possibility of increasing beam current to the linac without increasing the current from the ion source and accelerating column. (The components for this system have been included in the cost estimates given in Chapter 7.)

Space-charge neutralization of the beam in the transport line is expected to be nearly complete for a dc beam. In the absence of complete neutralization, the transverse space-charge forces are appreciably more severe than for a comparable proton beam at 750 keV and would be taken into account in aperture design in any region of chopped or bunched beam. The longitudinal space-charge forces in the bunching region should not play an appreciably greater role than in the case of the proton beam when the lower frequency and larger beam size at the input to the linac are taken into account.

There will be beam-current transducers and ion-profile measurements at three or more locations in the transport line, from which the control computer can calculate the beam emittance. An alternate method of direct emittance measurement will use a pair of multichannel measuring probes at the input to the linac. These can be used to measure beam emittance only for a low-duty-factor pulsed beam from the ion source.

4.2 The Linac Design Parameters

The linac design parameters are given in Table 4.2. Extensive design data exist for the Brookhaven and Fermilab linacs operating at a frequency of 201.25 MHz so that most parameters can be derived by scaling to the design frequency of 60 MHz. Some parameters in the first cavity must be extrapolated to the lower injection energy of 350 keV [$\beta = v/c = 0.02$] from the lowest energy in these operating proton linacs of 750 keV ($\beta = 0.04$). Parameters that are not scaled by the frequency are the drift-tube aperture and the drift-tube inner corner radius. These are kept as small as permitted from the requirement of lossless beam transmission. The resulting transit time factor is larger than that of the proton linac. This is especially important for the proposed CW operation because of a more efficient use of the accelerating rf power. The transit time factor T and other quantities that are needed for an accurate calculation of the linac drift-tube table are then obtained by the analytic formulas of Carne and Lapostolle.¹⁴ These formulas are known to be sufficiently accurate for an overall preliminary linac design. On the other hand, for the final preparation of the drift-tube table that is to be used for the construction, more detailed calculation of resonating structures by a computer program is essential in order to further optimize parameters and to avoid the installation of a bulky, power-consuming tuning device in the cavity. The program MESSYMESH,¹⁵ which was developed at MURA for the drift-tube structure of a proton linac, has been found to be ideally suited for this purpose.

This program has recently been revised at Fermilab so that it can be run with present-day computers.

4.2.1 Choice of Frequency and Injection Energy

The choice of the frequency of the accelerating field is naturally dictated by the available high-power vacuum tubes. Within this limit,

Table 4.2. Linac parameters

Cavity resonant frequency = 60 MHz
Injection energy = 0.35 MeV

Total length, including drift spaces = 45.83 m
Final energy = 39.44 MeV

Cavity number	1	2	3	4	5	6	7	8	9	10
Output energy (MeV)	2.06	6.11	10.14	13.98	18.44	22.44	26.74	31.18	35.23	39.44
Cavity diameter (m)	3.15	3.15	3.15	3.15	3.00	3.00	3.00	3.00	3.00	3.00
Cavity length (m)	2.92	4.75	4.13	3.93	4.56	3.65	4.00	4.34	3.71	3.93
Drift-tube diameter (cm)	60	60	60	60	54	54	54	54	54	54
Bore-hole diameter (cm)	3.5/4/4.5	5	6	7	8	8	8	8	8	8
Stem diameter (cm)	5 and 6	7	8	9	9	10	10	10	10	10
Number of cells	18	15	9	7	7	5	5	5	4	4
Cell length (cm)	9.9-23.0	23.9-39.6	40.8-51.1	52.3-60.0	61.3-68.9	70.2-75.9	77.3-82.8	84.1-89.3	90.7-94.8	96.2-100.2
Gap length (cm)	1.9-5.0	5.3-10.0	10.4-14.0	14.5-17.5	10.6-12.9	13.3-15.2	15.7-17.7	18.2-20.2	20.7-22.4	23.0-24.7
Full drift tube length (cm)	8.3-17.6	19.0-29.3	30.9-36.7	38.3-42.1	51.1-55.6	57.4-60.2	62.0-64.7	66.3-68.7	70.4-72.0	73.6-75.1
Average transit time factor	0.765	0.831	0.834	0.824	0.904	0.903	0.899	0.895	0.809	0.884
Average axial field (MV/m)	1.00	1.25	1.35	1.37	1.25	1.40	1.38	1.32	1.42	1.40
Gap field (MV/m)	5.16-4.56	5.66-4.96	5.31-4.93	4.95-4.70	7.23-6.67	7.37-6.98	6.79-6.46	6.11-5.84	6.22-6.01	5.07-5.69
Average shunt impedance ^a (MΩ/m)	28.3	32.8	34.9	35.5	35.3	35.5	35.8	35.8	36.0	37.8
Total cavity power ^b (kW)	140	284	283	277	259	274	283	275	282	276
Total beam power ^c (kW)	171	404	403	384	446	400	430	443	406	421
Stored energy (joules)	32.7	83.5	85.0	83.3	75.7	76.2	81.2	80.7	80.0	82.4
Unloaded Q value (in 10 ³)	88	111	113	113	110	105	108	111	107	113
Synchronous phase angle (deg)	-40	-35	-30	-30	-30	-30	-30	-30	-30	-30
Quadrupole length (cm)	5.5/ 7/10	15	25	30	35	35	35	35	35	35
Quadrupole field (kG)	9/7.5/5.9	4.3	2.8	2.7	2.6	2.6	2.6	2.6	2.6	2.6
Radius and aperture (cm)	2.25/2.5/2.75	3.0	3.5	4	4.5	4.5	4.5	4.5	4.5	4.5
Drift space after cavity (cm)	23	40	52	61	70	77	83	90	96	

^aEffects of stems are included.

^bLosses on stems and end plates are included.

^cFor 100-mA beam.

higher frequency is preferable because of the smaller dimension of the structure and more efficient use of the rf power. For a given final energy, the product of the linac length and the cavity power is approximately proportional to $(\text{frequency})^{-1/2}$. On the other hand, the reduced dimension of the drift-tube aperture should not be too small for the beam emittance. If the aperture is simply enlarged independent of the frequency scaling, the transit time factor becomes smaller. The reduced length of the drift tube, especially at the low-energy end, may not be sufficient for installing a quadrupole of sufficient strength. In order to avoid the harmful fringe field effects, it is desirable to make the quadrupole length larger than the aperture. The gap size between drift tubes must also be large enough to prevent possible sparking.

Once the frequency is chosen, the injection velocity of the beam fixes the initial cell dimension. There are again conflicting requirements: some favor a low injection energy while others indicate an injection energy as high as possible. For example, since the accelerating column of the injector will be one of the more critical elements of the system for a reliable operation, a low injection energy will definitely ease its design problem. Another important factor in favor of a low injection energy is the production of neutrons by the lost deuterons. That part of the beam which is outside of the stable area in the longitudinal phase space is lost before it gains a substantial amount of energy. A computer calculation for combined longitudinal and transverse motions has shown that approximately 70% of the lost particles are at or near the injection energy when they are lost on the drift-tube walls. Since the neutron yield from the reaction $D(d,n)He^3$ is a steep function of the deuteron energy, it is important to make the injection energy as low as practical. The required transverse focusing is, on the other hand, stronger for a lower energy beam due to greater space charge effects and stronger defocusing actions of the rf field. For a given frequency, higher injection energy makes the cell geometry more comfortable for installing quadrupoles. The present choice of 60 MHz and 350 keV has been made after careful studies of various combinations of the frequency and injection energy and consideration of the availability of high-power rf tubes.

4.2.2 First Cavity Parameters

Practically all problems in the linac beam dynamics are most serious in the first cavity where the energy is low and the rate of change in velocity is large. The rf defocusing force, as well as space charge effects, are more important there than in later cavities. The transmission of the beam through the linac is essentially the transmission in the first cavity and the increase in the beam emittance, which is expected to be by a factor of two to three, is encountered predominantly in the first cavity.

The synchronous phase angle of -40 deg for the first cavity is chosen for its large phase acceptance. The average axial field, 1 MV/m, is a compromise between a quick acceleration to avoid a prolonged space charge influence and a manageable rf defocusing force in the first few gaps. The resulting gap field of 50 kV/cm is not a serious factor. In the first gap of the linacs at Brookhaven and at Fermilab, it is 75 kV/cm. With the choice of -40 deg and 1 MV/m, one can operate the first cavity in various ways to achieve the optimum running condition. For example, the synchronous phase angle can be either increased to -50 deg or reduced to -30 deg by increasing the average field to 1.19 MV/m or decreasing to 0.88 MV/m. The total cavity power for a 100 -mA beam is then 385 kW and 290 kW, respectively. The position of the bunched beam can be shifted within the stable phase space area, either to change the beam shape in longitudinal phase space or to reduce the rf defocusing action in the first few gaps where it is strong.

If the output energy of the first cavity is too low, the drift space after the cavity, which is one $\beta\lambda$ long, becomes too short for installing a monitoring device. At the same time, it is desirable to terminate this special cavity with a relatively low acceleration rate as early as possible and to begin the next "normal" cavity. The choice of 2 MeV for the output energy is a compromise of these requirements.

4.2.3 Acceleration Rate

The average acceleration rate of ten cavities is 0.98 MeV/m. In each cavity (except for the first one), this corresponds to approximately 300 kW of cavity power, which is 75% of the 100-mA beam power. If the acceleration rate is reduced to 0.84 MeV/m, the cavity power becomes one-half of the beam power, the optimum ratio from the standpoint of power economy and the beam loading consideration. The total savings in power compared to the present design is ~700 kW. At the same time, the linac length is increased from 40 m to 46.5 m. Since each rf station is capable of delivering 1 MW, one can increase the beam current from 100 mA to 150 mA, and the ratio of the cavity power to the beam power, 300 kW to 600 kW in each cavity, becomes optimal. Clearly a more careful study of optimizing the overall cost is needed for the final design.

4.2.4 Transverse Focusing

The transverse focusing system is composed of 89 quadrupoles placed inside the drift tubes. The maximum pole tip field is 9 kG and the power for each magnet is 1 to 2 kW. Six quadrupoles in the first cavity, the first four and the last two, and the first two quadrupoles in the second cavity are independently adjustable, but other quadrupoles are all in series in each cavity. This is possible since all drift spaces between adjacent cavities are one $\beta\lambda$ long and there is no need for cavity-to-cavity matching. There is a small amount of discontinuity between the first two cavities due to the difference in the rf defocusing action. This accounts for the need for adjustable quadrupoles there. Beyond this point, the rf effect on the transverse motion is negligible.

The system is designed for the normalized beam emittance of $\sim 7 \pi$ mm-mr. It is expected that 90% of the beam will be within the emittance of 2π mm-mr at the exit of the accelerating column. This may increase to 3π to 4π mm-mr at injection into the linac. The average beam size is then

less than 2 cm in the linac. The bore-hole size changes in two steps from 3.5 to 4.5 cm in the first cavity. The stepwise increase is to maintain a comfortable acceptance in the presence of space charge effects and to minimize the deterioration of transit time factor as the bore-hole diameter is increased.

It is of course essential for the design of the focusing system to take into account space charge effects as well as rf defocusing actions.¹⁶ The usual procedure is to linearize longitudinal and transverse motions and to derive the equations of motion for beam envelopes.¹⁷ This leads to the so-called matched beam shape. With the linac parameters given in Table 4.2, the matched condition is

longitudinal	$\pm(15-17)$ keV, ± 30 deg
transverse	average beam size, 1.8 cm, maximum beam size, 2.5 cm.

The maximum pole tip field to achieve this is 9 kG. Quadrupoles operated in dc mode with a similar pole-tip field are used in the 50-MeV proton linac at Argonne.

4.2.5 Energy and Energy Spread of the Output Beam

The nominal energy of the output beam from the linac is 39.44 MeV. Since each cavity is electrically independent, the final energy can vary below this value in steps of 4 MeV. The step size can be made even smaller if it is needed for some experiments. It has been demonstrated at Fermilab¹⁸ that the output energy of the proton linac can be varied continuously by adjusting phases between cavities and coasting the beam through unexcited cavities. The energy spread of the final beam is also adjustable within a certain range.¹⁹ In particular, later cavities are short compared to the phase oscillation wavelength and it is possible to operate one or two cavities at the "unstable" synchronous phase angle (+30 deg instead of -30 deg). The central energy of the output beam

will be only slightly lower than the normal value but the energy spread will be much larger as shown below.

In the absence of space charge effects, the bunched beam in the longitudinal phase space lies within ± 30 deg and ± 17 keV at injection. There will be some dilution of this area due to space charge forces in the space between the buncher and the linac. It is therefore reasonable to assume that the charge distribution is Gaussian and 95% of the beam is inside an ellipse (± 40 deg, ± 23 keV). If there is no more dilution of the beam, the expected energy spread is as given in Table 4.3.

Table 4.3. Energy spread of the linac beam

End of cavity	Energy (MeV)	Energy spread (keV)
7	26.7	175
8	31.2	182
9	35.2	194
10	39.4	200

A more realistic estimate must be made by detailed numerical calculations which take into account the space charge effect and the dilution due to drift spaces between cavities. If the original 95% area is assumed to contain 80% of the beam after ~ 25 MeV, which is reasonable, the energy spread (FWHM) increases to 240 keV at 27 MeV and to 275 keV at 39 MeV. Larger energy spreads than these can be obtained by various modes of operation. Examples are as follows, where W = beam energy, ϕ_s = synchronous phase angle, and ΔW = energy spread:

- (1) Cavity 10 with $\phi_s = +30$ deg: $W = 39$ MeV, $\Delta W = 640$ keV.
- (2) Cavities 9 and 10 with $\phi_s = +30$ deg: $W = 39$ MeV, $\Delta W = 825$ keV.
- (3) Cavity 9 with $\phi_s = +30$ deg, cavity 10 off: $W = 35$ MeV, $\Delta W = 495$ keV.
- (4) Cavity 8 with $\phi_s = +30$ deg, cavities 9 and 10 off: $W = 31$ MeV, $\Delta W = 630$ keV.

4.3 The Radiofrequency System

The accelerating structure will be divided into ten cavities, the first of which will require about 300 kW of 60-MHz rf power, while the remaining nine will require 700 kW each. In order to simplify design and maintenance, the ten cavities will be powered by ten identical rf stations, each capable of delivering 1 MW of useful power. The excess power capability will allow for the acceleration of beam currents somewhat higher than the design figure of 100 mA, and, more importantly, will provide increased reliability. Each rf station will incorporate phase, accelerating gradient, and cavity frequency servo systems and will include the equipment necessary to interface to the linac computer control system. A single phase-stable reference line will provide low-level rf power to all stations. The major features of a typical rf station are shown schematically in Fig. 4.2.

Fig. 4.2. 1000-kW rf station equipment block diagram.

4.3.1 Power Amplifier (PA)

There are several possible amplifier designs for the 1-MW stations. For reasons of reliability, we have chosen to design the final stage around an array of five high-power tetrodes connected in parallel. With such a configuration, a failure of one tube will reduce the available power only slightly, permitting continued operation of the facility until a convenient opportunity occurs to replace the tube. Although the type of tube used does not significantly influence the cost of the system, it does affect its reliability. The tube chosen for this design study is the Eimac 4CW100000E. Other tetrodes with a similar power rating are available and these will receive further evaluation; however, a significant level of experience has been accumulated with the 4CW100000E at Fermilab. This tube is used in 34 rf stations in the two proton synchrotrons at Fermilab, both as a modulator and as an rf amplifier, and is giving an operational life of $\sim 20,000$ hr.

The PA must provide 1000 kW of useful output power in addition to the estimated 100 kW which will be lost in the anode cavity structure. The PA cavities serve to introduce the dc operating voltages to the tubes and to make the input and output rf connections. The load impedance (reflected to the 50-ohm transmission line impedance) will be matched to the required 579 ohms per tube anode impedance by means of a coaxial quarter length resonator.

The screen grid will be grounded at the operating frequency by separate screen blocking capacitors. This enables the screen grids of the individual tubes to be connected to their dc voltage power supply through switches so that in the event of an internal screen to control grid fault, the defective tube can be electrically removed from service, thus maintaining the amplifier operational at a reduced power level.

The PA will be operated as a grounded-grid cathode-driven amplifier which will result in an extremely stable operation at the contemplated frequency range. Drive power will be coupled to the cathode of the

tubes in five uncoupled input cavities. This arrangement plus a careful design of the screen blocking capacitors and the layout of the power amplifier should eliminate any dangerous operating modes.

Modulation of the output power level will be accomplished by varying the potential of the PA screen grid. A variable power supply of 2000 v and not more than 10A will provide a full range of power control.

The power dissipated in both the input and output cavities will be removed by water cooling because of their relatively low operating voltages. The cavities will not be pressurized but will be enclosed and sealed to prevent contamination from airborne dirt and moisture.

4.3.2 Anode Power Supply

The anode power supply will be a conventional three-phase solid-state converter operating as a series-connected 12-pulse (720-Hz ripple) rectifier. This arrangement minimizes both the reactive power presented to the ac utility system and the magnitude of the ripple voltage at the output of the power supply. The anode power supply will be located outdoors in an oil-filled enclosure.

The anode power supply will be rated to produce 20 kV dc at a current of 70 A. A power filter of modest capacity will be added to remove fast line voltage fluctuations. A fast acting energy diverting switch will be used to protect the PA tubes from dangerous levels of input energy from the power supply in the event of a fault in the tubes. The surge ratings of the transformer and rectifier will be coordinated to safely withstand repeated switching actions.

4.3.3 Intermediate Power Amplifier (IPA)

A single 4CW100000E will be used as a grounded-grid cathode-driven amplifier which can furnish in excess of 100 kW drive power to the PA.

There will be five outputs with independent loading adjustments to match the drive power to each of the PA tubes.

The IPA will be operated at constant supply voltages because the tubes in the PA will be driven to cathode emission saturation and thus the need for variable IPA drive power is removed.

4.3.4 Low-Level Amplifier

The low-level amplifier will have a power gain of about 60 dB with 40 dB occurring in a solid-state amplifier. The final stage of the low-level amplifier will be a tube-type in a cavity resonator similar to the IPA and the PA.

4.3.5 Transmission Lines

Power will be transported from the IPA to the PA and from the PA to the accelerating cavities by standard 50-ohm air dielectric coaxial transmission lines. The input to the five PA cavities will be by a 3-1/8 in. line.

The output of the PA will be into a 50-ohm 12-in. line. The transmission line is oversized inasmuch as the system must operate under conditions of high VSWR during periods when the cavity is not operating at its rated beam current or during periods of momentary cavity faults. Dangerous conditions which can exist in the PA during these periods of high VSWR can be minimized by adjusting the line length between the PA and the cavity. The line stretcher at the output of the PA facilitates this field adjustment.

4.3.6 Stabilization

The rf system operates as an open-loop amplifier and as such will require closed loop stabilization for both amplitude and phase. Schemes which have been employed on the Fermilab 200-MeV linac rf system and on other

contemporary machines will be adapted to this rf system with a goal of 1000 ppm in amplitude stability and less than ± 1 deg in phase stability as the operating objective.

4.3.7 Control System

The rf stations will have a control system that is independent of the accelerator system, allowing any stations to operate either with or without the accelerator control system. The principal functions of the control system are: (1) to provide for automatic protection of the equipment in the event of abnormal operations (which allows for unattended operation), and (2) to provide a convenient interface to the accelerator control system.

There will be two coordinated control systems. One, a relay-based and hard-wired system, will provide protection of the equipment where speed is not essential. The other system will use solid-state logic modules and will be used for operations such as cavity spark detection and PA tube arc-throughs where speed of detection and reaction is essential.

The rf system controls will be designed to provide for direct interfacing to the computer-based accelerator control system. As the rf system represents the bulk of the data that the computer control system must process, a data interface unit will be located at each rf station.

The rf control systems will be prewired and will be ready for connection directly to the interface unit, thus minimizing the amount of field wiring.

4.4 Mechanical Details

The accelerating cavities will be fabricated from copper-clad steel plates. The rolling and welding of copper-clad plates into cylinders can be done by a number of industrial firms, and this type of construction has proven to be very successful in maintaining close tolerances

for drift tube alignment under atmospheric loading and temperature stresses.

Each drift tube will be supported by a single stem. The stem diameters, which will vary from 5 cm for cavity 1 to 10 cm for cavities 6-10, are large enough to accommodate the power leads for the quadrupoles and the cooling water for both the quadrupoles and the drift tubes. Each drift tube will contain a bore tube so that the quadrupole and drift tube cooling channels can be isolated by a secondary vacuum system. This provides a backup in case of a weld failure and also allows a higher vacuum in the cavity itself.

The 89 quadrupole magnets, which will be run continuously, will be manufactured with ceramic coil insulation, following the techniques used at Los Alamos.²⁰ In order to ease the fabrication, only seven combinations of quadrupole length and aperture will be used. This will involve only minor compromises in the optimal beam focusing properties for each quadrupole. Fifteen power supplies will be sufficient to excite the 89 quadrupoles.

It is advantageous from beam dynamics considerations to keep the tank separation small, i.e., a distance of $\beta\lambda$ or less. In the early cavities this distance is too small to accommodate vacuum end covers. Therefore, the first four cavities will be contained in a single vacuum envelope. In order to minimize the tank pump-down times, the remaining six cavities will be divided between two additional vacuum envelopes. Because of the sensitivity of elastomer seals to radiation damage, the tanks will be provided with hard seals. One portable roughing pump system will be used for all three vacuum envelopes.

The temperature of the cavity walls and drift tubes must be stabilized to within 2°C in order to eliminate drifts of the cavity resonant frequency. The accelerator will be cooled by three separate cooling systems arranged in conveniently sized modules spaced along the accelerator length in the lower bay of the accelerator gallery. One system

will provide the high volume cooling for the accelerator tanks and will run at elevated temperature to take advantage of the existing ORNL cooling towers. A second system will provide low conductivity water for cooling the drift tubes and cavity end plates. This system will be provided with heaters to adjust the temperature to within 2°C of the nominal operating temperature at startup. This will minimize the cavity tuning, which would otherwise be necessary. A third cooling system will provide the very low conductivity water for the rf systems.

It is recognized that the rf vacuum window in the 12-in. coaxial transmission line to the cavity will present some special design problems due to the requirement of continuous operation. It is expected that a successful design can be made using high-purity alumina insulators with low rf loss tangents. Suitably sized insulators of this type have been used at Fermilab at a frequency and duty factor comparable to those specified for the machine proposed here. It is planned to test the design in a prototype cavity before production of the final units.

4.5 The Control and Diagnostic System

Nowadays no one seriously considers building an accelerator without incorporating a digital computer as the central element in the control system. The economic and operational justification for computer control systems has been adequately documented in the literature.²¹⁻²²

The control system requirements for the proposed accelerator are generally the same as those for the Fermilab accelerator. The system must provide control and monitoring for all the binary and analog parameters in the accelerator, transport lines, and target areas. In contrast to the operation of existing machines, this linac will be operated at full intensity for months at a time with little or no change in the operating parameters. In this type of operation, it is desirable to provide both for automatic reset of fault conditions wherever applicable and for long-term recording of the performance data for the various accelerator systems.

The control system consists of a 16-bit control computer with peripherals, interfaced to a standard serial Camac system as shown in Fig. 4.3. A Camac crate will be located in each rf system with additional crates at either end of the accelerator to accommodate controls for the injector, the transport lines, and the target area. The individual Camac control modules are now commercially available items and little development is required to implement the hardware of the control system. The software operating system may be patterned after the Fermilab control systems which have been developed and used for accelerator control for the past five years. These systems provide for the operator's interface to the accelerator and the simultaneous execution of operator-related application programs for measurement and display, automatic data acquisition, alarms and limit checking for fault location and reporting, and program development.

Fig. 4.3. Accelerator control system.

It is not expected that the control system perform personnel or equipment safety functions, although the status of all systems may be monitored by the control system. All equipment protection for individual components will be hard wired into those systems.

Microprocessors will be used as required. Obvious applications include communication with the high-voltage terminal and intelligent controllers for the linac tank temperatures.

Control system installation is potentially an expensive and time-consuming job. This work can be reduced by incorporating the Camac crates into the rf system control racks. The rf system I/O signals are internal to the system and need no on-site cabling except for the Camac serial link.

Because of the high beam power, beam diagnostic measurements for this machine must be accomplished through the use of nonintercepting detectors. Diagnostic equipment will include beam current transducers, position monitors and residual gas ion profile monitors. In addition to these, loss monitors will be placed along the accelerator and transport lines to detect the loss of beam. Data from these devices will be interfaced to the control system at the closest Camac crate.

4.6 High-Energy Beam Transport System

The function of the high-energy beam transport system is to capture all the beam from the linac and direct it to one of the two lithium targets. The system must be nondispersive, to accommodate the large energy spread in the beam, and must permit adjustment of the shape of the beam spot at the target to provide the required neutron flux contours in the target cell. The elements of the system should be located far from the target itself, to avoid undue radiation damage, and should not be buried too deeply in the shielding in case maintenance is required.

The simple system shown in Fig. 4.4 will satisfy these requirements. A 15-cm bore quadrupole triplet, Q1, captures the beam from the linac and

is followed by the 15-cm gap bending magnet M which provides the ± 45 deg deflection to direct the beam toward a target cell. A second triplet Q2 (A or B) focuses the beam onto the target. Small steering magnets S1 and S2 (A or B) serve to correct for minor misalignments in the system.

Fig. 4.4. High-energy beam transport system.

The first-order condition for the system to be nondispersive is that Q2 be adjusted so that a point source at the center of M is focused to a point at the target position.²³ Once Q2 is set to meet this condition, Q1 may be used to give the required beam shape at the target. OPTIK²⁴ calculations of the performance of this system have been made assuming that the beam emittance from the linac is 80 mm-mrad (98% of the beam) and that the beam energy spread is ± 1 MeV. When the beam spot size at the target is ~ 3.5 cm, the beam diameter elsewhere in the system is always < 6.5 cm, so that a bore of 15 cm should assure negligible beam losses.

Using this system the intensity profile of the beam spot at the target will be roughly gaussian. If a more uniform distribution is required the beam must be scanned across the target. As discussed in Chapter 3, fluctuations in the neutron intensity with a period $\sim 1 \mu\text{sec}$ could affect the radiation damage processes in the samples, so the scan frequency should be $\sim 1 \text{ MHz}$. This may be achieved by using electrostatic deflection plates in the beam line. A good location for these plates would be just before Q1, although their effect would then depend somewhat on the setting of Q1. Locating the plates after Q2 would simplify the initial tuning of the transport system but would expose the high-voltage system to lithium vapor from the target.

4.7. Shielding and Activation

During the acceleration process a certain fraction of the deuteron beam will be intercepted by the various accelerator structures, resulting in both prompt and residual radiation. The facility design requires that sufficient shielding be installed around the accelerator to reduce radiation levels in adjacent areas to a level of 0.25 mrem/hr or less to permit unrestricted access of personnel. Furthermore the residual activation levels must be low enough to permit access to the accelerator vault for maintenance and repair. Calculations have been made of the shielding required around the accelerator (see Appendix B) and the residual radiation levels to be expected (see Appendix C). The results are summarized below.

4.7.1 Shielding

The estimated beam losses along the accelerator during normal operation are given in Table 4.4. All losses are assumed to occur on copper surfaces.

For the shielding calculations the losses in cavities 6-10 were increased by a factor of ten to allow for abnormal losses during beam tuneup or minor accelerator malfunctions. For the higher energy losses, the

calculations are extremely sensitive to the high-energy tails in the neutron yields from the $d + Cu$ reaction. Unfortunately the available experimental data do not adequately define these tails, and additional measurements would greatly improve the shielding estimates.

Table 4.4. Beam losses in the accelerator

Energy	Particle	Current	Location
350 keV	D^+ (60%), D_2^+ (40%)	150 mA	Low-energy beam transport
~600 keV	D^+	50 mA	First cavity
1-20 MeV	D^+	2.5 $\mu A/m$	Cavities 1-5
20-40 MeV	D^+	0.25 $\mu A/m$	Cavities 6-10

The required thicknesses of concrete shielding at a few locations along the accelerator are given in Table 4.5.

Table 4.5. Concrete shielding of accelerator

Location	Source of neutrons	Shielding thickness (m)
Injector	$d + d \rightarrow {}^3He + n$	
Cavity 1	$d + d \rightarrow {}^3He + n$	1.2
Cavity 3 (10 MeV)	$Cu(d,nx)$	1.1
Cavity 7 (25 MeV)	$Cu(d,nx)$	1.6
Cavity 10 (40 MeV)	$Cu(d,nx)$	2.7

4.7.2 Activation

Using the beam losses in Table 4.4, we have made estimates of the residual radiation at various points along the accelerator from both direct deuteron activation and secondary neutron activation. The results are summarized in Table 4.6.

Table 4.6. Dose levels after 1 year of operation and 1 shift of cooling

Location	Source of activation	Dose level (mrem/hr)	Dominant radioisotope	$\tau_{1/2}$
Injector + first cavity	n + Cu n + Fe	<1	^{54}Mn	312 d
Cavity 6	d + Cu	4	^{64}Cu	12.9 h
Cavity 10	d + Cu	3	^{64}Cu	12.9 h
Cavity 10	n + Fe	5	^{54}Mn	312 d
Cavity 10	n + concrete	12.5	^{24}Na	15 h
Cavity 10	Total	~ 20		

The highest levels occur in the accelerator tunnel near cavities 6 and 10. Unfortunately these estimates are not very reliable as they depend on inadequate neutron yield data and upon the precise composition of the concrete used for shielding. However one can conclude that residual radiation levels can be kept to reasonable levels, particularly if certain precautions are taken. For instance, installing tantalum scrapers between the linac tanks will reduce the amount of beam lost on the drift tubes. The neutron yields from tantalum are less than half those from copper, as is the residual activity after deuteron bombardment. The overall activity levels would be significantly reduced and localized, permitting the use of local shielding during maintenance operations. The use of low activation boron-loaded concrete would further reduce the ^{24}Na activity.

Finally, estimates were made of the ^{13}N and T activities produced in the air inside the accelerator vault. ^{13}N is a 10-min β^+ emitter. The concentration inside the vault would reach equilibrium at ~ 0.5 mCi/cm³. Total tritium production would be ~ 0.2 $\mu\text{Ci/day}$. These levels can easily be accommodated by the air-handling system.

REFERENCES

1. P. V. Livdahl, private communication.
2. B. Austin, T. W. Edward, J. E. O'Meara, M. L. Palmer, D. A. Swenson, and D. E. Young, "The Design of a Proton Linear Accelerator for Energies up to 200 MeV," MURA Report No. 713 (1965).
3. Th. Sluyters, "High Intensity Proton Sources for High Energy Accelerators," p. 190 in Proceedings of the Second International Conference on Ion Sources, Vienna, Austria, 1972.
4. C. D. Curtis, "Emittance Measurements of a Proton Beam as a Function of Duoplasmatron Source Parameters," p. 215 of Vienna Conference Proceedings (see ref. 4).
5. C. R. Emigh and D. W. Muellen, "Observations and Calculations for a Duoplasmatron with Exact Pierce Extraction," p. 226 of Vienna Conference Proceedings (see ref. 4).
6. O. B. Morgan, G. G. Kelley, and R. C. Davis, Rev. Sci. Instr. 38, 467 (1967).
7. O. B. Morgan, "High Intensity Ion Sources for Thermonuclear Research and Development," Paper VI-I-I in Proceedings of the Second Symposium on Ion Sources and Formation of Ion Beams, Berkeley, California, October 22-25, 1974.
8. K. H. Berkner, W. R. Baker, W. S. Cooper, K. W. Ehlers, W. B. Kunkel, R. V. Pyle, and J. W. Stearns, "Performance of LBL 20-kV, 10-A, and 50-A Neutron Beam Injectors," Paper VI-12-1 in Proceedings of Berkeley Symposium (see ref. 7).
9. W. L. Stirling, R. C. Davis, T. C. Jernigan, O. B. Morgan, P. M. Ryan, D. E. Schechter, and L. D. Stewart, "Plasma Properties and Performance of the 10 Cm DuoPIGatron Ion Source," Paper VI-10-1 in Proceedings of Berkeley Symposium (see ref. 7).
10. Proposal for the Construction of a 150 keV Neutral Beam Injector Test Facility in the Thermonuclear Division of ORNL, March 7, 1975. (Now approved, funded and under construction; to be operational June 1976).

11. H. K. Berkner, Neutral Beam Development and Technology Program Plan and Major Proposal, LLL & LBL, September 1974. (Approved, funded and under construction.)
12. J. E. Osher, LLL, private communication.
13. J. E. Osher and G. W. Hamilton, "An Intense Steady-State 20 kV Multiple-Aperture Ion Source, 'MATS III,' " Paper VI-7-1 in Proceedings of Berkeley Symposium (see ref. 7).
14. A. Carne and P. M. Lapostolle, "Design Equations in a Alvarez-Type Proton Accelerator," p. 201 in Proceedings of the 1966 Linear Accelerator Conference, Los Alamos Scientific Laboratory, October 3-7, 1966.
15. T. W. Edwards, "Proton Linear Accelerator Cavity Calculations," MURA Report No. 622 (1961).
16. S. Ohnuma and J. N. Vitale, IEEE Trans. Nucl. Sci. NS-14, No. 3, 595 (1967).
17. R. Chasman, "Numerical Calculations of the Effects of Space Charge on Six Dimensional Beam Dynamics in Proton Linear Accelerators," Brookhaven National Laboratory, BNL 50124, 372 (1968).
18. C. D. Curtis, "Variability of NAL Linac Energy," Fermilab TM-443 (Feb. 16, 1972).
19. S. Ohnuma, "Momentum Spread of the 200-MeV Linac Beam at NAL," Fermilab FN-227 (April 10, 1971).
20. E. D. Bush and R. L. Rholes, "Construction of Alumina Insulated Bending Magnets for LAMPF," p. 191 in Proceedings of the 1972 Linear Accelerator Conference, Los Alamos, October 1972.
21. M. L. Shea, "Interaction of Accelerator Controls and Diagnostics," IEEE Trans. Nucl. Sci. 22, 1458 (1975).
22. R. E. Daniels, R. W. Goodwin, and M. R. Storm, IEEE Trans. Nucl. Sci. 20, 505 (1973).
23. James E. Draper, Rev. Sci. Instr. 37, 969 (1966).
24. T. J. Devlin, "OPTIK: An IBM 709 Computer Program for the Optics of High-Energy Particle Beams," UCRL 8727 (September 1961).

5. THE LITHIUM TARGET SYSTEM

As has been stated previously, the proposed facility will include two irradiation cells, each of which will be equipped with a lithium target. The target, shown schematically in Fig. 5.1, will be formed at the end of the beam pipe vacuum system by a rectangular jet of liquid lithium flowing downwards through the deuteron beam. The jet will be 10 cm wide and 2.5 cm deep and will flow at a velocity of 15 m/sec through a channel that encloses it on three sides. A free lithium surface approximately 10 cm square will be presented to the incident deuteron beam on its upstream side. The deuterons will interact and stop in the lithium, producing a beam of neutrons which will pass through a 3-mm end window into the experimental irradiation volume.

Fig. 5.1. Schematic of lithium target.

The lithium jet will be produced by a loop system that will operate at a base temperature of 286°C, which is sufficiently above the melting point of lithium (180°C) to ensure that the system will not freeze up if the 4-MW beam power is suddenly removed. Following interaction with the deuteron beam the average temperature of the lithium exiting the irradiation cell will be 343°C, which is well below the temperature ($\sim 400^\circ\text{C}$) at which erosion problems might be anticipated.

As is discussed in Section 5.1 below, the fluid dynamics of the lithium jet are such that no difficulty is expected from breakup or distortion of the jet, nor from any local boiling. However, the loop design is complicated by the generation of tritium at a rate of ~ 70 Ci/day and by the high concentration of ^7Be γ -activity, which will reach ~ 8 mCi/cm³ after a few months of operation (see Appendix C). Also, high levels of oxides are expected after periods of maintenance, and these, together with other impurities that will build up, will require a high-efficiency bypass purification system. The main lithium circuit and its auxiliary systems are described in Section 5.2 below.

5.1 Fluid Dynamics of the Lithium Jet

5.1.1 Stability of a Turbulent Lithium Jet

For a free jet issuing from a pipe or an orifice, Rayleigh¹ first showed quantitatively that certain surface disturbances that are carried along with the flow will grow in amplitude due to the destabilizing effect of interfacial tension until eventually the continuity of the stream is interrupted. The theory of Rayleigh is inadequate in that it does not include viscous damping effects and is applicable only to low-speed laminar jets for which the breakup length is a linearly increasing function of velocity. For viscous jets of circular cross section, the theory of Weber,² as recently extended by Phinney^{3,4} to include turbulent jets, seems to predict quite well the region in which the jet

remains coherent, particularly when the jet issues into a rarefied atmosphere and aerodynamic effects caused by interaction with the ambient medium can be neglected. To date, no theory has been proposed nor do any data exist for predicting the behavior of jets of noncircular cross section; nevertheless, consideration of the axisymmetric case should at least provide a reliable order of magnitude estimate of the breakup length.

Following Weber, the breakup length L is expressed in terms of the jet discharge diameter D , a stability parameter, λ , which is characteristic of the initial destructive disturbance level, and the dimensionless Reynolds and Weber moduli, N_{Re} and N_{We} , as

$$L/D = \lambda [N_{We}^{1/2} + (3N_{We}/N_{Re})] , \quad (5.1)$$

where

$N_{We} = \rho V^2 D / \Gamma$ = ratio of inertial-to-surface forces,

$N_{Re} = VD\rho/\mu$ = ratio of inertial-to-viscous forces,

V = jet discharge velocity,

ρ = liquid density,

μ = dynamic viscosity,

Γ = surface tension coefficient,

$\lambda = \ln(D/2\delta_0)$ = stability parameter,

δ_0 = amplitude of initial destructive disturbance.

From the form of Eq. 5.1, it is clear that surface tension acts to destabilize the jet while viscosity acts as a damping mechanism. The high surface tension of lithium, therefore, raises the possibility of early jet disintegration. Furthermore, the stabilizing effect of viscosity should be significant only for low-speed, small-diameter jets and probably will not be a contributing factor here.

If the level of the destructive disturbance δ_0 is taken as a constant independent of flow conditions, then Eq. 5.1 predicts the linear behavior

applicable to low-speed (laminar) jets. Beyond a certain critical velocity (Reynolds number), it is observed that the characteristics of the flow change with a resulting sharp increase in the disturbance level or, alternatively, a precipitous decrease in the stability parameter, λ . This decrease is usually attributed to the onset of turbulence which, for pipe flow, ordinarily occurs at Reynolds numbers greater than 2300.

From an analysis of the available data on circular jets, Phinney⁴ was able to successfully correlate the stability parameter, λ , with the dimensionless groups N_{Re} and $Z = \mu/(\rho \Gamma D)^{1/2}$ (Ohnesorge number). As expected, λ remains constant up to a certain critical value of N_{Re} , decreases in a laminar-to-turbulent transition region, and reaches a second, lower plateau for a fully developed turbulent flow ($N_{Re} \geq 2300$).

In the fully developed region, which is typical of the conditions being considered here, λ is only a weak function of the Ohnesorge number and has a value approximately equal to 3.0. This is to be compared with observed values of about 13 (refs. 2 and 5) for laminar jets. Obviously, from this result and from consideration of the form of Eq. 5.1, it is preferable to operate under flow conditions such that the Weber number is large, yet the Reynolds number is just below the critical value to ensure laminar flow and, hence, a maximum value of λ . If the geometry is not fixed by other considerations, this maximum stability criterion suggests small-diameter high-velocity jets that preserve the laminar flow condition $VD\rho/\mu \lesssim 2300$. For the conditions imposed here, Reynolds numbers will be in the 100,000 region and a value of λ of 3.0 must be used to calculate the breakup length. Equation 5.1 then simplifies to

$$L/D \approx 3[N_{We}^{1/2} + (3N_{We}/N_{Re})] , \quad (5.2)$$

Taking as the reference condition an orifice of dimensions 2.5×10 cm, a jet velocity of 15 m/sec, and liquid lithium at 300°C ($\mu \approx 4.5 \times 10^{-4}$ N sec m⁻², $\rho \approx 450$ kg m⁻³, $\Gamma \approx 0.38$ N m⁻¹), the following values for

N_{We} and N_{Re} result:

$$N_{We} = 11,570 ,$$

$$N_{Re} = 675,000 .$$

In calculating these results, the hydraulic diameter (4 x flow area/wetted perimeter) was used as the characteristic length scale.

For such a large value of the Reynolds number, the viscous damping effect is negligible and contributes little in Eq. 5.2. Then using a value of $D = 0.04$ m, the breakup length becomes

$$L = 0.04 \times 3 \times \sqrt{11,570} = 12.9 \text{ m} .$$

Given a coherent length of this magnitude, the target area should not be appreciably disturbed by surface instabilities. An estimate can easily be made of the magnitude of the initial destructive disturbance and the degree to which it grows at any point along the jet. At any axial position x downstream of the injection plane, the amplitude of the destructive disturbance will be given by the following expression:

$$\delta(x) = \delta_0 e^{x\lambda/L} , \quad (5.3)$$

where

$$\delta_0 = \delta(0) = (D/2) e^{-\lambda} .$$

For $\lambda = 3$ and $D = 0.04$ m, the initial amplitude of the destructive disturbance, δ_0 , is only 1 mm, and (with the breakup length being 12.9 m) this disturbance grows only to 1.26 mm after 1 m of travel.

If the stability parameter λ is kept high, then these levels can be decreased even further. Of course, sufficient care should be taken to eliminate abrupt area changes upstream of the nozzle that would create destabilizing flow disturbances. Care should also be taken to isolate

the delivery duct and nozzle from loop vibrations. Grant and Middleman⁵ report that in certain carefully designed experiments, the onset of turbulence may be delayed until a Reynolds number as high as 10,000 is attained.

From the above discussion, it seems certain that turbulence of the lithium jet in the target region will not be a problem. In any case, several additional precautionary measures could be taken to mitigate the effects of turbulence, one being the insertion of a fine honeycomb directly before the nozzle exit plane. Another possibility is the application of a transverse magnetic field in the duct region just upstream of the target or an axial magnetic field that would extend down into the target area. The effects of the magnetic fields are discussed in Appendix D.

5.1.2 Distortion of Jet from Initial Rectangular Shape

In addition to concern for the hydrodynamic stability of the jet, some consideration must also be given to the problem of distortion of the jet cross section from its initial rectangular shape to a series of patterns characterized by a circular shape transforming into a flat sheet, with orientation of the sheets alternating between directions first perpendicular to and then parallel to the width of the rectangular orifice. Similar transformations occur for all jets that originate from noncircular orifices and the phenomenon is attributable to nonuniformities in surface forces brought about by the irregular shapes.

The length of a complete waveform is predicted by Rayleigh's theory of jets subject to unsymmetrical surface disturbances. It is important that the target area be not more than one-half wavelength downstream of the injection plane to ensure that the deuteron beam does not intersect any of the flat sheet portion of the jet.

Following Rayleigh,¹ the wavelength L is given in terms of the Weber number, N_{We} , the hydraulic diameter, D , the orifice aspect ratio AR (width/height), and an integer wave number, n , which is characteristic of the disturbance (orifice shape):

$$L = 0.94 \frac{\sqrt{N_{We} D}}{\sqrt{n^3 - n}} \cdot \frac{(1 + AR)^{3/2}}{AR^{3/4}} \quad (5.4)$$

$$n = 2, 3 \dots$$

The hydraulic diameter, Weber number, and aspect ratio are fixed for this case at values of 0.04 m, 11,570, and 4 respectively. The value assigned to the wave number n is determined by the geometry of the jet orifice. For an ellipse, $n = 2$; a triangle, $n = 3$; a square, $n = 4$; etc. A rectangle with an aspect ratio of 4 probably exhibits flow characteristics similar to those of an ellipse, and, hence, a value of 2 may be assumed for n . The wavelength in this instance would be:

$$L = 0.94 \times \sqrt{11,780/6} \times 0.04 \times (25/4)^{3/4} = 6.53 \text{ m}.$$

Since the target area will most likely be located within one meter of the nozzle exit, distortion of the jet boundary should not be appreciable. The avoidance of sharp corners in the nozzle design would further minimize the effects of surface irregularities, and if the channel walls could be extended into the target area such irregularities would probably be eliminated entirely. It is pointed out in Appendix E that various nozzle designs could be studied in a small-scale hydrodynamic analog using mercury as the working fluid, and a study of the channel wall extension could be included.

5.1.3 Boiling of the Jet

Although the average temperature rise in the jet is only 57°C, much higher local temperature rises will occur due to the nonuniform intensity profile of the deuteron beam and the rapid increase in the rate of

energy deposition near the end of the deuteron range. The highest beam power density which will be used, i.e., the smallest beam spot, will occur for a circular beam spot 2 cm in diameter (fwhm) with a gaussian intensity profile. Assuming this intensity profile and a beam energy spread of ± 0.5 MeV, the spatial variation of the temperature rise in the lithium has been calculated. The results are shown in Fig. 5.2 in the form of temperature contours over the jet cross section taken just after passage through the deuteron beam. The maximum temperature rise is seen to be $\sim 700^\circ\text{C}$. As the base temperature is $\sim 300^\circ\text{C}$, this corresponds to a temperature of 1000°C .

Fig. 5.2. Temperature rise in lithium jet at deuteron beam axis.

This rapid temperature increase plus the fact that the jet will discharge into vacuum conditions raises the possibility of boiling and subsequent rapid bubble growth that could disturb the free surface of the target. Bulk boiling will proceed at a finite rate only when conditions are such that there are a sufficient number of gaseous embryos present of the size required for an unstable equilibrium. This critical size is a function of the bulk liquid pressure, P_∞ , the bubble (saturated vapor) pressure $P_{\text{sat}}(T)$ corresponding to the local bulk liquid temperature, T , and the surface tension Γ ; and it is determined by the following condition of mechanical equilibrium between the bubble and the mother phase (liquid):

$$r_c = \frac{2\Gamma}{P_{\text{sat}}(T) - P_\infty} \quad (5.5)$$

Bubbles of this size are in an unstable equilibrium with respect to perturbation in size; that is, any bubble smaller than r_c will disappear while bubbles larger than r_c will grow spontaneously. It is obvious that bubbles must pass through this critical size before boiling can proceed and the smaller r_c is, the more likely boiling will occur. If the local temperature is so high that the saturation pressure far exceeds the bulk liquid pressure, then boiling will proceed for very small embryos. The high surface tension of lithium and its low vapor pressure will make the critical size for lithium large even when expanding into a vacuum ($P_\infty = 0$). For example, at 1000°C , $P_{\text{sat}} \sim 0.055 \text{ bar}$ (41 mm Hg) and the critical radius will be ($P_\infty \sim 0$):

$$r_c = \frac{2 \times 0.37}{0.055 \times 10^5} = 1.35 \times 10^{-4} \text{ m.}$$

In contrast to this, room-temperature water expanding into a vacuum will have a critical radius half as large as this and will therefore boil more readily.

The rate of condensation will be proportional to the number of critical size bubbles present in the liquid bulk and this quantity is given by the expression⁶

$$N_c = N e^{-(\Delta\phi_c/kT)}, \quad (5.6)$$

where N is the number density of liquid molecules and $\Delta\phi_c = \frac{4}{3} \pi \Gamma r_c^2$ is the energy required to create a critical size embryo from the liquid phase. Substituting for r_c , the value of the exponent becomes

$$\frac{\Delta\phi_c}{kT} = \frac{\frac{4}{3} \pi \times 0.37 (1.35 \times 10^{-4})^2}{1.38 \times 10^{-23} \times 1300}$$

$$= 4.72 \times 10^{12}.$$

The obvious conclusion is that bulk fluid boiling is all but impossible even at these high degrees of superheat. Of course, liquid metals can be made to boil but only along the boundaries with solid surfaces that have cavities as large as r_c to serve as active nucleation sites. Cavities as large as those required here will not be present in the containing walls and consequently this mode of boiling will not occur.

5.2 Description of Lithium Circuit and Associated Systems

5.2.1 General Description of Lithium Circuit

The main lithium circuit is shown schematically in Fig. 5.3 as the heavily darkened line. It consists of 300 series stainless steel components and piping operating at modest temperature levels of 286 to 343°C. Lithium flows from the electromagnetic pump through 5-in. sched-10 pipe at a flow rate of 0.038 m³/sec (602 gpm) to a Dowtherm*-cooled intermediate heat exchanger. The lithium is cooled to 286° at the

---

* Trademark of the Dow Chemical Company.

Fig. 5.3. Schematic of lithium and heat dump circuits.

heat exchanger and then flows through an electromagnetic flowmeter before entering the target area, which is contained within an evacuated region having pressures as low as 1.33×10^{-5} Pa (10^{-7} torr). At the target area the lithium is heated to a temperature of 343°C by the 4-MW deuteron beam and then flows vertically downward through an aspirator into a sump, where it returns via a 6-in. sched-10 pipe to the pump suction. All lithium piping and components must be arranged to provide gravity draining into the drain tank, which is located in a shielded compartment at the bottom of the lithium equipment room. Miscellaneous engineering data for the lithium circuit are shown in Table 5.1.

As pointed out in Section 5.1.3, the existence of vacuum conditions in the target region and expected large temperature increases at the intersection of the jet with the deuteron beam prompted concern that boiling of the lithium might occur, but studies have shown that this is highly unlikely. Another matter which has required consideration is evaporation. Evaporation of lithium from the unconfined lithium jet within the target area is not expected to be a serious problem. At the bulk fluid exit temperature of 343°C the lithium vapor pressure is about 8×10^{-6} torr. It is estimated that evaporation losses would not exceed 10 g/day from the jet area exposed above the aspirator region. This amount could easily be accommodated by heating the vacuum walls just above the lithium melting point of 180°C and providing gravity drainage so that lithium condensate will be returned automatically to the aspirator inlet.

Past experience at ORNL has shown that vaporized lithium leakage into a high-vacuum system is not detrimental to the vacuum pumping system. Such a situation was encountered during corrosion tests of a refractory alloy piping system and lithium in a simulated space environment. A small lithium leak occurred, but the ion pumps were not affected because the lithium vapor traveled in straight lines and adhered to the first cool metal surface encountered. Therefore, if the vacuum pumps are located to eliminate line-of-sight communication with the target region, the lithium vapor should not be troublesome to the vacuum pumping equipment.

Table 5.1. Miscellaneous engineering data for lithium circuit

Energy in deuteron beam	4 MW	
Duration of typical test	4 months	
Material of construction	300 series stainless steel	
Pipe size	5 in. sched. 10 IPS (6 in. sched. 10 at pump suction)	
	<u>SI units</u>	<u>Engineering units</u>
Lithium flow rate	0.038 m ³ /s	602 gpm
Lithium bulk fluid temperatures		
Normal maximum	343°C	649°F
Normal minimum	286°C	547°F
ΔT	57°C	102°F
Lithium velocity in 5-in. pipe	2.9 m/s	9-1/2 ft/sec
Reynolds number in 5-in. pipe		392,000
ΔP per 100 ft of 5-in. pipe	8.274 kPa	1.2 psi
Lithium velocity at target area	15 m/s	49.2 ft/sec
Vacuum within deuteron beam enclosure	1.33 x 10 ⁻⁵ Pa	~10 ⁻⁷ torr
Lithium inventory being circulated	~2.8 m ³ ~1273 kg	~100 ft ³ ~2800 lb
Tritium production rate in lithium	81 ng/s	~70 Ci/day
Deuterium production from 4-MW beam	2.3 μg/s	4.4 x 10 ⁻⁴ lb/day
Evaporation rate of Li at target area	11.6 mg/s	~0.02 lb/day

For information purposes, selected data on lithium and its physical properties are shown on Table 5.2.

5.2.2 Primary Lithium Pump

An annular induction electromagnetic pump provides a lithium flow rate of 0.038 m³/sec (602 gpm) at a head of about 25 psi. Compared with most of our previous liquid-metal pump applications, the operating temperature

of 343°C (649°F) is relatively low and easily accommodated. To provide cavitation free operation, the pump must be located vertically below the evacuated target region to create adequate net positive suction head (NPSH) at the pump inlet. Precise data on NPSH required for our particular pump and operating conditions are not available. However, based on cavitation tests with small helical induction pumps at ORNL^{7,8} with potassium and on conversations with a pump vendor,⁹ there is reason to

Table 5.2. Lithium data

Possible vendor	Lithium Corporation of America	
Approximate cost	\$33/kg for reactor-grade material	
Volume change upon melting	1.5% increase	
	<u>SI units</u>	<u>Engineering units</u>
Boiling point	1330°C	2430°F
Melting point	180°C	357°F
Heat of vaporization	22.93 MJ/kg	9859 Btu/lb
Lithium properties at 315°C (600°F)		
Density	448 kg/m ³	28 lb/ft ³
Viscosity	0.455 mPa-s	1.1 lb/ft-hr
Electrical resistivity	0.3 μΩ-m	
Thermal conductivity	43.3 W/m-°C	25 Btu/hr-ft-°F
Heat capacity	418 J/g-°C	1 Btu/lb-°F
Surface tension	0.375 N/m	0.0257 lb _f /ft
Typical vapor pressure values		
At 1000°C (1832°F)	5.33 kPa	40 torr
At 343°C (649°F)	1.07 mPa	8 x 10 ⁻⁶ torr
At 288°C (550°F)	53.33 μPa	4 x 10 ⁻⁷ torr
At 265°C (509°F)	13.33 μPa	1 x 10 ⁻⁷ torr

expect that the lithium pump will operate satisfactorily if the pump is located about 25 ft below the free liquid lithium surface at the target area. References 7 and 8 showed that helical induction pumps will operate at lowered NPSH in the absence of inert gas, and fortunately no gas will be in contact with the circulating lithium in this pump application. The pipe line leading from the target area to the pump must be as short as practical and of a generous diameter (6-in. pipe size) to keep head losses minimal in the pump suction line and thereby keep the NPSH as high as practical at the pump inlet.

The electromagnetic pump will require auxiliary cooling air for the windings. Suitable instrumentation must be used to indicate loss of cooling air, excessive temperatures on the windings, or excessive temperatures on the stainless steel pump cell.

The annular induction pump cell will be designed to gravity drain completely. Complete drainage is desired because ^7Be in the lithium will provide a radiation field which would limit access to the pump after draining and shutdown.

5.2.3 Auxiliary Systems for the Lithium Circuit

The schematic drawing of Fig. 5.3 shows auxiliary equipment required on the primary lithium circuit. At the drain tank a resistance level probe is used to continuously monitor the lithium level, and a low-level alarm is provided to signal unintentional loss of lithium. A vapor trap is provided on the gas line leading from the drain tank to ensure that vapor deposits do not plug this line during the extended operating life of the facility. Helium pressure lifts the lithium from the drain tank into the equipment located above. When the lithium is returned to the drain tank, gas vented through the vapor trap must be processed to remove radioactive gases such as tritium.

All lithium piping and components are traced with electric heaters to provide preheating for filling. This preheating system will be capable of providing temperatures of about 500°C on all equipment. Tubular electric heaters are used, and they will be operated at de-rated voltage levels to improve their operating lifetimes and reliability. The preheating system remains energized at all times and is independent of the operation of the 4-MW deuteron beam. The system is controlled by manually set voltage controls with mechanical stops to prevent overheating by the operators. Normal TVA power supply is provided, but an emergency diesel generator and automatic transfer switching must be available in the event of loss of normal power.

5.2.4 Lithium Bypass Purification and Sampling Systems

Bypass purification and sampling systems are provided to purify and monitor the lithium. Remotely operated shutoff valves can isolate the bypass system from the main system, and a separate small electromagnetic pump will provide the desired bypass flow rates independent of the flow rates in the primary loop.

High levels of oxides are expected in the lithium after periods of maintenance, during which portions of the lithium system will be exposed to atmospheric contamination. The oxides must be removed in order to maintain low corrosion rates in the stainless steel piping and other components, and thereby to minimize the mass transfer of nickel, chromium, and iron, which would result in radiation buildups in the low-temperature portions of the primary system. A bypass cold trap will be provided to remove gross amounts of the oxides, but the cold trap cannot reduce the oxide levels below about 50 to 100 ppm due to the relatively high solubility of oxide in lithium.¹⁰ Therefore, a hot trap will be added to provide oxide removal down to a few ppm to ensure low corrosion rates.

Tritium and deuterium will be generated in the lithium by the 4-MW deuteron beam at rates of about 0.007 g/day and 0.2 g/day respectively.

The use of cold trapping was evaluated as a means of removing the resultant liquid metal tritide and deuteride from the primary lithium circuit, but this does not appear feasible. No precise data are available on the solubility of dilute solutions of LiH (or LiT and LiD) in lithium at temperatures just above the melting point, but large extrapolations of existing data¹¹ indicate solubilities of hundreds of ppm. The 0.007-g/day (70-Ci/day) tritium production rate in this facility is equivalent to a buildup of only 3.5 ppm per year in the primary lithium circuit inventory (assumed to be 2.8 m³) even when tritium loss by diffusion through the pipe walls is disregarded. At such low levels of LiT, cold trapping appears an unlikely way to prevent buildup of tritium in the lithium inventory. Hot trapping is expected to remove some tritium and deuterium from the lithium concurrently with oxygen, but the effectiveness has not yet been fully evaluated.

A regenerative heat exchanger is located between the main lithium loop and the hot trap. The regenerator reduces the amount of heat input required to attain gettering temperatures (~700°C) and also reduces the temperature of the bypass lithium before it is returned to the main lithium stream. The temperature of the returning lithium must be lowered to reduce thermal shock at the pipe walls where the two streams meet. A regenerative heat exchanger will also be required in the cold trap but it is not specifically shown because it will probably be built as an integral part of the cold trap itself.

An enclosed glove box sampler will be used, if radiation levels permit, for direct manual removal of lithium samples for calibration of oxide and hydrogen isotope monitoring equipment. At a minimum, such a sample box must be enclosed to contain tritium during sampling operations. Other radiation from materials such as ⁷Be or corrosion-product buildup have not yet been evaluated, but such radiation may indeed be high enough to prevent direct glove box sampling techniques.

5.2.5 Intermediate Heat Exchanger and Dowtherm Circuit

As has been pointed out previously, the cooling of the lithium before it re-enters the target cell is accomplished by means of an intermediate heat exchanger system for which Dowtherm has tentatively been selected as the coolant fluid (see Appendix F). We initially considered direct air cooling of the lithium, but discarded this concept primarily because of the production of 800 Ci/day ^7Be (53-day half-life) during operation. Also tritium (12.3-year half-life) is produced in the lithium at a rate of about 70 Ci/day. Considerations of accidental leakage and burning of lithium at an air-cooled heat exchanger led to the addition of a Dowtherm circuit to provide double containment for the radioactive lithium loop and thereby to ensure minimal release of radioactive materials to the environment. Tritium and deuterium will, of course, diffuse through the intermediate heat exchanger walls into the secondary cooling circuit, but hydrogen-tritium exchange in the Dowtherm will reduce the release of tritium to the environment via water-cooled heat dump circuits.

The intermediate heat exchanger will transfer 4 MW of heat from the lithium circuit to the intermediate Dowtherm circuit as the lithium temperature is reduced from 343 to 286°C. Dowtherm coolant at a flow rate of $3.9 \times 10^{-2} \text{ m}^3/\text{sec}$ (620 gpm) will accept the heat energy as the Dowtherm temperature increases from 232 to 288°C. Assuming Dowtherm velocities of 6.1 m/sec (20 ft/sec) within 1-in.-OD x 0.065-in.-wall heat exchanger tubing results in heat transfer coefficients of 6.8 kW/m²-°K (1200 Btu/hr-ft²-°F). Overall heat transfer coefficients are about 4 kW/m²-°K (700 Btu/hr-ft²-°F). As is typical of heat exchangers involving liquid metal, the stainless steel tube wall and Dowtherm represent the major resistances to heat flow. A log mean temperature difference of 56°C is used between the two liquid streams to keep thermal stresses in the stainless steel tubing at reasonable levels. Such a heat exchanger contains 17.2 m² (185 ft²) of the heat transfer area, has a Dowtherm inventory of 0.1 m³ (3.5 ft³) within the tubes, and requires about 244-m (800-ft) lineal length of 1-in.-OD tubing. A tube and shell U-bend configuration is envisioned to accommodate thermal expansion.

The Dowtherm intermediate circuit is shown schematically in Fig. 5.3. Dowtherm flows at $0.039 \text{ m}^3/\text{s}$ (620 gpm) and at 232°C through the pump to the intermediate heat exchanger where the Dowtherm temperature increases to 288°C . The heated Dowtherm flows to a steam generator where the Dowtherm is cooled to 232°C and then returns to pump suction. A canned-rotor centrifugal pump has been selected to circulate the Dowtherm since commercial pump equipment is available at reasonable cost. A canned-rotor pump provides zero seal leakage which is desired because of both the tritium content and obnoxious odor of the Dowtherm.

A liquid expansion tank is located near the pump suction to accommodate volume changes associated with temperature variations. The expansion tank is pressurized to 90 psia to suppress boiling of the Dowtherm in the event of misoperation. For example, if the Dowtherm flow accidentally stopped, the liquid in the intermediate heat exchanger might approach 343°C , i.e., the maximum lithium temperature. The vapor pressure of Dowtherm at 343°C is 71 psia and, therefore, no boiling would occur due to the system pressurization. During normal operation at a maximum bulk fluid temperature of 288°C the Dowtherm vapor pressure is only 28 psia.

The tentative selection of Dowtherm A as the intermediate heat transfer fluid was primarily because of the much lower cost of fabrication and assembly of an organic fluid intermediate circuit compared to a liquid metal system. Dowtherm A is a eutectic mixture of about 26% biphenyl and 74% diphenyl oxide which has been used for many years as an industrial heat transfer fluid. This organic fluid is rated by the vendor for service up to about 400°C and for radiation doses up to 10^{10} rads. Tests at ORNL¹² for a different application confirmed that Dowtherm A was not discolored and was little affected by the 14,000 hr exposure at 315°C and 10^6 rad of gamma radiation. It has been estimated that Dowtherm in our proposed intermediate circuit would receive about 10^7 rad in 5 yr operation from the ^7Be within the intermediate heat exchanger. Therefore, this organic heat transfer medium seems adequate for our application in regard to both operating temperature and radiation damage. A tabulation of the physical properties of Dowtherm A is attached as Table 5.3.

Table 5.3. Physical properties of Dowtherm A

Property	Engineering units	SI units
Atmospheric boiling point	494.8°F	257.1°C
Freezing point	53.6°F	12.0°C
Flash point, c.o.c.*	255°F	123.9°C
Fire point, c.o.c.*	275°F	135.0°C
Auto ignition temperature ASTM	1150°F	621.1°C
Density at 75°F	66.0 lb/ft ³ 8.83 lb/gal at 25°C	1.056 Mg/m ³ @ 25°C
Volume contraction upon freezing	6.63%	
Volume expansion upon melting	7.10%	
Heat of fusion	42.2 Btu/lb	97.97 kJ/kg
Specific resistivity	1.2 x 10 ¹² ohm cm @ 32°F 6.4 x 10 ¹¹ ohm cm @ 68°F 3.9 x 10 ¹¹ ohm cm @ 104°F	12 GΩ·m 6.4 GΩ·m 3.9 GΩ·m
Surface tension in air	40.1 dyn/cm @ 68°F 37.6 dyn/cm @ 104°F 35.7 dyn/cm @ 140°F	40.1 mN/m 37.6 mN/m 35.7 mN/m
Critical temperature	927°F	497°C
Critical pressure	30.93 atm	319.6 Mg/m ²
Critical volume	0.0508 ft ³ /lb	3.17 cm ³ /g
Heat of combustion	15,500 Btu/lb	36 kJ/kg
Molecular weight (avg.)	166.0	

* c.o.c., Cleveland open cup.

The effects of accidental leakage of Dowtherm into lithium via the intermediate heat exchanger walls must be further evaluated before final selection of intermediate heat transfer fluid is made. No references were found on lithium-Dowtherm (or biphenyl-diphenyl oxide) reactions in literature searches of Nuclear Science Abstracts (1957 to date) and Chemistry Abstracts (1947 to date, English only). Only one reference of interest was found thus far in which preliminary information is presented on the reaction of sodium with Dowtherm at temperatures to 250°C.¹³ It seems likely that Dowtherm reactions with lithium would be similar to those with sodium, but specific bench tests will be required to determine the effects of greater temperatures (up to 343°C), the heat of reaction, reaction products, gas evolved (if any), and potential solvents and cleanup procedures for the reaction products. These bench tests should be carried out immediately so that further design can proceed on a sound basis. In addition, hydrogen-deuterium-tritium exchange in Dowtherm must be further evaluated at our specific operating conditions.

5.2.6 Instrumentation

The liquid-metal instrumentation must be of nuclear reactor quality, and all critical parameters will require two out of three signals to initiate scram action; i.e., critical instruments will have to be installed in triplicate. A few of the required alarm and control actions are shown on the preliminary schematic diagram of Fig. 5.3.

REFERENCES

1. Lord Rayleigh, "Theory of Sound," Vol. II, Dover Publications, Inc., New York, 1945.
2. C. Z. Weber, *Angew. Math Mech.* 11 (1931).
3. R. E. Phinney, "Stability of a Laminar Viscous Jet — The Influence of the Initial Disturbance Level," *A.I.Ch.E. Journal* 18(2), 432 (March 1972).
4. R. E. Phinney, "The Breakup of a Turbulent Liquid Jet in a Gaseous Atmosphere," *J. Fluid Mech.* 60(4), 689 (1973).
5. R. P. Grant and S. Middleman, "Newtonian Jet Stability," *A.I.Ch.E. Journal* 12(4), 669 (July 1966).
6. J. Frenkel, "Kinetic Theory of Liquids," Dover Publications, Inc., New York, 1955.
7. W. R. Huntley and A. G. Grindell, "Performance and Cavitation Characteristics of Two Helical Electromagnetic-Induction Pumps Operating with Potassium," ORNL-TM-1793 (December 1967).
8. H. C. Young and D. L. Clark, "Hydraulic Performance and Cavitation Characteristics of an Electromagnetic Helical Induction Pump Operating with Potassium and Prediction of Performance with Lithium at 2200°F," ORNL-TM-2995 (November 1970).
9. Communication with Mr. Barker of Mine Safety Appliance Research, Callery, Pa., September 12, 1975.
10. E. E. Hoffman, "Solubility of Nitrogen and Oxygen in Lithium and Methods of Lithium Purification," ASTM Special Technical Publication No. 272 (1960).
11. E. Velekis, E. H. Van Deventer, M. Blander, "The Lithium — Lithium Hydride System," *Journal of Physical Chemistry* 78, 1933 (1974).
12. A. M. Smith, "Tests of the Stability of Dowtherm A at 600°F with Radiation Doses up to 10^6 Rad," ORNL-TM-4403 (January 1974).
13. D. E. Horner and W. H. Baldwin, "Reactions of Sodium with Dowtherm," ORNL-TM-4186 (May 1973).

6. BUILDING, UTILITIES, AND EXPERIMENTAL FACILITIES

The design of this facility combines the construction techniques of the new medium-energy high-current accelerators with many techniques commonly used in reactors and hot cells. The placement of the large amounts of shielding required interacts with the design of everything from building structures to the individual components. Some of the shielding itself will be heated and activated by the neutron beam, and will therefore require special consideration as to composition, location, and methods of handling. All items near the beam, such as vacuum seals, electrical insulation, water tubing, and beam-line components, must be fabricated with radiation-resistant materials. Further, to ensure maximum operating time, all components must be designed for replacement with minimum downtime. The level of residual activity in a target cell will be several thousand rem/hr. Therefore, no one will be able to enter a target cell once the beam has been on. The replacement of the end window and piping for the lithium target region, for example, requires that special tooling, remote viewing, and other techniques developed in hot cell and fission reactor technology be applied here to limit the radiation dose to personnel.

6.1 Building

The INGRID building is divided into five principal parts: the experimental area, the linear accelerator, the control rooms, the laboratories, and the offices. An artist's conception of the outside of the building is depicted in Fig. 1.2 of Chapter 1 and floor plans and selected sectional views are shown here in Figs. 6.1 through 6.4. The general construction, appearance, and size will be similar to that of the High Flux Isotope Reactor at Oak Ridge. Tables 6.1 and 6.2 give pertinent data for each part of the building.

The experimental area, which will be discussed in more detail in Section 6.6 below, has overall dimensions of 80 ft x 130 ft and contains the two 6-ft x 9-ft x 12-ft target cells, the hot cell, and the lithium loop

Table 6.1. Building data for contained areas (all exhaust double HEPA filtered)

Room	Inside dimensions (ft)	Floor area (ft ²)	Enclosed volume (ft ³)	Shielding (ft)	Pressure (in. of water)	Special atmosphere
High bay	79 x 129 x 50	10,191	509,550	None	-0.5	
Target cells (2)	6 x 9 x 12	54	648	14 on end, 13 on sides	-1.0	Helium
Lithium loop cell	(18 to 30) x 45 x (12 to 33)	954	16,436	2 on top, underground	-1.0	Argon
Hot storage cell No. 1	18 x 18 x 18	324	5,832	2 on top, underground	-1.0	
Hot storage cell No. 2	18 x 38 x 18	684	12,212	2 on top, underground	-1.0	
Hot cell	(21 to 28) x 10 x 21	250	5,250	3 on sides and top	-1.0	
Linac tunnel	168 x 22 x 20	3,696	73,920	4 to 9 on sides and top, 4 on injector end, 9 on target end	-0.5	
Injector	18 x 30 x 18	540	9,720	1-1/2 on all sides and top	-0.5	

Fig. 6.1. Basement floor plan of INGRID building. See sections in Fig. 6.4.

(FIN. FL. EL. 818'-0")

Fig. 6.2: First floor plan of INGRID building. See sections in Fig. 6.4.

Fig. 6.3. Second floor plan of INGRID building. See sections in Fig. 6.4.

cell, the hot storage cells, and the beam line components. An artist's conception of this room is depicted in Fig. 1.3 of Chapter 1.

Table 6.2. Building data for noncontained areas

Room(s)	Dimensions (ft)	Floor area (ft ²)	Volume (ft ³)
User labs	31 x 117 x 12	3,627	43,524
Ion source lab	21 x 31 x 19	651	12,369
Office area (1st floor)	31 x 117 x 12	3,627	43,524
Office area (2nd floor)	31 x 105 x 12	3,255	39,060
Counting room	12 x 20 x 12	240	2,880
Control rooms	37 x 62 x 12	2,294	27,528
Linac equipment rooms (2)	157 x 23 x 12	3,611	43,332
Mechanical equipment room	50 x 30 x 12	1,500	18,000
Air lock	50 x 22 x 16	1,100	17,600
Stairs on two floors	12 x 10 x 12 x 2 }	2,460	29,520
Elevator, stairs, toilet, change room on three floors	37 x 20 x 12 x 3 }		

A 50-ton crane covers the entire experimental area. For initial assembly of the linac and any major maintenance that may be required in the linac tunnel, the roof of the linac tunnel in the experimental area can be removed to allow crane access. A truck air-lock entry (50 ft x 22 ft) is provided so that any heavy components may be loaded or unloaded directly in the experimental area with the crane. A mechanical equipment room (50 ft x 30 ft) houses the Dowtherm loop components, the Dowtherm steam generator for recovery of the 4 MW of heat from the beam, and the larger air-handling components.

The portion of the building for the linear accelerator includes the linac tunnel, 168 ft x 22 ft, the injector room, 18 ft x 30 ft, and the two linac equipment rooms, each 157 ft x (20-1/2 to 25-1/2) ft. The injector room is, of course, a Faraday cage. A 2-ton crane serves the linac tunnel. On the northeast side of the linac tunnel, the shield wall need be only about 2 ft of ordinary concrete since that side can be earth filled. On top of the earth fill, a substation will be located

containing the plate power supplies for the 10 rf power amplifiers and all of the other 13.8-kV components. In addition to the water systems and rf equipment, the two-floor equipment space will contain the vacuum pump power supplies, the roughing pumps, the quadrupole power supplies, and the air-handling equipment for all of the linear accelerator area. Space will be provided for the maintenance operations required for all accelerator components.

The control room area (62 ft x 37 ft) is divided into three parts: the linac control room, the computer room, and the control room for experiments. This area will have a raised finish floor for easy access to all wiring and piping. The experimental control room is located so that the length of all electrical leads and piping to the experimental area can be minimized. Windows will allow the operators and experimentalists to observe the experimental area at all times. An air lock permits direct access from the control room to the top of the target cell shielding and to the valve boxes.

A counting room is located near the control rooms.

A laboratory area (31 ft x 117 ft) divided into a setup laboratory, an electronics laboratory, and a shop area is provided for the preparation of the experimental apparatus prior to irradiation. Facilities will be provided for users to assemble the specimens and instrumentation into the probes. Light hand and power tools, a small machine shop and electronic instrumentation, for example, will be available to users. Any hot materials may be handled in the hot cell in the experimental area.

An ion source laboratory (18 ft x 30 ft) adjacent to the injector room will contain equipment for testing sources prior to installation.

The office area is divided into 26 offices and a conference room to be shared by the operating personnel and the users, as required. A design-drafting room is provided both for machine operations and for the needs

of experimentalists. An elevator and stairwell are centrally located between the offices, laboratories, and control rooms.

6.2 Site

INGRID will be located in the Melton Valley area as shown in the plot plan in Fig. 6.5. This region, located south of Haw Ridge about 1-1/2 mi from the main ORNL (X-10) site, is occupied by the High Flux Isotope Reactor (HFIR), the Thorium-Uranium Recycle Facility (TURF), and the Transuranium Processing Plant (TRU). In addition, adjacent areas include both liquid- and solid-waste handling facilities.

The site selected is underlain by the Conasauga Group composed of shale and siltstone with thin limestone layers in the lower two-thirds and massive limestone in the upper one-third. This group is suitable for the building foundation. The gently sloping hillside location allows the use of earth shielding along the northeast side of the linac tunnel with little excavation.

6.3 Electrical Substation and Transmission Line

The electrical load that will be presented by INGRID (9.5 MW) requires that a new 13.8-kV transmission line be built from the primary ORNL substation north of the X-10 site to the Melton Valley site. Further, the primary substation will be modified to provide the additional load by adding a new transformer and new 161-kV and 13.8-kV switchgear as shown on the one-line diagram (Fig. 6.6). This equipment is required for the facility to be tied into either of the two existing 161-kV lines. It will ensure minimum downtime and no conflict with existing ORNL facilities.

6.4 Environmental Control - Containment

The hot cell, target cells, storage cells, and lithium loop cell, all of which are primary containment areas, will be maintained at a negative

Fig. 6.5. Plot plan showing proposed location of INGRID building.

X-21269-ED-002-A

ELECTRICAL ONE-LINE DIAGRAM
MODIFICATIONS TO X-10 PRIMARY SUBSTATION FOR INGRID PROJECT

Fig. 6.6. Electrical one-line diagram. Modifications to ORNL primary substation for INGRID project.

pressure of 1-in. H₂O with respect to atmosphere. The high bay experimental area and the linac tunnel and injector room, both secondary containment areas, will be maintained at 0.3-in. H₂O negative. In these regions all inlet air will be HEPA filtered. All exhaust gases will be double HEPA filtered and discharged through a local 120-ft stack to the atmosphere.

All normal working areas (experimental room, laboratories, offices, shops, control rooms, etc.) will be temperature controlled year round, and all inlet air will be filtered. The linac tunnel and linac equipment rooms will be heated as necessary in cold weather.

6.5 Energy Conservation

The 4 MW of high-temperature heat generated by the deuteron beam stopping in the lithium will be removed from the lithium loop and used to produce high-pressure steam. In this design, the steam, in turn, will be used to drive the large mechanical equipment. Whenever the beam is off, auxiliary electric motors normally on standby will be switched on automatically to provide the drives. This plan is in compliance with ERDA Design Criteria, Appendix 6301. Further study is planned to ensure effective utilization of this energy.

6.6 Experimental Facilities

The major components in the experimental areas will be the two irradiation cells, each of which will contain a lithium target and provisions for the location and servicing of several experimental capsules; the hot cell in which experimental apparatus that has already been irradiated can be dismantled or repaired; and the liquid-lithium system which serves one or other of the two lithium targets.

6.6.1 The Irradiation Cells

Each irradiation cell will be 12 ft long, 6 ft wide and 9 ft high. The lithium targets will be located 6 ft off the floor and 4 ft from the front wall of the cell, with experimental capsules placed immediately after the target end-window. The concrete walls of the cells will be 13 to 14 ft thick in order to keep radiation levels in the staging area below 0.25 mrem/hr while the beam is on. Figure 6.7 shows a cross section of one of the cells in a plane perpendicular to the beam axis. Major replaceable penetrations will be provided above and on either side of the cell. The upper one will be used for insertion of large experimental apparatus, and for the replacement of lithium target components or the liner of the cell. Experimental probes will be mounted in these major penetrations so that future unforeseen experimental requirements may be accommodated without major modifications to the main structure.

Fig. 6.7. Section through target cell.

Most of the neutrons emitted from the target will be absorbed in the first foot or so of the cell walls. Because of the power dissipated (~ 70 kW), the walls will be cooled by a closed-loop water system. To allow for repairs to this system, the inner two feet of the cell walls will be in the form of a replaceable liner. Following removal of an outer shield (shown with a hook eye in Fig. 6.7), the water lines to the liner could be remotely disconnected and the liner removed in sections. Although the liner material can be ordinary concrete, the use of a low-activation material such as gypsum or marble will be investigated.

The experimental capsules will be supported and serviced by probes which extend through the cell walls into the high-flux regions of the neutron beam. The probes must satisfy the following requirements:

- (1) They must permit the best possible utilization of the available experimental volume.
- (2) They must provide space for the electrical leads, gas lines and other services required to control and measure the chemical and physical environment of the samples.
- (3) They should be easily changed, with a minimum of disturbance to other experiments.
- (4) They must be retracted from the irradiation cells and placed into the hot cell without exposing personnel to excessive amounts of radiation.

A possible design which can satisfy these criteria is discussed below. Figure 6.7 shows probes entering an irradiation cell from five different directions perpendicular to the beam axis. Each probe is approximately 5 m long and 25 cm by 8 cm in cross section. To ensure the best utilization of the experimental volume, the experimental capsules must be positioned in the neutron flux to a precision of ~ 1 mm. The shield penetrations themselves, and the openings in the main structure which receive them, will be fabricated to sufficient accuracy for primary alignment, while precision alignment will be achieved by simply keying

the probes to the target assembly. As the cell will be filled with helium at negative pressure, the probes will be provided with gas-tight seals.

The residual radiation level inside the cells after a brief cooling period will be several thousand rem/hr, and experimental capsules and probe ends will be extremely radioactive. All transfers of material into or out of the cells must, therefore, provide for adequate shielding while opening and closing the penetrations and transferring the material. Calculations indicate that some cell components will require up to 25 cm of lead shielding. In Fig. 6.8 we show the layout of a transfer case and shutter system for probe removal. Rollers built into the shield and the penetrations would allow precise movement with little friction.

Fig. 6.8. Section through target cell wall and probe transfer case.

During normal operation the outer end of the probe penetrations will be covered by valve boxes which will provide shielding of the penetration itself and of the piping, pumps, etc. required for the circulation of gases or liquids to the experimental capsules.

The arrangement outlined above can be extended to more than five probes. For example, if each experimental capsule occupied a distance along the beam axis of 2 cm, then the set of five probes would account for a total of 10 cm. A second set of probes located 10 cm from the first set could then be used to service five more experimental capsules and so on.

6.6.2 The Lithium Target System

The target components located inside the irradiation cell are shown in Fig. 6.9. Material in this region, particularly the target end window, will suffer severe radiation damage and must be replaced at regular intervals. The whole nozzle-to-aspirator section will be replaced as a unit to preserve a good geometry for the lithium jet. Flanged metal gasket seals are planned for the joints, but their reliability for this application must be evaluated. Special tools will be designed to change out this section through an opening in the top of the cell. Transfer will be handled using a transfer case operating in a similar manner to that shown in Fig. 6.8. The High Radiation Examination Laboratory (HRLEL) at ORNL contains the hot cells and machine tools required for removing the end window and making specimens for post-irradiation studies on the material itself.

After several months of operation the lithium in the target system will contain about 8 mCi/cm^3 of ^7Be γ -activity. In the event of a leak occurring in the system, the hot lithium must be contained and kept from contact with concrete to avoid spallation. As is common in liquid-metal systems, the irradiation cells and other areas containing lithium piping will be lined with a thin metal sheet that is in poor thermal contact with the surrounding concrete. In general, the material will be stainless steel, although vanadium may be a better choice for the irradiation cells because of the reduced activation. Furthermore, the irradiation cells will be filled with helium under a slight negative pressure, and the lithium component room will be filled with an inert gas, probably argon. These precautions will eliminate the possibility of a lithium fire.

Fig. 6.9. Lithium target system.

Because of the ^7Be activity mentioned above, the lithium piping and the lithium component room will be shielded with concrete. The component room is placed under a 2-ft thick movable concrete shield in the area between the two irradiation cells. This location minimizes the length of piping required, and allows the use of the 50-ton crane for maintenance. The loop is designed so that the lithium can be drained into the dump tank, leaving little activity on other components. The channels through the irradiation cell shielding shown in Fig. 6.1 and sections A and B of Fig. 6.4 will allow the lithium piping to be replaced if it should ever be necessary.

6.6.3 The Hot Cell

The hot cell shown in Figs. 6.1 through 6.4 is designed to accept the probes from their transfer case in the same manner as the cells. Following irradiation of an experimental capsule, the probe will be disassembled in the hot cell and the specimens recovered for post-irradiation examination. Facilities will be provided for simple modifications to the probes and for the packaging of any radioactive waste. A side-wall pass-through for small objects and an overhead plug for larger objects will be provided. It is anticipated that at least a portion of the probe that penetrates the irradiation cell interior will be discarded. If more elaborate work on an active probe should be required, it could be done at the HRLEL on the main ORNL site.

7. PROJECT MANAGEMENT, SCHEDULE, AND COSTS

Planning of the INGRID project is proceeding with three underlying assumptions.

- (1) The CTR Materials Program will require a facility of this type to be operational as soon as possible.
- (2) The accelerator design and fabrication will be done in collaboration with with a group from Fermilab.
- (3) Overall responsibility for the project will rest with ORNL.

7.1 Management

As ORNL will have overall responsibility for the project, the management system will follow normal ORNL procedure for projects of this type, which is patterned after the guidelines set forth in ERDA Manual (AECM) Chapter Appendix 6101, Part IC 3a,b.

The INGRID project will involve a group from Fermilab as a major participant; however a straightforward adaptation of the standard procedures can accommodate this participation. Figure 7.1 illustrates the pertinent management structure for the project team, with the Fermilab Group shown explicitly as one of several program groups concerned with specific parts of the project and reporting directly to the Program Director's Office.

The Program Organization shown in Fig. 7.1 has the responsibilities assigned to the "Program Divisions" in ERDA Manual (AECM) Chapter 6101, while the "Division of Construction" responsibilities are associated with the ORNL Capital Project organization of UCC-ND Engineering. The

Fig. 7.1. Management structure for INGRID Project Team.

responsibilities of the Engineering Organization include the establishment of schedules, cost estimates and cost control. Liaison between the Program and Engineering Organizations is normally achieved by contact between corresponding Team Members. In the case of the Fermilab Group, this contact will be assured by assigning appropriate ORNL team members to Fermilab for the design and development stages of the project.

The Fermilab Group will have the technical responsibility for the design, procurement, fabrication and testing of the prototype linac section. It will also have the technical responsibility for the final design and drafting of specifications of the accelerator. Procurement will be done by UCC-ND. In this context "Accelerator" is defined as:

the low-energy beam transport system from the 350-keV injector to the linac,

the 40-MeV linear accelerator structure,

the rf system,

the accelerator cooling systems,

the beam-focusing elements,

the vacuum systems, and

the control and diagnostics system for the accelerator.

In the later stages of the project the activities associated with the accelerator will be shifted to ORNL. While overall responsibility for the installation will rest with ORNL, the Fermilab Group will continue to cooperate with ORNL during the installation and testing of the accelerator, to provide the best possible assurance that the machine will reach its design specifications.

Referring to the six project phases for the accelerator shown in Fig. 7.2, the Fermilab participation may be summarized as follows:

Phases 1-3 will be undertaken at Fermilab with the participation of the ORNL team assigned to Fermilab. Phase 4 will involve personnel from ORNL and Fermilab, with all procurement being handled by UCC-ND. Phases 5 and 6 will be undertaken entirely at ORNL with the cooperation of the Fermilab Group members. It is anticipated that some of the ORNL technical personnel assigned to work with the Fermilab Group will form the nucleus of the operating staff of the completed facility.

Project team members responsible for other facets of the project such as the injector, the lithium loop, experimental equipment, etc. will be made up of personnel from the appropriate UCC-ND divisions and several ORNL divisions, in particular, the Metals and Ceramics Division, the Physics Division, the Reactor Division, and the Thermonuclear Division.

Fig. 7.2. Schedule of six project phases for accelerator, injector, and lithium circuit.

The entire Project Team will continue to be aided by an existing Steering Committee which was formed to advise the project.

7.2 Schedule

An outline of the fastest possible construction schedule is given in Fig. 7.3, which shows conceptual design starting in February 1976 and completion of the facility at the end of FY-80. The critical path for this schedule goes through building design and construction followed by the installation of the lithium target system. Refinement of the schedule, which will be undertaken during the conceptual design phase, is not likely to significantly shorten the overall time required.

FY-76				T.Q.	FY-77				FY-78				FY-79				FY-80				FY-81														
CY-76				CY-77				CY-78				CY-79				CY-80																			
J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D

* SCHEDULE BASED ON CONCEPTUAL DESIGN SUPPORT IN FY-76 AND CP & D FUNDS FY-77

10-7-75

Fig. 7.3. Proposed schedule for the design and construction of INGRID.

In order to adhere to this schedule, the necessary development work must be started as soon as possible. The areas involved are the 350-kV injector and the first tank of the linear accelerator, both of which require major prototype development, and some chemical and hydrodynamic modeling studies for the lithium target system. The proposed schedules for these components are shown in more detail in Fig. 7.2.

The costs to be incurred in the first two years of the project, shown as FY-76 and FY-77 on the schedules, are given in Table 7.1.

Table 7.1. Estimates of initial costs for the INGRID project

	<u>Thousands of dollars</u>	
	<u>FY-76</u>	<u>FY-77</u>
Conceptual design	850*	
A/E Title I and II		2,000
Building and equipment engineering		500
Target design		545
Early procurement of target components		455
Prototype development (injector)		870*
Prototype development (linac)		1,450*
Target development tests	100*	120*
Total	950	5,940
Escalation (16% to mid-FY-77)		950
Contingency (14%)		960
		<u>7,850</u>

* Other than line item project funds.

7.3 Construction Costs

A summary of the total costs of the installation, exclusive of prototype development, is shown in Table 7.2. (The prototype costs are described separately in Section 7.4.) A more detailed listing of the Lump Sum Subcontractor items is given in Table 7.3, and the items furnished directly by UCC-ND are shown in Table 7.4. All of the costs are stated in terms of October 1975, with the final cost of the project escalated to the midyear of construction — the second quarter of FY-79.

Table 7.2. Summary of total costs of INGRID project*

	Thousands of dollars		
	Lump sum items	UCCND	Total
Site preparation	50		
Improvements to land	76		
Structures	2,460		
Environmental control	1,413		
Piping	300		
Electrical	1,884		
Special facilities	80	17,576	
Standard equipment	230		
Security systems	50		
Subtotal	6,543	17,576	
Contractors overhead & profit @35%	2,290		
Subtotal	8,883	17,576	26,409
25% engr. on lump sum (8,833,000)			2,208
30% engr. on UCCND (17,576,000)			5,273
Subtotal			33,890
Contingency 30%			10,167
Subtotal			44,057
Escalation ~35%			15,943
Total			60,000

* Excluding prototype development.

Table 7.3. Detailed cost estimate of lump sum items for INGRID

	Thousands of dollars	
Site preparation		50
Earth excavation	20	
Rock excavation — hard shale	30	
Improvements to land		76
Access road	19	
Parking lot	15	
Storm drainage	17	
Fencing	15	
Walks	5	
Two-acre landscaping	5	
Structures		2,460
Target cells	388	
Accelerator tunnel	536	
Hot cell	30	
Lithium component room	96	
Hot storage rooms	54	
High bay area	520	
Injector room	34	
Ion source lab	27	
Two-story structure, linac equipment	177	
Three-story structure, offices, electronic labs, and setup area	364	
Toilets, change room, stairs, elevator	70	
Mechanical equipment room	45	
Truck air lock	35	
control rooms	84	
Environmental control		1,413
3000-ton cooling tower w/concrete basin, pumphouse, pumps, valves, piping, water treatment, electrical power in pumphouse, power to pumphouse	240	
20 ea. HEPA intake filters	40	
200-ton building air conditioner	400	
Cost for turbine drives on A/C equipment	44	
16,500-lb/hr Dowtherm-to-water system generator	60	
40-GPM water softener	24	
40-GPM 250-psi w/75-ft head w/turbine electric drive	14	
Filter pit w/120 double filtration filters	240	
Exhaust ductwork	240	
2 ea. 40,000-CFM exhaust fans at stack, primary w/steam drive, standby w/electric drive	24	
Exhaust stack	57	
Normal air-handling controls	20	
Lithium loop space cooling system	10	

Table 7.3 (continued)

	Thousands of dollars	
Piping		300
Underground steam supply from plant steam	50	
Septic tank and drain field	7	
Outside potable and fire water	12	
Steam distribution controls	20	
Steam piping-steam generator to building equipment	100	
Plumbing	29	
Wet sprinkler system	50	
Roof drains	10	
Argon/helium piping	7	
Argon/helium trailer stations	15	
Electrical		1,884
X-10 0901 substation additions-INGRID	706	
Modification to 0901 substation	191	
13.8-kV transmission line	220	
Building services	390	
Experimental services	253	
Cooling tower	30	
Outside utilities	94	
Special facilities		80
Demineralized water	80	
Standard equipment		230
High bay area crane	150	
Miscellaneous hoists	20	
Elevator	50	
Change room equipment	10	
Security systems		50
Guard portal, TV monitors, personnel control, etc.	50	
Total	6,543	6,543

Table 7.4. Detailed cost estimate of UCCND items

	Thousands of dollars	
Linear accelerator		
Injector		705
High-voltage power supply	275	
Modulator	150	
Accelerating column	60	
H. V. equipment dome	30	
Vacuum pumps, manifold	60	
Ion source w/electronics, telemetry system and controls	65	
Installation equipment	10	
Interlock and safety system	5	
Water system	10	
Installation	40	
Injector-to-linac transport		310
Bending magnets (6), trim coils w/power supplies	10	
Quadrupole triplets (7)	90	
Quadrupole power supplies	40	
E.S. septa (2) and wigglers (3)	15	
Bunchers (2) w/power supplies	70	
Diagnostic equipment and controls	35	
Vacuum pumps and valves	10	
Supports	10	
Installation	30	
Accelerator tanks		3,200
Tank material, fabrication and shipping costs	1,700	
End covers, flanges and seals	130	
Tuners, servos, pickup ports and loops	130	
Supports	50	
Vacuum pumps and power supplies	495	
Vacuum valves, plumbing, seals and disconnects	270	
Vacuum monitors, leak detectors, controls	60	
Tank cooling system	200	
Installation	165	
Drift tubes and quadrupoles		1,780
D.T. material, machining and fabrication	535	
D.T. supports, alignment equipment and fixtures	200	
Quadrupole magnets	500	
Quadrupole power supplies, cables, rack, and controls	145	
Drift tube and end-plate cooling system	250	
Installation	150	
rf systems (10)		5,194
PA cavities, filament P.S., screen modulator	1,450	
PA tubes	125	
Anode power supplies	850	

Table 7.4 (continued)

	Thousands of dollars	
Linear accelerator (cont.)		
Intermediate-power amplifiers; tubes, cavities and power supplies	775	
Low-level amplifiers	500	
AC utility power distribution	100	
Transmission lines, line stretchers	270	
Controls instrumentation, phase and amplitude regulation, control system interface	200	
Shared system components; rf source, trans- mission line, dummy load, test equipment	164	
rf cooling system	350	
Installation	410	
Controls and diagnostic equipment		614
Computer, disc files and peripherals	100	
Camac interface stations	164	
Console electronics	35	
Cable, racks, and hardware	30	
Beam intensity, beam-loss, profile monitors	175	
Communication system	15	
Safety system and access control	15	
Installation	80	
Subtotal		11,803
Lithium circuit		
Lithium		1,695
Heat exchanger, intermediate	150	
Valves, SS, 5 and 6 in., 6 each	180	
Pumps, electromagnetic, 2 each, tested	435	
Tank, fill and drain	25	
Purification - lithium	360	
Pumps, vacuum	15	
Piping, target area, sump tank	80	
Piping and insulation	60	
Instrumentation and controls	195	
Electrical heaters and control	55	
Emergency diesel generator	65	
Lithium	75	
Dowtherm		108
Pump, canned rotor	25	
Tank, dump	16	
Tank, expansion	12	
Piping and insulation	15	
Instrumentation and controls	35	
Dowtherm	5	
Installation	950	950
Subtotal		2,753

Table 7.4 (continued)

	Thousands of dollars
Special handling equipment	3,000
Beam transport equipment	225
1 - Bending magnet and power supply	
3 - Quadrupole triplets and power supply	
Vacuum piping and pumping stations	
Hot cell equipment	250
Manipulators, 3 sets	
Windows, hot cell, 3 each	
Port, pass-through	
Crane, hot cell	
Equipment for handling hot waste	
Valve boxes	400
Periscopes and lighting with penetrations for remote cell viewing	150
Penetrations for specimen holders	400
Special tooling for specimen penetrations	150
Special tooling for major penetrations	175
Mechanism for transfer of specimen penetrations	200
Mechanism for transfer of lithium target	300
Mechanism for transfer of cell liner blocks	250
Mechanism for transfer of major penetrations	200
Handling and servicing equipment for lithium loop components	300
Personnel radiation detection and alarms	20
Total	17,576

The estimate for the cost was prepared by the General Engineering Division of Union Carbide Corporation's Nuclear Division in collaboration with ORNL and Fermilab staff members. The cost of the linac was based on the design and construction experience at Fermilab with the 200-MeV proton linac after suitable updating of costs and discussions with vendors. The ion source values follow from the experience of the Thermonuclear Division of ORNL in developing sources for the earlier DCX and the current Tokamak projects. Lithium circuit costs were based on similar liquid-metal circuits designed and fabricated in the Reactor Division of ORNL. The items in the category of Special Handling Equipment are similar in many respects to various parts in use at the Oak Ridge Isochronous Cyclotron (ORIC), hot cell facilities (TURF, TRU, HRLEL), and research reactors (ORR, HFIR). Costs were based on general engineering experience at these facilities. All the other costs, which include the site and structure, are based on general engineering experience at ORNL. Of particular interest here is the HFIR building, which is similar in overall size and construction to that required for INGRID.

The percentage values for engineering and contingency are based on experience with similar projects at ORNL and in the General Engineering Division of UCC-ND and are as follows:

- 25% engineering for site, building and utilities,
- 30% engineering for linac, lithium circuit, and special handling facilities,
- 30% contingency for all items.

The escalation of costs is based on the midpoint of construction as the second quarter of FY-79. The escalation factor furnished for this date by the Cost Engineering Division of ERDA-ORO is 34.9%.

7.4 Prototype Development

Three components of the facility will require some development work, which must be done as soon as possible in order to adhere to the proposed schedule. The costs, which are listed in Table 7.5, would be incurred almost entirely in FY-77 under the proposed scheduling assumptions. Approximately 60% of the total would be used for procurement of components for the prototype injector and first linac tank. These estimates are based on recent experience with similar systems at ORNL and Fermilab and recent conversations with possible vendors. The relatively minor work for the lithium system involves chemical compatibility tests of Dowtherm and liquid lithium, and some small-scale hydrodynamic modeling of nozzle configurations for the target.

Table 7.5. Prototype development costs

	Thousands of dollars	
Prototype injector		
Power supply	275	
Modulator components	125	
Column	60	
HV dome w/generator	30	
Vacuum pumps and manifold	60	
Ion source w/electronics	65	
Installation equipment	10	
Interlock and safety system	5	
Water system	10	
Installation labor	40	
Manpower	500	1,180
Prototype linac		
Accelerator tank	300	
Accelerator drift tubes	200	
rf system	470	
Installation	50	
Manpower/computing, etc.	430	1,450
Li target hydrodynamic modeling	120	
Chemical tests	100	220
		2,850
Plus 30% (escalation to FY-77 and contingency)		850
		3,700

7.5 Operating Costs

An estimate of the operational manpower requirements and associated costs for the completed facility is given in Table 7.6.

Table 7.6. Operating costs for INGRID

	Accelerator systems ^a (many years/year)	Irradiation facilities ^b (many years/year)	Total manpower (many years/year)	Total cost (thousands of dollars)
Scientific and engineering	9	8	17	1,020
Technical	17	16	33	1,155
Support	16	21	37	1,295
Materials				650
Utilities				1,250
Total				5,370
Add escalation to 1981 (1.60)				8,600

^aIncludes the injector and the linear accelerator.

^bIncludes the target, hot cell facilities, experimental areas, experimental support and buildings.

The costs per many year which were used are the current figures for the ORNL Physics Division personnel, including both Laboratory and Division overheads. The utility costs are based on a current price of \$15/MW-hr.

For these estimates we have assumed that the tasks that would be undertaken by the INGRID staff would include:

- (1) Routine operation, maintenance and repair of all the facilities;
- (2) Development work to increase the current capabilities of the injector and linac and to improve the reliability of the facility;
- (3) Improvements to the experimental areas as the users' needs become well defined or change;
- (4) Engineering, design, instrumentation, and controls support to users, and users liaison;
- (5) Limited dosimetry and flux characterization service to the users.

The major responsibility for design, instrumentation, and fabrication of experiments would lie with the individual users. It is worth noting here that the experimental apparatus is likely to be sophisticated and expensive.

With the in-house responsibilities defined above, manpower estimates were made based on comparison with:

- (1) The neutral beam injection efforts in the ORNL Thermonuclear Division;
- (2) The Fermilab linac staff;
- (3) Liquid-metal loops in operation in the ORNL Reactor Division;
- (4) The staffing of the HFIR irradiation facility at ORNL;
- (5) The various accelerator operations within the ORNL Physics Division.

Appendix A

HIGH-EFFICIENCY BEAM BUNCHER SYSTEM

Although the radiation and induced radioactivity problems arising from a loss of 50 mA of 350-keV deuterons at injection into the linac are quite manageable, it is still desirable to increase the injection capture efficiency. We propose to develop an improved buncher system which, in principle, can give a capture efficiency close to 100%.

This buncher system is based on an idea introduced many years ago by Beringer and Gluckstern.¹ A conventional buncher groups a 360-deg (linac phase) section of beam so that ~ 240 deg of it is contained in an rf bucket 90 deg wide. In fact, 180 deg of it can be contained in a bucket ~ 22 deg wide. The basic idea for the proposed buncher system is to cut the beam into 360-deg sections and send alternate sections through two different buncher cavities operating at half the linac frequency. Each beam section is, then, 180 deg long in buncher phase. When bunched, it should fit inside a bucket 22 deg wide in buncher phase or 44 deg wide in linac phase. The capture efficiency is, therefore, easily 100%. Beam loss occurs only during branching and recombining.

A.1 Beam Sectioning and Branching

This is accomplished by a sinusoidal transverse deflector D (wobbler), a d.c. septum, and two compensators (C_1 and C_2) which annul the deflection given to the beam by the wobbler as shown in Fig. A.1. The lens K (a symmetric quadrupole triplet) provides point-to-point imaging between D and C (C_1 and C_2) so that the cancellation between the effects of the wobbler and the dewobbler is straightforward. The lenses L_1 and L_2 (identical to K) provide point-to-point imaging between S and B (B_1 and B_2). The beam is focused at S by the lens K and other lenses preceding the whole buncher system; thus the two beam sections are refocused at the buncher cavities B_1 and B_2 . In the other plane the beams should also be focused at B_1 and B_2 to reduce the required aperture in the buncher cavities to a minimum. Since there are no other focal requirements elsewhere in this plane, this should be easy to accomplish.

Fig. A.1. Layout of Buncher System.

A.2 Beam Recombining

After the debuncher the beams have sizeable momentum spread; therefore the transport lines must be achromatic. Lenses M_1 and M_2 provide point-to-point imaging between B (B_1 and B_2) and S' . Elements $E_1 - E_6$ are electrostatic dipoles. In the upper beam, E_3 and E_5 are located at the foci of M_1 and the bending angles at E_3 , E_5 , and S' are all equal in magnitude. Such a beam line is achromatic from B_1 to S' .

The two beam sections are focused at septum S' so that the separation between the beams can be made small. The beams come out of S' at small but nonvanishing separation and angle (not shown in Fig. A.1) and cross each other downstream at C where a final recombining deflector (combiner) is located. The combiner takes out the remaining small angle between

the, now, bunched beams which then enter immediately into the linac. The buncher voltage is adjusted to optimize bunching at the combiner or, equivalently, at the entrance to the linac. The first three or four quadrupoles in the linac are used to match the transverse optics of the beam.

A.3 Typical Buncher Parameters

One set of crude parameters is worked out to demonstrate the principle and the feasibility. The 350-keV deuteron beam is assumed to have an emittance of 10π cm-mrad.

(1) Quadrupole triplets. All triplets are 20 cm long and operating in the FDDF plane. The quadrupoles can be either magnetic or electrostatic. With no gap between elements and a magnetic field gradient of 2.7 kG/cm (or an electric field gradient of 16 kV/cm²), the foci are 5 cm and the point-to-point locations are ~ 35 cm beyond the ends of the triplet. The aperture should be ~ 4 cm in diameter.

(2) Transverse beam size and divergence. We assume a beam size at a focus to be ± 0.2 cm. With an emittance of 10π cm-mrad, the beam divergence there will be ± 50 mrad, giving a maximum size at the entrance and exit of a quadrupole triplet (except triplet K) of $\sim \pm 1.8$ cm.

(3) Bending dipoles. The septa are electrostatic dipoles. It is simpler, therefore, to make all dipoles electrostatic so that they have similar dispersive properties, although E_1 and E_2 can just as well be magnetic. The required (field x length) to bend the beam $\theta = 0.34$ rad is 240 kV/cm x cm, which can correspond to, say, a 10-cm-long dipole with a field of 24 kV/cm.

(4) Wobbler and dewobblers. These are identical lumped-circuit 30-MHz transverse rf dipoles. To wobble the beam ± 2 cm at the septum requires a deflection angle of $\sim \pm 67$ mrad, which can be produced by a 5-cm-long dipole with a peak field of 9.3 kV/cm. The wobbler and dewobblers should be properly phased to the linac and relative to one another.

(5) Septum. With a peak wobble of ± 2 cm a 0.6-mm-thick septum will intercept 1% of the beam. The heating of the septum by 1 mA (1% of 100 mA) of the 350-keV beam is 350 W. With only radiation cooling and assuming a 10-cm^2 radiating area, the septum temperature will be $\sim 1300^\circ\text{C}$. A tungsten septum can easily withstand this temperature, especially with water cooling supplied at the ends. When properly adjusted, the beam-recombining septum (septum') should not be struck by any noticeable amount of beam.

(6) Combiner. At the exit of septum' the beam center lines are separated by ± 0.23 cm, allowing 0.6 mm for the septum thickness. An angle of ± 11.5 mrad between the beams will make them cross each other at C, 20 cm downstream of S'.

The combiner is a lumped-circuit 30-MHz transverse rf dipole similar to but much weaker than the wobbler and the dewobblers. It is phased so that the beam bunches are deflected at the peaks of the field. To take out the remaining ± 11.5 mrad one needs a peak field only of 4.0 kV/cm over a length of 2 cm. The variation of the field near the peak over the beam bunch length of ± 11 deg is negligible.

(7) Buncher cavity. At a frequency of 30 MHz the optimal (voltage x distance to linac) is ~ 30 kVm. In this design, because of dispersion, the equivalent (distance to linac) ~ 1.135 m and the required peak voltage is, therefore, ~ 26.4 kV. The aperture should be just large enough for the focused beam to pass through (~ 1 cm diameter) to reduce the effect due to the transit-time factor. The buncher rf should, of course, be properly phased to the linac rf.

(8) Scaling. The parameters given here are only one set of consistent values to serve as an example. The beam geometry can easily be scaled up to lower the required field strengths and field gradients. In addition, if the lateral separation of the two beam branches can be reduced by using slimmer components the strengths of the dipoles can be decreased.

In principle, except for the 1% loss on the upstream septum, there should be no other beam loss through this buncher system and through capture into the linac rf buckets.

REFERENCE

1. R. Beringer and R. L. Gluckstern, "1964 Linear Accelerator Conference," MURA-714, p. 564 (July 20-24, 1964).

Appendix B

CALCULATIONS OF NEUTRON SHIELDING FOR LINAC AND IRRADIATION CELLS

Calculations for the neutron shielding required around this facility were made using published results^{1,2} from the discrete ordinates neutron transport code ANISN.³ Figure B-1 shows the tissue dose equivalent (in mrem/hr) as a function of incident neutron energy due to a flux of 1 neutron/cm²-sec normally incident on the surface of a concrete shield. The different curves indicate the dose expected at various depths inside the concrete. The composition of this concrete (TSF) is given in Table 3 of ref. 1. By using these curves the dose due to an arbitrary neutron spectrum may be generated.

The calculations are, in general, extremely sensitive to the high-energy tails in the various neutron spectra considered. Unfortunately, the available experimental data are not sufficiently precise in these regions, so that the quoted values for shielding thickness must be treated with caution. In all cases the goal has been to reduce the tissue dose equivalent at the outer surface of the shielding to a level of 0.25 mrem/hr, which corresponds to that specified for areas of unrestricted access.

B.1 Shielding for the Injector

The beam from the injector, a mixture of D^+ and D_2^+ ions at an energy of 350 keV, will be momentum-analyzed and matched to the acceptance of the linac. In the process approximately half the beam will be lost on beam dumps, apertures, etc. As a result, deuterium will build up below the bombarded surfaces and will interact with the beam particles to produce neutrons ($E_n \sim 2.5$ MeV) from the reaction

The equilibrium neutron yields from this process have been calculated by Kim⁴ and scale roughly as the square of the incident beam energy.

Fig. B.1. Dose at various depths in a concrete shield as a function of incident neutron energy. (From refs. 1 and 2.)

We assume that 150 mA of 350-keV deuterons (40% D_2^+ , 60% D^+) are lost on copper surfaces. The total neutron yield is 7.1×10^{10} neutrons/sec. This is regarded as a point source located 2 m from the walls of the injector vault.

The dose (ψ) at a depth t in the concrete from Fig. B.1 can then be used to calculate the dose ϕ at the outer surface of the shield from the expression

$$\phi(t) = \psi(t) \times \frac{7.1 \times 10^{10}}{4\pi(200 + t)^2} \text{ mrem/hr.}$$

The results, plotted in Fig. B.2, show that 130 cm of concrete is required around the injector to reduce the dose to 0.25 mrem/hr.

Fig. B.2. Dose on outer surface of concrete shield around injector and first linac tank (first cavity) as a function of shield thickness.

B.2 Shielding for First Linac Tank (First Cavity)

For this calculation a beam loss of 50 mA of D^+ was assumed to occur at an energy of 600 keV on the copper drift tubes in the first tank (first cavity). The distance to the shield in this case is 3 m. A calculation similar to that for the injector shielding produced the second curve shown in Fig. B.2, from which a shielding thickness of 125 cm around the first linac tank may be inferred.

B.3 Shielding for Higher Energy Cavities

A beam loss of 0.1% (i.e., 100 μA) is assumed to occur uniformly along the length of the linac, corresponding to about 0.025 $\mu A/cm$. This loss occurs principally on copper surfaces, and if the deuteron energy exceeds the Coulomb barrier (~ 8.5 MeV) neutrons will be produced from reactions in the copper.

The spectrum of neutrons emitted 0 deg from a deuteron beam on thick copper targets has been measured using time-of-flight techniques at $E_d = 16$ MeV, 33 MeV, and 50 MeV.⁵ Figure B.3 shows the spectra for the two lower energies taken from ref. 5, and Fig. B.4 shows the total forward-angle yields ($E_n > 4$ MeV) as a function of deuteron energy. Relative angular distributions have been measured for $E_d = 15$ MeV (ref. 6) and $E_d = 20$ MeV (ref. 7) out to 65 deg from the beam using foil activation detectors. The work at 20 MeV was done with various activation thresholds between 2 MeV and 11 MeV, and the shape of the measured angular distribution appears to be insensitive (to within a factor of 2 or so) to the threshold energy, with the measured yield at 65 deg being $\sim 10\%$ of the 0-deg yield. On the basis of these measurements, we make the following assumptions:

- (1) The shape of the neutron spectrum is given by the 0-deg measurements for all angles.
- (2) The yield at wide angles (~ 60 deg) is isotropic and given by 1/10 of the 0-deg yield.

Fig. B.3. Forward-angle neutron yields from thick copper targets bombarded by deuterons. (From ref. 5.)

Fig. B.4. Total forward-angle neutron yields ($E_n > 4$ MeV) produced by $d + \text{Cu}$ reactions. Solid line drawn only to guide the eye.

With the above assumptions, the spectra shown in Fig. B.3 and the dose vs depth information given in Fig. B.1 were used to calculate effective concrete dose transmission curves for 0-deg neutrons produced by 16-MeV and 33-MeV neutrons incident on copper. Figure B.5 shows these calculated curves fitted in the region of interest ($t = 50$ to 200 cm) by exponentials of the form

$$\psi = \psi_0 e^{-t/\lambda}, \quad (\text{B-1})$$

where ψ is the dose per incident neutron at depth t in concrete, and ψ_0 and λ are constants that are dependent on the incident deuteron energy. By assuming this dependence to be linear, we may generate curves for other energies.

Fig. B.5. Dose at various depths in concrete due to neutrons produced by 16-MeV and 33-MeV deuterons incident on copper.

The lateral shielding required at any point in the accelerator was calculated by the approach shown in Fig. B.6. Consider the element of drift tube dx a distance x from point B. The beam lost on the copper at this point is

$$dI = \frac{dI}{dx} dx ,$$

and the neutron yield is

$$Y(\phi) \frac{dI}{dx} dx \text{ neutrons/sec-sr} ,$$

so that the dose at A is

$$\begin{aligned} d\psi &= Y(\phi) \frac{dI}{dx} dx \frac{\cos^2 \theta}{(d + t)^2} \psi_0 e^{-t/\lambda \cos \theta} \\ &= \frac{Y(\phi)}{(d + t)} \frac{dI}{dx} \psi_0 e^{-t/\lambda \cos \theta} d\theta . \end{aligned}$$

Fig. B.6. Geometry for calculating neutron shielding around cavities 2-10.

In all cases of interest $t/\lambda \gg 1$ so that only a narrow range of θ near 0 deg is significant. We therefore replace $Y(\phi)$ by $Y(90^\circ) = Y(0^\circ)/10$, where $Y(0^\circ)$ is the yield corresponding to the deuteron energy at point B, and we replace $t/\lambda \cos \theta$ by $(t/\lambda)(1 + \theta^2/2)$. Then

$$\begin{aligned} \psi &= \frac{Y(0^\circ)}{10(d + t)} \frac{dI}{dx} \psi_0 \int_{-\pi/2}^{+\pi/2} e^{-(t/\lambda)(1+\theta^2/2)} d\theta \\ &\approx \frac{Y(0^\circ)}{10(d + t)} \frac{dI}{dx} \psi_0 e^{-t/\lambda} \int_{-\infty}^{+\infty} e^{-t\theta^2/2\lambda} d\theta \\ &= \frac{Y(0^\circ)}{10(d + t)} \frac{dI}{dx} \psi_0 e^{-t/\lambda} \sqrt{2\pi\lambda/t}, \end{aligned} \quad (B-2)$$

where ψ_0 and λ are defined as in Eq. B.1 and Fig. B.4, $Y(0^\circ)$ is taken from Fig. B.3, dI/dx is 0.25 $\mu\text{A}/\text{cm}$, and d is assumed to be 300 cm.

With Eq. B-2 the shielding required at different points along the linac was calculated as a function of deuteron energy. Figure B.7 shows the results of these estimates, together with the previously calculated shielding required in the first tank.

B.4 Shielding for Irradiation Cells

The yield of neutrons from a thick lithium target bombarded by 40-MeV deuterons has been measured at ORNL using time-of-flight techniques at angles from 0 to 20 deg. Smooth curves drawn through these data are shown in Fig. B.8, with arbitrary extrapolations below $E_n \sim 4$ MeV for which no data exist.

In the proposed facility the lithium target is near the entrance face of the irradiation cell, which is approximately 3 m deep. The information in Figs. B.8 and B.1 was used to define dose-depth curves for this

ORNL-DWG 75-11057

Fig. B.7. Thickness of concrete required around linac to maintain dose level of 0.25 mrem/hr.

Fig. B.8. Neutron yields from 40-MeV deuteron bombardment of lithium.

geometry as described previously (see Eq. B-1). In the forward direction the dose at a depth t inside the concrete was defined as

$$\psi = \frac{Y(0^\circ)}{(300 + t)^2} \psi_0 e^{-t/\lambda},$$

which yielded a value of 440 cm for the required shielding thickness.

For the side walls the yield at 90 deg was assumed to be 25% of the 20-deg yield, with the same neutron energy spectrum, so that the dose in this case becomes

$$\psi(t) = \frac{Y(20^\circ)}{4(150 + t)^2} \psi_0 e^{-t/\lambda},$$

leading to a value of 390 cm for the shield thickness.

It may be noted that at these depths in concrete, 97% of the transmitted dose is due to neutrons incident with energies >25 MeV.

REFERENCES

1. R. W. Roussin and F. A. R. Schmidt, Nucl. Eng. Design 15, 319 (1971).
2. R. W. Roussin, R. G. Alsmiller, Jr., and J. Barish, Nucl. Eng. Design 24, 250 (1973).
3. W. W. Engle, Jr., "A Users Manul for ANISN," K-1693, Union Carbide Corporation Computing Technology Center, Oak Ridge, TN (1967).
4. J. Kim, TCC Report No. 3014, The Cyclotron Corporation, Berkeley, California (September 1974).
5. J. P. Meulders, P. Leleux, P. C. Macy, and C. Pirart, Phys. Med. Biol. 20, 235 (1975).
6. C. E. Falk, Phys. Rev. 83, 499 (1951).
7. L. Schecter, Phys. Rev. 83, 695 (1951).

Appendix C

CALCULATIONS OF RESIDUAL ACTIVATION IN FACILITY

Residual activity levels in this facility will be far higher than those normally encountered around accelerators. The design philosophy will be to keep levels in the accelerator vault low enough to avoid the need for remote maintenance, and the calculations described here indicate that this can probably be achieved. Remote maintenance will be required for the lithium loop and target cell areas, however.

The calculations are based on the following assumed values for the beam losses during normal operation of the facility:

- (1) Low-energy beam transport systems: 150 mA of a mixed D^+ and D_2^+ beam at an energy of 350 keV striking copper surfaces in the low-energy beam transport system.
- (2) The first linac tank (first cavity): 50 mA of D^+ beam at a mean energy of 600 keV striking the copper drift tube walls.
- (3) The first half of the linac ($350 \text{ keV} < E_d < 20 \text{ MeV}$): a uniform loss of $2.5 \text{ } \mu\text{A/m}$ on the drift tubes.
- (4) The second half of the linac ($20 \text{ MeV} < E_d < 40 \text{ MeV}$): a uniform loss of $0.25 \text{ } \mu\text{A/m}$ on the drift tubes.
- (5) The target system: 100 mA of 40-MeV deuterons lost in the lithium target.

C.1 Deuteron Activation

C.1.1 Activation of the Copper Drift Tubes

The residual activity of copper after deuteron bombardment has been tabulated by Fulmer and Kindred.¹ In Fig. C.1 the upper curve shows

Fig. C.1. Residual radiation levels due to deuteron activation of copper.

the activation level $\phi(E_d)$ at a distance of 1 m from a copper target which has been bombarded by 1 μ A of deuterons for 1 month and then allowed to cool for 8 hr. To estimate the activity outside the linac tank wall the geometry shown in Fig. C.2 was used, where the structural material is assumed to be a 3-in.-thick stainless steel cylindrical shell representing the drift tube structural materials and the real tank wall.

At a distance l from the beginning of the linac where the beam energy E_d (in MeV) and l (in meters) are equal, the radiation level $\phi(l)$ is given by

$$\phi(l) = \int_{-l}^{40-l} \frac{dI}{dx} \frac{d(E_d = l + x)}{r^2 + x^2} e^{-t\mu/\cos \theta} ,$$

where

dI/dx = beam loss at $(\ell + x)$,

r = outer radius of the linac tank,

t = thickness of structural material,

μ = appropriate energy absorption coefficient.

For the integration we assume

$$dI/dx = 2.5 \mu\text{A/m} \quad (0 < \ell < 20 \text{ m})$$

$$= 0.25 \mu\text{A/m} \quad (20 \text{ m} < \ell < 40 \text{ m}) ,$$

$$r = 1.6 ,$$

$$t = 7.5 \text{ cm} ,$$

$$\mu = 0.204 \text{ cm}^{-1} .$$

The result is the lower curve in Fig. C.1. The dose level is $< 5 \text{ mrem/hr}$ at all points along the accelerator. After one year of operation the dose level will be essentially the same.

ORNL-DWG 75-13541

Fig. C.2. Geometry for calculating dose rates due to deuteron activation of copper drift tubes.

C.1.2 Activation of the Lithium Target

The production rate of ^7Be from deuteron bombardment of thick lithium targets has been measured at energies up to 30 MeV (refs. 2 and 3). Extrapolating these data to 40 MeV, we have estimated the rate to be 300 $\mu\text{Ci}/\mu\text{A-hr}$, corresponding to an average cross section of ≈ 40 mb.

With a 100-mA beam the production rate would be 30 Ci/hr. The half-life of ^7Be is 53 days. After one year the production of ^7Be will have reached equilibrium at 5.5×10^4 Ci. Only 12.3% of the ^7Be decays by gamma-ray emission, so that the final gamma activity concentration is 8 mCi/cm³ when distributed throughout the lithium inventory (≈ 1300 kg).

The radiation level 1 m from a 6-in.-diam pipe filled with the lithium would, therefore, be ≈ 40 r/hr, requiring about 60 cm of concrete shielding to reduce the level to 2.5 mrem/hr.

The cross section for tritium production from $d + \text{Li}$ has been measured at energies up to 7 MeV (ref. 4), where the value is 165 mb and still rising. For the purposes of this calculation an average cross section of 300 mb was assumed, which leads to a tritium production rate of 70 Ci/day for a 100-mA 40-MeV deuteron beam.

C.2 Neutron Activation

C.2.1 Activation of the Linac Structure

It has been shown in Appendix B that the total neutron yield from beam losses in the low-energy beam transport system will be 7×10^{10} neutrons/sec, the neutron energy being 2.5 MeV. In the first linac tank (first cavity), the total yield will be about 9×10^{10} neutrons/sec. These neutrons will activate nearby materials, such as copper or iron, before reaching the shield walls and being lost. We assume each neutron passes through an average of 1 in. of iron and 1 in. of copper and neglect contributions from lower energy neutrons reflected back from the

walls. The three significant reactions are given in Table C.1. After equilibrium is reached, the total amount of activity from these three reactions will be ~ 1 mCi. Even if this activity were concentrated in one spot, this would give a dose < 1 mrem/hr at 1 m.

Table C.1. Neutron activation reactions in linac structure

Reaction	σ (at $E_n = 2.5$ MeV)	$\tau^{1/2}$
$^{63}\text{Cu}(n,\gamma)$	~ 10 mb	12.9 h
$^{65}\text{Cu}(n,\gamma)$	~ 5 mb	5.1 min
$^{54}\text{Fe}(n,p)$	68 mb	312 days

The neutron yields and spectra from $d + \text{Cu}$ reactions in the drift tubes also have been discussed in Appendix B. With the beam losses given in assumptions 3 and 4 above, the maximum neutron flux at the linac tank wall will be $\sim 6 \times 10^5$ neutrons/cm²-sec. The most important neutron activation reaction in the steel is $^{54}\text{Fe}(n,p)^{54}\text{Mn}$, which results in a 303-day gamma activity for which $E_\gamma = 0.835$ MeV. From published cross-section data⁵ and the spectra given in Appendix B, the spectrum-averaged cross section is approximately 0.32 b both at $E_d = 16$ MeV and at $E_d = 33$ MeV. We, therefore, assume it to be the same at $E_d = 40$ MeV. Based on these figures, the ^{54}Mn activity in the tank walls after one year of operation will be approximately $0.02 \mu\text{Ci/cm}^3$, leading to a dose of 5 mrem/hr at a position 10 cm from the 1-in.-thick tank wall. No allowance has been made for self-shielding effects.

C.2.2 Activation of the Concrete in the Linac Vault

Calculations of the residual activity in the concrete around accelerators have shown⁶ that the dose rate is dominated by the production of ^{24}Na . This nuclide decays mostly (99%) by emission of two gamma rays, $E_\gamma = 2.75$ MeV and 1.37 MeV, with a half life of 15 hr. The most important reactions which result in this activity are listed in Table C.2, together with the

number densities of the appropriate nuclei in concrete and the reaction cross section at appropriate energies. It should be noted that the number densities can vary widely for different samples of concrete.

Table C.2. Neutron activation reactions in the concrete in the linac vault

Isotope	Number density (atoms/cm ³)	Reaction	$\sigma(E)$ (barns) (ref. 5)	E (MeV)
²³ Na	0.8×10^{21}	²³ Na(n, γ)	0.25	10^{-7}
²⁴ Mg	1.5×10^{21}	²⁴ Mg(n,p)	0.2	13
²⁷ Al	0.6×10^{21}	²⁷ Al(n, α)	0.13	13

For these calculations the accelerator tunnel was assumed to be a cylinder of radius 3 m, with the accelerator centered along the axis. The maximum neutron flux at the wall from d + Cu reactions is then $\sim 3 \times 10^5$ neutrons/cm²-sec near the high-energy end of the accelerator. From calculations by Alsmiller⁷ based on the similar spectrum from d + Li reactions, the thermal-neutron flux ($E_n < 0.4$ eV) will build up rapidly inside the concrete to $\sim 6 \times 10^5$ neutrons/cm²-sec, remaining constant to depths ~ 25 cm. The equilibrium ²⁴Na disintegration rate in the concrete may be written as

$$\frac{dn}{dt} = \phi \sigma N ,$$

where

ϕ = neutron flux,

σ = spectrum-averaged activation cross section,

N = number density for the appropriate isotope.

For the three reactions listed in Table C.2, we find that

$$\frac{dn}{dt} = 233 \text{ disintegrations/sec-cm}^3,$$

with approximately half the activity being due to $^{23}\text{Na}(n,\gamma)$ reactions.

The energy absorption length for 2.75-MeV gamma rays in concrete is ~ 15 cm. We approximate the effect of this by assuming the transmission to be unity for path lengths < 15 cm and zero for path lengths > 15 cm. The dose rate on the axis of the accelerator tunnel due to the calculated ^{24}Na concentration is then approximately 20 mrem/hr. After one shift of cooling, the level will drop to 12.5 mrem/hr. It can be shown⁷ that this dose is almost independent of position inside the tunnel.

If boron-loaded concrete is used to line the accelerator vault, the contribution from the $^{23}\text{Na}(n,\gamma)$ reaction can be largely eliminated,⁶ bringing the dose rate down to 6 mrem/hr.

C.2.3 Activation of the Air in the Accelerator Vault

The most important activities produced in the air are ^{13}N , a 10-min β^+ activity from the $^{14}\text{N}(n,2n)$ reaction, and tritium from $^{14}\text{N}(n,t)$ reactions. The activation cross sections for these reactions at $E_n = 15$ MeV are 10 mb and 20 mb respectively.

The total high-energy neutron yield from $d + \text{Cu}$ reactions in the accelerator will be $\sim 3 \times 10^{11}$ neutrons/sec. If each neutron is assumed to pass through 3 m of air, the equilibrium concentration of ^{13}N will be ~ 0.5 mCi in a volume of 10^3 m^3 , or 0.5 mCi/m^3 . The total tritium production rate will be $0.2 \text{ } \mu\text{Ci/day}$.

C.2.4 Activation of the Lithium Target Window

The target window will be made of a vanadium-titanium alloy, such as 80% V and 20% Ti. The dominant activities which will be produced are $^{48}\text{Sc}(\tau_{1/2} = 44 \text{ hr})$ and $^{46}\text{Sc}(\tau_{1/2} = 84 \text{ days})$. The most important

reactions for production of these isotopes are listed in Table C.3, together with their cross sections at $E_n = 15$ MeV and the number densities of the initial nuclei in an alloy that is 80% V and 20% Ti.

Table C.3. Neutron activation reactions in vanadium-titanium alloy (80% V, 20% Ti)

Reaction	σ (at $E_n = 15$ MeV) (mb)	Number density (atoms/cm ³)	Radioactive product
$^{51}\text{V}(n,\alpha)$	25	17×10^{21}	^{48}Sc
$^{48}\text{Ti}(n,p)$	60	3.1×10^{21}	^{48}Sc
$^{49}\text{Ti}(n,pn)$	40	0.23×10^{21}	^{48}Sc
$^{46}\text{Ti}(n,p)$	250	0.33×10^{21}	^{46}Sc
$^{47}\text{Ti}(n,pn)$	120	0.31×10^{21}	^{46}Sc

The end window is 3 mm thick, and approximately 10^{16} neutrons/sec will pass through it. If we assume the values of the spectrum-averaged cross sections to be equal to their values at $E_n = 15$ MeV, then the equilibrium quantities of ^{44}Sc and ^{46}Sc activities are 170 Ci and 33 Ci respectively. The dose rate 1 m from the end window will be ~ 300 r/hr after 1 shift of cooling, dropping to 40 r/hr in one week.

C.2.5 Activation of the Irradiation Cell Walls

Activation of the walls of the irradiation cells due to ^{24}Na production can be estimated from the results of Section C.2.2 above, in which a flux of 3×10^5 neutrons/cm²-sec was estimated to give a ^{24}Na concentration of 233 disintegrations/sec-cm³. The average neutron flux on the back wall of the irradiation cell will be $\sim 10^{11}$ neutrons/cm²-sec, so that the equilibrium ^{24}Na activity will be

$$\begin{aligned} \frac{dn}{dt} &= \frac{10^{11}}{3 \times 10^5} \times 233 \text{ disintegrations/sec-cm}^3 \\ &= 7.8 \times 10^7 \text{ disintegrations/sec-cm}^3 . \end{aligned}$$

Using the same approximations applied in Section C.2.2 for the transmission of the gamma rays through concrete, the residual radiation field in the center of the cell due to the activation of the back wall will be ~ 1000 r/hr. The contributions due to the other concrete surfaces have not been estimated, but are presumably rather similar.

C.2.6 Activation of the Helium Atmosphere in the Irradiation Cell

The only significant activity in the helium atmosphere will be due to tritium production. An approximate value of the ${}^4\text{He}(n,t)$ cross section may be obtained from the measured values of the $T(d,n){}^4\text{He}$ cross section by using detailed balance. The threshold for the ${}^4\text{He}(n,t)d$ reaction occurs at $E_n = 21$ MeV and the cross section remains constant at about 100 mb up to $E_n = 30$ MeV. We have, therefore, assumed 100 mb to be the spectrum-averaged cross section for $\text{Li}(d,n)$ neutrons with energies >20 MeV.

The total neutron yield in an irradiation cell for neutrons above 20 MeV will be approximately 5×10^{15} neutrons/sec, and the path length of the average neutron inside the cell will be ~ 3 m. Using these figures yields a tritium production rate of ~ 200 $\mu\text{Ci/day}$.

A more important source of tritium in the cell may be due to (n,t) reactions in the concrete, with subsequent diffusion of the tritium into the helium.

REFERENCES

1. C. B. Fulmer and G. Kindred, "Calculated Residual Radiation Levels from Elements Used in Cyclotron Structures," ORNL-TM-2834 (1970).
2. P. P. Dmitriev, N. N. Krasnov, G. A. Molin, and M. V. Panarin, Soviet Atomic Energy 31, 876 (1972).
3. A. Aton and J. Halberstadt, Philips Tech. Rev. 1 (1954).
4. R. L. Macklin and H. E. Banta, Phys. Rev. 97, 753 (1955).
5. W. E. Alley and R. M. Lessler, Nuc. Data Tables 11, 622 (1973).
6. T. W. Armstrong and J. Barish, Nucl Sci. Eng. 40, 128 (1970).
7. R. G. Alsmiller, Jr., private communication.

Appendix D

TURBULENCE DAMPING AND JET STABILIZATION BY MAGNETIC FIELDS

If the degree of jet stability reported in Chapter 5 should prove to be insufficient, advantage could be taken of magnetic damping mechanisms to either (1) suppress the duct turbulence and thereby increase the stability parameter to that of the laminar case or (2) act directly upon the surface instability to increase its wavelength and delay breakup.

In the first case, a transverse magnetic field could be applied in the duct region just upstream of the target area. The resulting magnetic body forces would suppress the motion of the longitudinal eddies that are responsible for extracting energy from the mean flow and feeding the turbulence. With this type of field orientation, it is theoretically possible to suppress turbulence entirely. In practice, exponential damping of turbulence intensities has been observed in large-scale channel flow experiments with mercury for Reynolds numbers as high as 200,000 (ref. 1).

The magnetic field strength required to completely suppress turbulence in the nozzle is found from the expression²

$$N_{Ha} \geq N_{Re}/215, \quad (D-1)$$

where N_{Ha} , the Hartmann number, is a relative measure of the importance of the magnetic body force and is given in terms of the electrical conductivity, σ , and the magnetic induction, B , by the relationship

$$N_{Ha}^2 = \frac{\text{magnetic body force}}{\text{viscous force}} = \frac{\sigma B^2 D^2}{\mu}.$$

For Reynolds numbers of the order of 700,000 and a hydraulic diameter of 0.04 m, the required field strength will be ($\sigma = 3.3 \times 10^6$ ohm/m; $\mu = 4.4 \times 10^{-4}$ N sec m⁻²):

$$B' \geq \frac{700,000}{215 \times 0.04} \sqrt{(4.4 \times 10^{-4}) / (3.3 \times 10^6)} = 0.94 \text{ tesla} .$$

Producing a field of this strength is well within the capabilities of present-day water-cooled magnet technology. And since the region of suppressed turbulence should extend to at least 10 hydraulic diameters downstream of the point where the field terminates, the magnet could be located ~0.5 m upstream of the nozzle injection plane where it will not interfere with the experiment (even at a field strength of 1 tesla, the Larmor radius of 40-MeV deuterons will be of the order of 1 m). Furthermore, convection of magnetic field lines by the flowing lithium should not be important at the low magnetic Reynolds numbers present here (~1). Existing liquid-metal loops could be readily modified to explore this concept.

Suppression of the capillary instability may also be accomplished, in this case by the application of an axial magnetic field of sufficient strength to render all but the longest wavelength disturbances stable. Rayleigh showed that (without magnetic fields) a circular jet is unstable only to symmetric disturbances of wavelength greater than the jet circumference. The effect of an applied magnetic field is to increase the minimum wavelength for which the jet is unstable. By modifying the theory of Rayleigh to include the magnetic effect, Chandrasekhar³ demonstrated that the minimum unstable wavelength can be made essentially infinite in extent for magnetic field strengths exceeding the following value:

$$B \geq \sqrt{20/\sigma} (\rho \Gamma / D^3)^{1/4} . \quad (D-2)$$

For lithium, the required axial field will be

$$B \geq \sqrt{20/(3.3 \times 10^6)} [(500 \times 0.35)/(0.04)^3]^{1/4} = 0.1 \text{ tesla} .$$

This is of considerably smaller strength than that required to dampen the turbulence but it might be more difficult to implement since the

field must extend into the target area to be effective. An additional benefit of this arrangement would be the partial damping of transverse turbulent fluctuations that the longitudinal field would give.

REFERENCES

1. H. Hau and P. S. Lykoudis, "Turbulence Measurements in a Magneto-Fluid-Mechanic Channel," Nucl. Sci. Eng. 54 (1974).
2. H. H. Branover, "Transition Criteria and Turbulent Flow in MHD Ducts," in Proceedings of a Symposium in Warsaw, July 24-30, 1968, Vol. III, Held by the International Atomic Energy, Vienna, 1968.
3. S. Chandrasekhar, "Hydrodynamic and Hydromagnetic Stability," Oxford Press, 1961.

Appendix E
HYDRODYNAMIC SIMILARITY EXPERIMENTS WITH MERCURY

As has been mentioned in Chapter 5, it is possible to simulate the behavior of the lithium jet in an experiment that operates under different conditions with an alternative fluid. From such an experiment, one could expect to obtain optimized nozzle configurations under more favorable conditions and on a smaller scale than would be possible with a full-scale liquid-lithium experiment. Since the dynamics of the jet are completely determined by specifying the Weber and Reynolds numbers, N_{We} and N_{Re} , and the nozzle aspect ratio, AR, it is possible to model the lithium jet by preserving these three characteristic numbers in the mockup experiment. Implicit in this is the assumption that the ambient medium plays an insignificant role in the hydrodynamic behavior of the jet and this condition must be met in the mockup, although it does not necessarily mean that the experiment operate at near-vacuum conditions.

Denoting by primed and unprimed quantities the conditions applicable to the mockup and lithium experiments respectively, similitude will apply when the velocity and hydraulic diameter of the mockup obey the following relationships:

$$V' = \left(\frac{\Gamma'}{\Gamma} \right) \left(\frac{\mu}{\mu'} \right) V, \quad (E-1)$$

$$D' = \left(\frac{\rho}{\rho'} \right) \left(\frac{\Gamma}{\Gamma'} \right) \left(\frac{\mu'}{\mu} \right)^2 D, \quad (E-2)$$

$$AR' = AR, \quad (E-3)$$

where the terms are defined in Chapter 5. The scale of the mockup will be small if a fluid having a high density, high surface tension, and low viscosity is used. However, the latter two properties would result in higher velocities in the mockup; and consequently only higher density fluids would reduce the scale without affecting the velocity. A fluid

having a very high relative density and a somewhat higher relative viscosity would have the effect of reducing both the length scale and the velocity. Mercury, for example, would exhibit these qualities and since it has a higher boiling point it could also serve as a test fluid for study of the heated target region. Furthermore, its high electrical conductivity makes possible the study of the various magnetic stabilization techniques discussed earlier.

An experiment simulating lithium but employing mercury at room temperature would have the following characteristics ($\rho' = 13,550 \text{ kg m}^{-3}$, $\mu' = 1.55 \times 10^{-3} \text{ N sec m}^{-2}$, $\Gamma' = 0.47 \text{ N m}^{-1}$):

$$V' = \left(\frac{0.47}{0.38} \right) \times \left(\frac{4.5 \times 10^{-4}}{1.55 \times 10^{-3}} \right) \times 15 = 5.39 \text{ m/sec} ,$$

$$D' = \left(\frac{450}{13,550} \right) \times \left(\frac{0.38}{0.47} \right) \times \left(\frac{1.55 \times 10^{-3}}{4.5 \times 10^{-4}} \right)^2 \times 0.04 = 0.013 \text{ m} ,$$

$$AR = 4 .$$

For an aspect ratio of 4, this corresponds to a channel with dimensions 8 mm high by 32 mm wide. This is considerably smaller than the lithium jet and since the velocity is also greatly reduced, the experiment should not be difficult to perform. Furthermore, there is the possibility that the tests could be performed at atmospheric conditions. This is so because the Weber number evaluated at the density of atmospheric air is less than unity and from the work of Fenn and Middleman,¹ a value exceeding 5.3 is required for the ambient medium to have an appreciable effect upon the stability of the jet.

REFERENCE

1. R. W. Fenn, III, and S. Middlemann, "Newtonian Jet Stability: The Role of Air Resistance," A.I.Ch.E. Journal 15(3), 379 (May 1969).

Appendix F

CONSIDERATION OF ALTERNATE FLUIDS FOR INTERMEDIATE HEAT EXCHANGER COOLANT

As has been pointed out in Chapter 5, Dowtherm, a product of Dow Chemical Company, has been tentatively selected as the coolant for the intermediate heat exchanger (see Fig. 5.3). Several other fluids were considered before Dowtherm was chosen. Inert gases looked unattractive because of the large heat exchanger surfaces required and the high cost of large volume circulators. Lithium was evaluated as the secondary fluid since it is an excellent heat transfer agent and because accidental leakage problems at the intermediate heat exchanger would be minimized with identical fluid in both circuits. However, use of lithium in the secondary circuit was discarded because of the high cost of liquid-metal components, the relatively high freezing point of lithium, and because use of any liquid metal precludes final heat dump to water due to safety considerations.

Sodium was given extensive consideration as the intermediate heat transfer fluid because of (1) excellent heat transfer characteristics, (2) gamma radiation resistance, (3) the possibility of tritium cold trapping, (4) the compatibility of lithium and sodium in the event the two fluids accidentally mix, and (5) a lower melting temperature than lithium. A particular advantage of sodium is that NaT can be cold trapped and sequestered after tritium enters the sodium circuit by diffusing through the intermediate heat exchanger walls. Therefore, the amount of tritium in the circulating sodium would be kept at very safe levels.

Some detailed comments on tritium cold trapping are included here in case uncertainties related to the use of Dowtherm secondary coolant force a return to the use of sodium. Reference 1 demonstrates that tritium content in an experimental sodium test loop could be reduced from a starting point of 1.37 nCi/g to as low as 0.04 nCi/g by concurrent trapping of hydrogen and tritium. In the specific test discussed, the cold trap was operating at 116 to 121°C and a flow rate of 63 $\mu\text{m}^3/\text{s}$

(1 gpm) which gave a trap residence time of 2.2 min.² The experimental loop had a total sodium inventory of 0.37 m³ (100 gal). Tests on hydrogen cold trapping alone showed that hydrogen levels of 50 PPB could routinely be obtained. On a far larger scale, the EBR-II sodium-cooled fast reactor operated with a typical tritium content in the sodium of 50 nCi/g with continuous cold trapping at a temperature of 110-116°C. Even if one assumes an equilibrium tritium content of 50 nCi/g in a likely sodium inventory of 2500 kg (100 ft³), the resultant activity in circulation would only be about 0.1 Ci. Therefore, a gross sodium leak at the air-cooled heat exchanger would not provide a serious radiation hazard to the environment.

Normal diffusion of tritium through the air-cooled heat exchanger walls to the atmosphere would be very low due to the cold trapping of sodium tritide. If one assumes that 1% of the tritium produced eventually reached the atmosphere (0.01 x 70 = 0.7 Ci/day), the dilution by the cooling air flow of 52 m³/sec would reduce the concentration to 0.16 pCi/cm³. This value is a factor of 30 below the maximum permissible concentration of 5 pCi/cm³ for tritium stipulated in ERDA regulations for 40-hr exposure in a restricted area.

REFERENCES

1. R. Kumar, A. F. Panek, D. J. Rave, and P. A. Nelson, "Continuous Monitors for Tritium in Sodium Coolant and Cover Gas of an LMFBR," ANL-8079 (Mar. 1974).
2. Communication with R. Kumar, Argonne National Laboratory on August 21, 1975.

Internal Distribution

1-2. Central Research Library	28. J. A. Martin
3. ORNL Y-12 Technical Library	29. C. J. McHargue
4-6. Laboratory Records Department	30. S. L. Milora
7. Laboratory Records, ORNL-RC	31. O. B. Morgan
8. ORNL Patent Office	32. J. A. Murray
9. R. G. Alsmiller	33. F. G. Perey
10. M. Bender	34. H. Postma
11. E. E. Bloom	35. C. R. Richmond
12. A. L. Boch	36. J. B. Roberto
13. J. F. Clarke	37. M. T. Robinson
14. F. L. Culler	38. M. W. Rosenthal
15. G. G. Fee	39-70. M. J. Saltmarsh
16. J. L. Fowler	71. J. L. Scott
17. A. P. Fraas	72. D. Steiner
18. T. A. Gabriel	73. P. H. Stelson
19. R. F. Hibbs	74. J. O. Stiegler
20. R. M. Hill	75. D. B. Trauger
21. H. W. Hoffman	76. J. R. Weir
22. J. A. Horak	77. F. W. Wiffen
23. W. R. Huntley	78. M. K. Wilkinson
24. G. R. Jasny	79. R. E. Worsham
25. G. G. Kelley	80. F. W. Young
26. R. F. MacPherson	81. A. Zucker
27. F. C. Maienschein	

External Distribution

82. J. Blewett, Brookhaven National Laboratory, Upton, New York 11973.
83. T. H. Blewitt, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439.
- 84-115. Marvin M. Cohen, Division of Controlled Thermonuclear Research, U. S. Energy Research and Development Administration, Washington D. C. 20545.

116. C. Curtis, Fermi National Accelerator Laboratory, P. O. Box 500, Batavia, Illinois 60510.
117. A. N. Goland, Brookhaven National Laboratory, Upton, New York 11973.
118. E. L. Goldwasser, Fermi National Accelerator Laboratory, P. O. Box 500, Batavia, Illinois 60510.
119. P. Grand, Brookhaven National Laboratory, Upton, New York 11973.
120. D. H. Gurinsky, Brookhaven National Laboratory, Upton, New York 11973.
121. E. A. Knapp, Los Alamos Scientific Laboratory, P. O. Box 1663, Los Alamos, NM 87545.
122. J. A. Lenhard, Research and Technical Support Division, U. S. Energy Research and Development Administration, Oak Ridge, Tennessee 37830.
123. P. V. Livdahl, Fermi National Accelerator Laboratory, P. O. Box 500, Batavia, Illinois 60510.
124. D. R. Miller, Division of Physical Research, U. S. Energy Research and Development Administration, Washington, D. C. 20545.
125. C. Owen, Fermi National Accelerator Laboratory, P. O. Box 500, Batavia, Illinois 60510.
126. P. J. Persiani, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439.
127. G. L. Rogosa, Division of Physical Research, U. S. Energy Research and Development Administration, Washington, D.C. 20545.
128. J. M. Teem, Assistant Administrator for Geothermal and Advanced Energy, U. S. Energy Research and Development Administration, Washington, D. C. 20545.
129. L. C. Teng, Fermi National Accelerator Laboratory, P. O. Box 500, Batavia, Illinois 60510.
130. R. R. Wilson, Fermi National Accelerator Laboratory, P. O. Box 500, Batavia, Illinois 60510.
131. D. E. Young, Fermi National Accelerator Laboratory, P. O. Box 500, Batavia, Illinois 60510.
- 132-158. Technical Information Center, Oak Ridge, Tennessee 37830.