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MASTER

A PROPOSAL FOR THE Mc^2
ISOCHRONOUS CYCLOTRON

OAK RIDGE NATIONAL LABORATORY
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

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ORNL 3540

Contract No. W-7405-eng-26

A PROPOSAL
for
THE Mc^2 ISOCHRONOUS CYCLOTRON

A General Purpose High-Intensity
810-MeV Proton Accelerator

November 1, 1963

OAK RIDGE NATIONAL LABORATORY
Operated by
UNION CARBIDE CORPORATION
for the
U. S. ATOMIC ENERGY COMMISSION
Post Office Box X
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ABSTRACT

The Oak Ridge National Laboratory proposes to build an isochronous eight-sector proton cyclotron to provide an extracted beam in excess of 100 μ A at 810 MeV. The primary proton beam and the secondary meson and neutron beams will be used to investigate nuclear structure, and the interactions between elementary particles. Biomedical and Space-oriented research programs are also planned. Shielded research areas and an extensive beam transport and analysis system are provided. Theoretical and experimental studies have shown that the Mc² Cyclotron is a practical concept; high extraction efficiencies can be obtained, and the residual radiation problems are manageable. The project would require less than seven years to complete, and would cost about \$43,000,000.

SUMMARY

An accelerator complex for the production and use of very intense beams of protons and pi and mu mesons is described. An eight-sector isochronous cyclotron with maximum internal energy of 900 MeV and an extracted beam of 810 MeV is planned. Intensities up to 6×10^{14} protons/sec, 10^9 pions/sec, 10^7 muons/sec can be obtained within suitably small solid angles.

The research program currently envisions that the accelerator will be primarily used for the study of nuclear structure from the inelastic scattering and nuclear reactions produced with highly monoenergetic proton beams. The accelerator and its associated facilities will also permit new and more precise investigations of both weak and strong interactions of the elementary particles. More refined studies of muonium, mesic atoms, and mesic molecules will be possible. In addition to its use for physics research, the facility can be an important tool for fundamental research into the effects of high-energy radiation on biological systems, including applications in radiation therapy and the problems of space radiation. Facilities for cancer therapy and for neutron time-of-flight studies can be added to the proposed research complex.

A radial resonance beam extraction system for Cyclotron Analogue II was developed and successfully tested; an extraction efficiency in excess of 80% was achieved. A similar efficiency is predicted for the full-scale machine.

An extensive ion optics system has been designed to assure highly monoenergetic particle beams for physics research, and a flexible beam-transport arrangement for all experimental areas. The system includes a high-resolution beam analyzing magnet, several steering magnets, beam transport quadrupoles, and a muon channel.

The shielded area includes the cyclotron vault, a beam handling corridor, and three large experiment rooms; it provides a total usable area of 56,000 sq. ft. The adjacent research building contains laboratories, offices, shops, and storage and staging areas; the usable area is 43,000 sq. ft.

ARCHITECT'S RENDITION OF THE PROPOSED Mc^2 CYCLOTRON LABORATORY

Because of the large flux of penetrating particles, concrete shield walls of up to 40 feet in thickness, or equivalent, are required. Low strength ordinary concrete with minimum reinforcing is the most economical of several possible systems considered for wall construction. Earth, supported by concrete arch structures provides the roof shielding for the experiment area.

The Mc^2 Cyclotron is an eight-sector, low-spiral, proton cyclotron. Two rf cavities between the sectors give four accelerations and a total energy gain of 1 MeV per turn; this large rate of energy gain is obtained without use of the expensive magnet gap space required for conventional accelerating structures. The vacuum chamber encloses the whole cyclotron, including the magnet. Some pertinent physical characteristics of the machine are as follows:

Beam energy	810 MeV
Mean orbit radius	230 in.
Central magnetic field	4,500 gauss
Maximum magnetic field	18,000 gauss
Magnet diameter	53 ft
Total power (magnet, rf, vacuum)	12 MW
Vacuum chamber volume	2.6×10^6 liters
Energy gain	1 MeV/turn

Experiments performed on the CERN synchrocyclotron and computer calculations were used to ascertain the hazards due to residual radiation in the Mc^2 complex. It is concluded that for the cyclotron the radiation problems are manageable, assuming efficient beam extraction and maximum use of graphite. Targets, slits, and beam stops are an additional problem which will require special shielding measures.

The cost of the cyclotron and its facilities are summarized as follows:

Buildings	\$ 5,067,000
Shielded area	8,288,000
Cyclotron	10,097,000
Ion optics	<u>5,167,000</u>
Sub-total	28,619,000
Engineering	4,293,000
Contingency and escalation	<u>9,777,000</u>
Total project cost	\$42,689,000

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1. INTRODUCTION

In the summer of 1962 we informed the Atomic Energy Commission through a special project status report, The Mc² Isochronous Cyclotron,* that a program of computation, technological study, and model experiments had shown that a relativistic cyclotron can be built that will deliver an extracted beam of about 100 μ A of protons at 810 MeV. We examined the usefulness of such a radiation source for research in nuclear structure, pion and muon physics, fundamental particle physics, and in radiological bio-medicine.

Since the cyclotron and the research complex that would surround it are very expensive, we have spent the past year in a complete re-examination of the scientific and technological problems as well as the costs of such an undertaking. In the following pages we present the results of this more critical study and now propose that such an accelerator be constructed at the Oak Ridge National Laboratory.

National Policy

This proposal is being submitted at a time when, once again, an overall national policy concerning new accelerators is being formulated. The Ramsey Panel,** which met earlier this year, concluded that high-intensity accelerators below 1 BeV, such as the Mc² Cyclotron, should probably not at the present time receive priority status among proposed new high-energy facilities. Nevertheless, there seems to be no doubt that excellent work related to high energy physics can be done below 1 BeV. The trend, on the other hand, is to ever higher energies, and the Mc² project goes counter to this trend.

*ORNL 3324, June 15, 1962.

**TID-18636 GAC/PSAC Panel on High Energy Accelerator Physics, April 26, 1963.

At this point, we must stress, as we have done in the past, that the Oak Ridge National Laboratory's central interest in the Mc^2 Cyclotron is for its capabilities for the study of the nucleus. This, rather than the interactions of elementary particles, will likely be the principal line of physics research. The Ramsey Panel has specifically stated that it did not consider the needs of nuclear physics in recommending against pion factories.

Subsequent sections in this report will develop the great promise that the Mc^2 Cyclotron holds for the investigation of nuclear structure by inelastic scattering and reactions with 810-MeV protons, and by mu and pi mesons.

Finally, the Ramsey Panel has purposely ignored the question of geographic distribution for the new accelerator sites. The argument, and it is a valid one, is that Brookhaven, Berkeley, or Chicago can be reached from any point in the country in a day's travel. Proximity, unless one is within an hour's automobile driving range, is probably irrelevant so far as the experimenters' access to a machine is concerned. There is, however, another side to this coin which is particularly applicable to the Oak Ridge location. A large accelerator installation has a great impact on the technical development and the progress of education in the region in which it is located, and which it serves. The South has long been underprivileged both in the growth of modern industry and in the ability to train its youth in the natural sciences. Clearly, the Mc^2 project alone will not change all this, but will help to develop new talent not only in the vicinity of the accelerator, but also at many Southern universities which would participate in the research.

Graduate Education

In this connection it may be of interest to note the extent to which the Oak Ridge National Laboratory is engaged in education and in collaborative research with universities in the South. (1) There are now 27 full-time graduate students, mostly from Southern universities, in residence at Oak Ridge and doing thesis research. We expect this number to quadruple in a few years. (2) About 100 students, both graduate and undergraduate, come to ORNL each summer to assist with research programs. (3) Sixty to seventy research participants, mostly staff members of the science faculties of Southern universities, do research at ORNL each summer. (4) There are about 50 post doctoral fellows currently at the Laboratory. (5) About 20 Laboratory staff members are part-time professors at the University of Tennessee, under a new Ford Foundation grant.

With these growing ties to the regional education community there can be little doubt that the Mc^2 accelerator facility would contribute effectively to the advancement of higher education in the underprivileged southern quarter of the nation.

Technical Competence at ORNL

The staff at the Oak Ridge National Laboratory has demonstrated its competence to design and build the Mc^2 Cyclotron, and upon its completion to employ it in a vital and fruitful research program.

A cyclotron design group has been in existence at ORNL since 1948. By tradition this group has concentrated on high intensity accelerators. Its achievements include: the highest energy fixed frequency proton cyclotron (before AVF); the first cyclotron built for the acceleration of ions heavier than helium; pioneering work in the theory and development of AVF cyclotrons; the construction of the Oak Ridge Isochronous Cyclotron and with it the development of a new generation of medium energy cyclotrons; theoretical and experimental work on Mc^2 , including the construction of two working electron analogues; and the invention of the separated-orbit

cyclotron. Competence has been developed in ion source design, high-power rf design and development, magnet design including modelling and testing, high vacuum techniques, and superconducting magnet design. Thus, an experienced organization is in existence which can efficiently undertake a large development and construction project such as the Mc^2 cyclotron.

By tradition and experience the research staff at ORNL is best equipped to use the Mc^2 Cyclotron as a tool for research in nuclear physics. In this field the Laboratory has contributed in many important ways in the past, and now enjoys the position of one of the leading research centers in nuclear physics in the world.

We will not list here the achievements of the Laboratory in nuclear physics: they are well known. However, it may not be equally well known that the Laboratory is actively engaged in the study of Auger processes, optical spectroscopy, and nuclear alignment, all of which have important potential for the Mc^2 Cyclotron research program. The Biology Division of ORNL will use mesons and high energy protons for biophysics research, and the Medical Division of the Oak Ridge Institute of Nuclear Studies will carry out bio-medical research primarily with stopped negative pions.

It appears inevitable that a high intensity accelerator located at Oak Ridge would be effectively and efficiently exploited both for nuclear physics and for other kinds of research.

Why the Mc^2 Cyclotron?

There are several kinds of accelerators which will produce intense proton beams with energies below 1 BeV. Why did we choose the Mc^2 Cyclotron?

First, there is a long tradition at ORNL in building cyclotrons. Then, by virtue of the two electron analogues it is believed that the acceleration problems are well understood and, most important of all, that deflection efficiencies in excess of 80% can be practically obtained. Because of the analogues, and extensive rf and magnet studies including model work, the problems connected with the Mc^2 Cyclotron are well in hand; only the usual problems of a large project are likely to be encountered.

We will not dwell here on the advantages and disadvantages of other accelerators: linacs, negative ion cyclotrons, or separated orbit cyclotrons. Suffice it to say that we have looked carefully at all of them, and that to us the Mc^2 Cyclotron seems the best choice.

The energy and current limits we propose for the Mc^2 Cyclotron have also been decided upon only after considerable study. A machine whose average deflected beam current is 100 μA would satisfy all the demands which our research program imposes on it. For nuclear physics research much lower intensities are needed on the target, but the requirement of very good energy resolution means that a large part of the beam must be discarded. This trading of intensity for energy resolution and beam purity holds for pions and muons as well as for protons.

The beam energy is really a three way compromise between cost, the advantages of higher energy, and the ability to extract a large fraction of the beam. In this way 810 MeV was arrived at, and it seems to be a satisfactory energy for the work which is proposed.

As a research tool, the Mc^2 Cyclotron has a recognized limitation: the proton energy is not variable. After some study it appeared to us that this was not serious, except possibly where extensive nucleon-nucleon scattering experiments are concerned. There, it would be advantageous to have data at as many energies as possible. For nuclear physics, the higher the energy the better, provided energy and angular resolution are not sacrificed. Mesons are produced with a continuous spectrum of energies, so the fixed proton energy is no disadvantage for any work with pions or muons.

When needed, the Mc^2 Cyclotron can be used to accelerate polarized protons directly, although provision has also been made to use scattering for the production of such particles. Polarized proton sources for cyclotrons are now under development, and will clearly be available when the Mc^2 is completed. Moreover, it has been shown that the passage of polarized protons through the azimuthally varying guide field of the cyclotron will not produce significant depolarization. As is shown in a later chapter, polarized protons will be required for nuclear physics research if all the possibilities inherent in the use of the impulse approximation are to be exploited.

The Medical Facility

When negative pions come to rest in matter, energetic stars result. This phenomenon was observed early, and suggestions were made that this process could be used to irradiate tumors by depositing large doses of radiation inside the body, while the entrance dose could be kept moderate on account of the low specific energy loss of a moving pion. A research program to investigate this avenue for treating cancer is proposed by the ORINS Medical Division. Negative pion beams from the Mc^2 Cyclotron would be available for this work.

At this writing it is by no means clear whether this method of cancer therapy could be made practical, even on a modest scale for humans. Much experimental work on animals is needed before a definite conclusion regarding the practicability for human patients can be reached. We, therefore, envision that the experimental work up to and including animal irradiations could be done in one of the three large shielded experiment areas. Then, if the results are promising, a separate medical facility is to be built which would satisfy all the clinical requirements involved when human patients are irradiated.

Provisions have been made in all plans to make the addition of the medical facility as simple and as economical as possible. The medical facility has been designed and cost estimated along with the other parts of the Mc² facility. The cost of the medical facility is not included in the initial cost of the project, however, since it will not be built at the same time. In the estimate of research costs, the medical program is included, and the required office and laboratory space is provided in the research building.

The Neutron Time-of-Flight Facility

The large neutron production rate achievable with 800-MeV protons, combined with the beam programming versatility of the planned ion injection system, give the Mc² Cyclotron a valuable capability for neutron cross-section studies by neutron time-of-flight techniques. Approximately 10 neutrons per incident particle are obtained from a heavy element target bombarded with 800-MeV protons. At a beam current of 100 μ A the average total neutron production rate is 6×10^{15} n/sec; due to the microstructure of the beam, however, the peak neutron rate is at least a factor of ten higher, 6×10^{16} n/sec. When operated in the pulsed mode, as required in this application, the accelerator is capable of peak currents at least another factor of ten higher, giving a peak neutron yield of 6×10^{17} n/sec. Pulse lengths variable from 1 to 15 nanoseconds at repetition rates up to at least 10^5 pulses per second will be available. This performance exceeds that of most existing installations.

The neutron facility is suggested as a valuable possible addition to the Mc² research complex. It is not intended to compete with the High Intensity Short-Burst Linear Accelerator proposed for ORNL. In this respect the capability of the proposed electron machine exceeds that of the Mc² facility, and it could be made available several years earlier.

The Structure of the Report

In subsequent chapters of this report the fields of research made possible by the Mc^2 Cyclotron are outlined, the successful extraction of the electron beam in the Cyclotron Analogue and the results of other development work are summarized, the plans for the facility are described, and the final cost estimates are presented.

The production of secondary beams, an analysis of the proposed experimental programs, and the plans for beam analysis and beam piping are described in Chapters 2, 3, and 4 respectively. Chapter 5 is a brief account of the very successful beam extraction studies on Analogue II. Residual radioactivity and special target and slit shielding requirements are reviewed in Chapters 6 and 7. Chapter 8 gives a summary of the design concepts of the Mc^2 Cyclotron including the injection system, while Chapter 9 pertains to the details of magnet design, including recent results from model tests. Chapter 10 discusses the radio-frequency system for the machine and gives results from experiments with test models. Chapter 11 describes the methods used for estimating the shielding thicknesses required. Preliminary architectural plans for the facility are presented in Chapter 12. Chapter 13 summarizes the substantial amount of work undertaken in preparing the cost estimate. Chapter 14 reviews the project schedule. Appendix A contains an outline of cyclotron theory, a description of the Cyclotron Analogue II, and some recent measurements on its performance. Appendices C, D, E, and F describe the proposed site, a preliminary estimate of personnel requirements, structural analysis of the buildings and shielding and some details of cost estimating. The many contributors to this report are listed immediately following the table of contents.

2. Mc^2 CYCLOTRON BEAMS

The cyclotron under consideration is designed to provide an intense extracted beam of 810-MeV protons. The high flux of 810-MeV protons will in turn make it possible to produce secondary beams which will make the machine a most useful tool for many kinds of research.

Secondary beams include pi mesons, mu mesons, neutrons, neutrinos, and partially or totally polarized particles. The particles expected from the Mc^2 cyclotron for typical energy regions and with a useful angular divergence are tabulated below:

Particle	Energy (MeV)	ΔE (MeV)	Solid Angle (steradian)	Particles/sec
Proton	810	0.5	—	6×10^{14}
Polarized proton*	~ 800	2	5×10^{-3}	10^{10}
Neutron	> 100	—	—	$2 \times 10^9 / 100 \text{ cm}^2$
π^+	100-400	1	5×10^{-3}	$10^8 - 10^9^{**}$
μ^+	50-400	1	5×10^{-3}	$10^6 - 10^7$
Neutrino	broad band	—	—	$2 \times 10^7 / \text{cm}^2$

* Polarized protons in this table are obtained by scattering. The intensity and quality of protons from a polarized ion source is expected to be much better.

** The π^0 ^{yield} ~~beam~~ is probably 50% of π^+ intensity; the π^- is 15% of π^+ intensity.

For specific experiments the desired and necessary requirements on the beam may vary considerably, even though the experiments require identical particles at some energies. Both "good"-geometry and "poor"-geometry pion beams are required. The latter is needed, for example, to produce an intense muon beam. To achieve high resolution a sacrifice in intensity may be necessary. Thus, it becomes clear that no single beam-optics arrangement can be used as a permanent set up for all experiments with any given particle. Similarly, the characteristics of a beam cannot be specified, except for general considerations of the capabilities with this cyclotron.

Data for estimating beam characteristics were obtained from reports on the 970-MeV synchrotron at Birmingham, the synchrocyclotron at Dubna, and from other sources.

Proton Beam

The cyclotron will accelerate protons to 810 MeV, with an extracted beam intensity of 100 μ A. From experiments on Cyclotron Analogue II it appears that the emittance of the extracted 810 MeV proton beam will be between 20 and 80 mm mrad.

Pion Beam

The threshold for single- π production by protons on a single nucleon is at 290-MeV proton energy; higher proton energies must be attained, however, before the yield reaches a useful value. Two- π production starts at 600 MeV, and three- π at 935 MeV. For bombardment of heavy nuclei the threshold is lower, due to the Fermi motion of the nucleons inside the nucleus. Although two- π production will be energetically possible for the 810-MeV cyclotron, the yield will be negligible compared with single- π production.

The maximum pion energy possible (with Fermi momentum) is 520 MeV for 810-MeV protons; the shape of the expected yield curve is shown in Fig. 2.1. This shape is not affected by the material of the bombarded target. However, higher yields will be available from higher-Z targets, the dependence being $A^{2/3}$.

Yields of π^+ and π^- mesons obtainable from the beam will differ considerably. According to the isobaric nucleon model one expects the ratio of mesons to be $\pi^+ : \pi^0 : \pi^- = 11 : 6 : 1$ for a target nucleus with equal number of protons and neutrons. In practice, a ratio of $\pi^+ : \pi^- = (7 \pm 1) : 1$ is expected from light targets.

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Fig. 2.1. Estimated π^+ flux for 810-MeV protons incident on carbon, for a 2-MeV energy spread and a solid angle of 4.5×10^{-3} sr.

A 100- μ A proton beam on a 10-cm thick carbon target is estimated to yield a π^+ flux of $1.0 \times 10^8/\text{s}$ at 45° for a pion energy of 310 ± 2 MeV, into a solid angle of 4.5×10^{-3} steradians. The yield vs energy is shown in Fig. 2.1. The maximum pion intensity does not occur at 45° , however. For example, at 970 MeV the intensity at 20° is about 5 times, and at 10° about 10 times, its value at 45° for the solid angle used above. In addition, a pion beam of higher momentum is obtained at the smaller angles. Therefore, it is not unreasonable to expect from the proposed machine a π^+ beam of 150-300 MeV kinetic energy and with $\Delta E = \pm 1$ MeV and an intensity of 10^8 to $10^9 \pi^+/\text{sec}$.

Negative pion beams will be produced in a manner identical to that for the π^+ beam. Since with an external proton beam there is no problem of momentum and charge analysis by the fringing field of the accelerator, one can switch from π^+ to π^- simply by reversing the polarity of all magnets involved. The expected π^- intensity will be lower by a factor of about seven.

Muon Beam

A muon beam cannot be produced in a target, but must result from the decay of pions. Consequently, muons originate from an extended source, and will form a beam at a small angle to the pion direction. For 400-MeV pions the decay length corresponding to the pion lifetime is 30 meters; thus, unless the decay path is very long, only a fraction of the pions can contribute to the muon beam.

For monoenergetic pions of momentum p , the lab-system momentum of the muons is distributed almost uniformly over a momentum band from $0.6 p$ to slightly above p . Thus, to obtain a muon beam having a momentum in an arbitrary momentum band within the above limitation, one selects the pion beam with as wide a momentum range as possible just above the momentum band of the desired muons. From a 250-MeV pion beam ($p_\pi = 365$ MeV/c) with a decay path length of 15 meters one could obtain a muon beam with a momentum of 220 ± 1 MeV/c and with an intensity of about 0.1% of that of the pion beam.

One must remember that for certain experiments the purity of the muon beam is required to be very high. Thus, for studies of nuclear interactions with μ^- it is desirable to have less than 0.01% pion contamination. Even at this high purity the number of events due to muons and to the contaminant pions will be comparable. With good beam optics and a long additional path length the beam purity can be increased without great loss in muon intensity, since the decay length for 400-MeV muons is close to two miles. Use of counter arrays and absorbers can in some instances increase the effective beam purity by as much as a factor of 1000.

Neutrino Beam

The neutrinos from pion decay can be utilized to study the weak interactions. The maximum intensity is at zero degrees and is independent of the pion momentum (except of course for $p_\pi = 0$). For 250-MeV pions roughly half of the neutrinos lie within 20° of the beam direction and have energies greater than 85 MeV. Let us assume for the purpose of a calculation that the neutrinos are parallel to the pion beam and that the pion beam is focused by an 8-in. quadrupole subtending a solid angle of 4.5×10^{-3} radians at the target. For a pion flux of $5 \times 10^8/\text{sec}$ MeV, and if the quadrupole or system of quadrupoles can focus a pion beam with a 50-MeV energy spread into a beam which will remain parallel over a distance of 30 meters (1 pion decay distance) the neutrino intensity at the target would be about $1.5 \times 10^7/\text{cm}^2\text{-sec}$. It should be recognized that the estimate is extremely optimistic. It indicates, however, that neutrino experiments will probably be feasible with the proposed machine.

The neutrinos from muon decay are very rare particles. They can only be obtained from intense, low energy, muon beams such as are produced by the Mc^2 cyclotron. Although fewer in number than the pion-decay neutrinos, they may, by improvements in detectors, become proper subjects for experimental study.

High-Energy Neutron Beam

Neutron beams can be obtained from targets placed in the external proton beam of the cyclotron. A typical setup may consist of a 3-in. thick neutron-producing beryllium target, with the emergent neutron beam defined by concrete and lead collimators and cleaned of charged particles by a magnet placed close to the target. It may be desirable to eliminate charged particles produced in the collimation by a second magnet. A high flux of γ -radiation will, of course, contaminate the beam and must be reduced through the use of lead filters. It may be necessary to deduce the neutron effect from measurements with at least two different filters. (The collision mean free path in lead is 13.8 cm and the radiation length is 0.51 cm.)

A considerable fraction of high-energy neutrons, almost equal in energy to the incident proton energy, will come off near zero degrees. The spectrum contains two broad (~ 150 -MeV) maxima superposed on an intense continuum. Energy resolution of such a neutron beam is not possible unless some means of discrimination for either the neutrons or the neutron-produced particles is provided. For example, for (n, p) elastic scattering measurements a filter can be used in front of the proton detector to accept only the upper end of the neutron spectrum. These methods, however, only ignore part of the beam rather than eliminating it, and, hence, do not reduce the background originating from neutrons of undesired energies.

Pulsed Low Energy Neutrons

The Mc^2 Cyclotron beam can be used to provide a powerful source of pulsed neutrons for nuclear structure studies by neutron time-of-flight spectrometry. The time-averaged yield of evaporation neutrons for 100 μA of protons on a heavy element target is 6×10^{15} n/sec, for 10 neutrons per proton. The peak yield is about a factor of ten higher because of the fine structure of the beam. When the injector is operated in the pulsed mode, as required for neutron time-of-flight work the accelerator is easily capable of a factor of ten higher output; then a peak neutron rate of 6×10^{17} n/sec is available. Because of

the unique injector system, see Chapt. 8, the effective duty factor can be adjusted over a wide range. The pulse width can be varied in the range 1 to 15 nanoseconds, the repetition rate varied from a few to more than 10^5 pulses per second.

For the production of pulsed neutrons in the energy range from 10^4 to 10^7 eV the performance described above exceeds that of existing pulsed neutron sources and is competitive with most proposed devices. The performance of the Mc^2 system will be exceeded by only the most powerful electron linear accelerators.

For the neutron time-of-flight facility, described in Chapt. 12, the development of a beam sharing system is envisioned to avoid direct competition with other research. It may be possible to develop a pickoff system to direct individual pulses of the microstructure of the beam to the neutron production target. This would permit nearly continuous use of the neutron time-of-flight facility without appreciable effect on other experiments since one pulse in every hundred, at most, is required for neutron production. The intensity of the injected beam can be programmed at the source to satisfy simultaneously the beam intensity requirements for both neutron production and for other experiments.

Polarized Proton Beam

A polarized proton beam can be obtained either by starting with a polarized proton beam source, prior to acceleration, or by scattering the initially-unpolarized beam.

To use a polarized ion source it is necessary to determine whether the polarization can survive the acceleration process. Since the Mc^2 Cyclotron makes use of azimuthally varying fields, it is possible that ions off the median plane can interact with fields of the proper frequency perpendicular to the spin-vector, leading to depolarization. Calculations were made to determine the presence of such depolarizing resonances and their net effect. It was found that there are no important intrinsic resonances. While resonances due to sector imperfections and displacement of the median plane are possible, gross misalignments and/or large axial amplitudes would be necessary to excite them.

It is also possible to use the diffraction scattering of protons on nuclei as a source of polarized protons. At these energies the protons are concentrated in a narrow forward cone with an angle of $2\lambda/R$ and with a maximum energy close to the incident energy. (λ is the reduced wavelength of the proton, R the radius of the target nucleus.) The maximum polarization of protons produced by scattering from beryllium is about 60%, and is largely independent of energy. Of the two methods, the acceleration of pre-polarized protons will most probably be used.

3. RESEARCH PROGRAMS

The research programs of the Mc^2 cyclotron can conveniently be divided into four categories:

- A. Nuclear Structure
- B. Elementary Particle Interactions
- C. Biological and Medical Research
- D. Applied Research

The cyclotron will have two principal advantages over existing machines. It will have about 100 times the intensity, and the experimental facilities will be designed to take advantage of this by providing high-quality beams of various particles to well shielded areas. High intensity without a carefully planned and well equipped experimental layout would be wasteful.

In what follows we describe some proposed fields of research which may be performed with the cyclotron. Obviously, not all of them can be attacked with equal vigor; the emphasis they receive will depend largely on the state of science when the machine is completed. One can, however, discern two kinds of research even now: one includes specific experiments of particularly great interest, the other is programmatic research. Some experiments mentioned below which are in the former category may have been done by the time this cyclotron operates, but almost certainly vast areas of research will remain in the latter group. To give an example: in π -nucleon scattering the present ambiguity as to which of four sets of phase shifts at 310 MeV is the correct set may be resolved within the next five years by a laborious measurement, with an existing machine, of one of the triple scattering parameters; but the solution of this problem will stimulate the demand for further related information, and the whole field of π -nucleon scattering will present great opportunity for creative and important investigation for years to come.

A. Nuclear Structure

The primary proton beam as well as the beams of polarized protons, neutrons, muons, and pions are appropriate particles with which to study nuclear structure. Beam requirements are most stringent here; good energy resolution, $\Delta E < 1$ MeV, is necessary to perform meaningful measurements.

High-energy protons, when used as a nuclear structure probe, have the fundamental advantage of a short de Broglie wave length, that is, a wave length small in comparison with the spacing of the nucleons in a nucleus. Several consequences follow from this property. First, the scattered wave can be treated as the sum of waves scattered from individual nucleons. Second, the impulse approximation becomes valid, which means that the scattering from each nucleon in the target occurs as if it were free, and thus the scattering amplitude is just the one well known from nucleon-nucleon scattering experiments. Thus, we actually know the interaction, a situation which contrasts with that at lower energies where we have to mock up the interaction by constructing nuclear models. The complicating effects of multiple scattering and distortion are minimized. Indeed it is the last mentioned effect which supports the requirement for high energy; the proton wave length is small even at 185 MeV, but the distortion there affects the cross section by a factor of ten. This is lowered to a factor of two at 300 MeV, and becomes about a 20% effect at 810 MeV. The well-known disadvantage of working at high energies, the compression of the cross section into a forward cone, is still manageable at this energy.

Inelastic Proton Scattering

Inelastic proton scattering is the simplest of all proton-nucleus interactions, from the theoretical standpoint. The impulse approximation leads to a transition amplitude T between the ground state and n 'th excited state:

$$T = \sum_i \langle \chi^{(-)}, n \quad t_i \quad \chi^{(+)}, 0 \rangle ,$$

where t_i is the free nucleon-nucleon scattering amplitude which depends on spin and isospin. The χ 's are the incident and outgoing waves, and the sum is performed over all i particles in the nucleus. When the scattering amplitude is integrated over the nuclear wave function, nuclear form factors are obtained. In other words the matrix element $\langle n | t_i | 0 \rangle$ Fourier transforms into effective nuclear form factors. A successful nuclear theory then must lead to precisely these form factors.

The scattering amplitude, t_i , is a function of the spin and isotopic spin, and has to be expressed, in general, in terms of ten form factors. This complexity is due to the nature of the nucleon-nucleon interaction, and might at first sight seem to present serious obstacles to the interpretation of inelastic scattering experiments. If, however, one is prepared to perform complicated experiments, involving polarized incident protons, and measurement of the polarization of outgoing particles, the complexity of the problem turns out to be an advantage. It is the richness of the amplitude t_i which makes the inelastic scattering such a sensitive probe of nuclear structure.

It may be added here, that a similar experiment can be performed with pions, but that on account of the zero spin of the pion only four of the ten form factors appear in the expression of the scattering amplitude. In addition the pion-nucleon amplitudes are not as well known as the nucleon-nucleon ones.

Finally there is the possibility that the inelastic scattering experiment can be, so to speak, turned around to investigate the nucleon-nucleon interaction. In some cases where the selection rules are quite restrictive we may have enough confidence in our understanding of nuclear structure to use the experimental results to derive the effective interaction between the projectile and a target nucleon, and to test the assumption that it is the same as between free nucleons.

Nuclear Reactions

In principle, nuclear reactions such as $(p, 2p)$, (p, d) , (p, t) , and (p, pa) are no different from inelastic scattering. They are here discussed separately because their interpretation is perhaps not so clear-cut, and because the information obtained is in terms of nuclear models, rather than a deep theoretical understanding. In fact, high energy protons even now provide ever increasing amounts of information about low-lying states in light nuclei.

Highly monoenergetic protons from the proposed cyclotron would provide a valuable probe of nuclear shell structure, pair correlations, and cluster effects. The advantage of the high energy again lies in the fact that the impulse approximation becomes valid. The high-energy protons probe the nucleon bound states by knocking out single nucleons, e. g., $(p, 2p)$ and (p, pn) reactions, or by picking up a single neutron, e. g., (p, d) reactions. Clusters can be investigated by knockout processes, (p, pd) and (p, pa) , for example.

Although the value of high-energy proton nuclear collisions for probing nuclear structure has been recognized for some time and a general description of the reaction mechanisms has been given, experiments up to the present time have been done with poor resolution and are limited to the lightest elements. At 810 MeV protons provide a clean probe of shell structure. There are fewer complications in the reaction mechanism, e. g., due to distortion effects and to the possibility of interacting with more than one nucleon. This feature may make possible the acquisition of new information on some fine details of nuclear structure. For example, in low-energy (p, d) experiments it is not always clear whether some of the less strongly excited states are reached directly through the reaction mechanism, or whether they are produced only because they are inherently connected through nuclear structure with the states directly associated with the removal of a neutron. Comparison of high- and low-energy data should shed light on this point. There is, however, no apparent need for a continuously variable energy.

Probably sufficient information could be obtained by using the proposed 810-MeV cyclotron for the high-energy data and comparing these results with a few experiments done with other existing machines. It might be said that one well-understood probe is more valuable than several poorly-understood probes, and the high-energy protons should constitute a well-understood probe.

Another kind of information can be obtained from (p, 2p) experiments. The incident proton of momentum k_0 impinges on a light nucleus, say Li^6 , and two protons of momentum k_1 and k_2 are observed at angles θ_1 and θ_2 respectively. In all cases so far studied $k_1 = k_2$, $\theta_1 = \theta_2$, and k_0 , k_1 , and k_2 are coplanar. A typical energy spectrum from such a reaction is shown in Fig. 3.1 for $\theta_1 = \theta_2 = 30^\circ$. The high energy peak is interpreted to be due to quasi-free scattering of the incident proton from a p-proton, and the lower-lying peak from an s-proton. Angular distributions support this assignment. The information gained from this kind of experiment is very valuable, and is not now obtainable in any other way. First of all, there is the unique evidence on the shell structure of nuclei, the energy differences between shells, and the variations from nucleus to nucleus. Second, there is good reason to believe that correlation curves will lead to a determination of the nucleon momentum distribution in the nucleus, a very important piece of data.

Of particular interest to the Brueckner theory would be a detailed determination of the nucleon-nucleon pair correlation function, to be compared with predictions of, say, the Bethe-Goldstone equation. This function can be obtained as the Fourier transform of the diffraction pattern in the angular distribution of inelastic scattering corresponding to excitations up to a few tens of MeV. For this experiment levels need not be resolved so that heavy nuclei, representative of "nuclear matter", could be studied. High intensity would be useful in the necessary elimination of exactly elastic events by demanding coincidence with gamma rays indicating nuclear excitation. Also one may search for "giant" collective resonances. The high intensity permits p, p'- γ correlation and p' polarization experiments yielding more detailed information.

Fig. 3.1. An energy spectrum typical of (p, 2p) reactions.

Nuclear Physics with Mesons

Both π and μ mesons can be used to probe nuclei. They are quite different because, although both interact with nuclei via electromagnetic interactions, the pion also interacts via a strong interaction whereas the muon interacts via a weak interaction. The experiments which can be done fall into two classes: scattering experiments and bound-state (mesic atom) experiments. In scattering processes, in which the probe is near the target for a short time, the strongest interaction available dominates the others. Thus, pion scattering from nuclei is due to the strong Yukawa interaction but muon scattering is produced by the electromagnetic interaction. In mesic atoms, just as in ordinary atoms, the electromagnetic interaction gives rise to the capture of the meson into outer atomic orbits, and also to atomic transitions, accompanied by X-rays and Auger electrons, in which the meson comes nearer to the nucleus. Finally, the meson either decays or is absorbed by the nucleus. The capture of a pion is brought about by its strong interaction with nucleons whereas a muon is absorbed weakly.

Nuclear reactions leading to excited residual nuclei can be initiated by energetic pions and by stopped muons or pions. One can examine these reactions either by looking at scattered particles and energetic decay products or by examining the residual nuclei by radiochemical means. The latter technique defines an area of research, nuclear chemistry, under which heading it will be convenient to discuss many of the meson-induced nuclear reactions. The discussion of studies of nuclear reactions by measurements of cross sections or angular correlations will, on the other hand, be included below under various headings pertaining to the different kinds of mesonic processes.

π Meson Scattering. - Since pions have no spin, the amplitude for pion-nucleus scattering is much simpler than the amplitude for nucleon-nucleus scattering. This fact, together with the possibility of charge exchange scattering, makes pions a most interesting projectile for testing the high-energy optical model. Good elastic scattering differential cross-section measurements would be compared with the predictions of optical potentials calculated from the basic pion-nucleon potential along the lines of Watson's multiple scattering theory. The higher energy available with the Mc^2 cyclotron would improve the validity of the impulse approximation in comparison with Rainwater's earlier work at 80 MeV.

Inelastic scattering measurements would also yield important information complementing that from proton inelastic scattering. Knock-on $(\pi^-, \pi^- p)$ reactions have been studied at the Berkeley 184-in. cyclotron. As with $(p, 2p)$ reactions, measurements of these meson reactions at higher energy should become a powerful tool. With high intensity, the $\pi^- - p$ angular correlation and the proton polarization could be measured.

Cross sections for π -nucleon and π -two nucleon reactions will also give direct information about nuclear structure.

π Mesic Atoms: Nuclear Absorption. - Pion absorption leading to one-nucleon emission is forbidden by energy-momentum conservation and the low Fermi momentum, $\sim 250 \text{ MeV}/c$, in nuclei. Consequently, pion absorption leads mainly to two-nucleon emission. Photon absorption also gives rise predominantly to two-nucleon emission, but its usefulness is impaired by poor energy resolution (bremsstrahlung). The pion, on the other hand, is absorbed from a rather sharp bound state.

The nuclear excitation energies will be reflected in the total energy of the two emitted nucleons. Moreover, the two-nucleon momentum distribution in the nucleus will be obtainable from the angular correlation of the two nucleons.

Polarized Muon Scattering from Nuclei. - Although the intensity of the muon beam would be too low to compete seriously with unpolarized electron scattering in measuring nuclear charge distributions, the muon beam has the advantage of being already polarized. Its intensity would be considerably greater than the intensity of polarized electrons which could be obtained from existing electron beams. The polarized muon beam could be used to measure nuclear magnetic moment distributions, an important subject which has not as yet been explored.

Nuclear Quadrupole Moments from Mesic Atom Spectroscopy. - Mesonic orbits lie inside the nuclear radii of all but the lightest nuclei. If sufficient intensity were available, mesic atoms could provide a novel probe of nuclear shapes by means of X-ray line splittings. This possibility is included in a discussion of mesic atoms in Section B, below.

Muon Absorption in Complex Nuclei - Once the muon absorption interaction is well understood (see Section B, below) the muon capture process in complex nuclei may be used to obtain nuclear structure information much like that from electron capture. Because of the large muon mass specific new transitions, not at all available in β -decay or K-capture, can be investigated. The matrix elements for these transitions should provide interesting new data for nuclear theorists.

Nuclear Chemistry with Mesons

A strong program in what is currently called nuclear chemistry can be established with the beams available from the cyclotron. (Nuclear chemistry differs from nuclear physics principally by the fact that the former usually studies the residual nuclei in a reaction, and the latter the scattered particle or energetic light products.) Separation and identification of the residual nuclei following a pion interaction can reveal the type of reaction. For example, Te^{123} obtained from an I^{127} target bombarded with π^- can only result from $\text{I}^{127} (\pi^-, 4n) \text{Te}^{123}$. Such information would supplement cloud chamber and emulsion data as well as the results of counter experiments in the investigation of nuclear cascade or fragmentation processes.

The bulk of the nuclear chemistry work has been done at the University of Chicago by Turkevich, Sugarman, and collaborators. Relative yields for π^- induced reactions were measured for N, O, Zn, Br, As, and Hg. Large targets, of the order of kilograms, were used to stop all the mesons. Reactions such as (π^-, xn) , (π^-, xp) , and $(\pi^-, xpyn)$ were found. Te^{127} was found in reactions with I^{127} , which may result from a $\pi^- - \pi^0$ charge exchange process.

Intense pion beams would make a whole new class of experiments possible. Cross sections could be measured precisely at various energies for a number of interesting reactions, such as the charge exchange reaction mentioned above. Differences between π^+ and π^- induced reactions could be investigated. Past experiments with emulsions suggest that (π^+, n) reactions are much less probable than (π^-, n) . In fact π^+ "no prong" events are not seen. These experiments should be repeated with nuclear chemistry techniques since one would expect (π^+, n) events to occur in analogy to (p, n) reactions.

So far, very little work has been done on pion-induced fission, all with loaded emulsions. Intense pion beams would make several classes of experiments feasible. The "classical" fission measurements: cross sections, total yields, independent yields, fission-spallation competition, could be done. Muon-induced fission, for example, also presents some tantalizing possibilities. Although it might be assumed that fission would follow μ^- capture, Zaretsky has suggested that nuclear excitation as a result of the $2p - 1s$ μ -mesonic atomic transition can cause fission. This mechanism could be distinguished from the absorption-fission process, since a 5-6 MeV γ -ray would follow μ -capture.

Neutron Spectroscopy

Pulses of neutrons with energies from a few eV to several MeV will be available at the Mc^2 facility. Programmatic research with these particles, involving measurements of the total and differential cross sections, should be of considerable importance. Aside from the applied aspects relevant to the choice of reactor materials, the program would be of fundamental interest for the study of the nucleus. The measurements of nuclear level spacings and other properties of well resolved levels, especially those of spins higher than zero, are expected to be of continuing importance to the development of nuclear physics.

B. Elementary Particle Interactions

The Mc^2 cyclotron can be used to produce a variety of elementary particles in great numbers. The study of the interactions among these particles constitutes one of the most fundamental and important fields in physics. The basic interactions fall into three classes: the strong "Yukawa" interactions, responsible for nuclear forces and the complex internal structures of the "elementary" particles; the electromagnetic interactions; and the weak "Fermi" interactions which produce the slow decays of the unstable particles.

At least two stages in the investigation of these topics should be distinguished. Broadly speaking the first or kinematical stage consists of the discovery of the particles, of the basic processes they undergo, and of the quantum numbers and symmetry properties governing them. This glamorous task has already been accomplished for the non-strange particles, and is being accomplished for the strange particles at high energy accelerators. The second stage consists in the attempt to really understand the dynamics of the fundamental processes. The desired information does not lie so near the surface and apparently can be obtained only by a laborious inferential process. The classic examples are the study of the nucleon-nucleon interaction and of the beta decay interaction.

For detailed understanding of elementary particle dynamics there are two main needs. First, a high degree of precision, such as has been achieved in low energy nuclear physics, but has not often been possible at high energy. Precise measurements would not be made merely to add another decimal to an already known value. It is to be expected that for the strong and weak interactions, just as in the case of quantum electrodynamics, there will be many instances where improved precision will be decisive for the success or failure of a theory. The second important need is completeness, that is, the ability to perform all of the different kinds of experiments which can give complementary information bearing on a given interaction. For example, to obtain unambiguous phase shifts for the strong interactions one needs not merely differential cross sections but also polarization measurements, often in considerable variety.

The Mc^2 cyclotron will enable one to achieve improved accuracy and to do more difficult experiments by virtue of the high beam intensities. It will be possible to use thin targets, high resolution detectors, and to observe very improbable events.

Strong Interactions

Even after thirty years of extensive study, nucleon-nucleon scattering still continues to furnish valuable new information concerning nuclear forces. Major advances in experimental techniques during the past decade have made possible polarization, triple-scattering, and spin-correlation experiments. These in turn have led to refinements in the phenomenological phase-shift analyses used to fit the energy dependence of the data. The phases thus obtained have been interpreted by theories which can be categorized according to whether they employ phenomenological potentials, meson-theory, or dispersion theory. The first approach has been the most explored to date, but the last holds the highest hope for success.

The threshold for pion production by nucleon-nucleon collisions is about 290 MeV, but the cross section is sufficiently small below about 400 MeV to be neglected in the nucleon-nucleon elastic scattering analysis. At higher energies, interest centers in the ratios of pion production for the various isotopic spin states, because of the direct evidence for charge symmetry and charge independence of nuclear forces.

Analogously to nucleon-nucleon scattering, the corresponding pion-nucleon experiments can give insight into the basic π -p and π -n interactions. For many years measurements of the differential cross sections and polarizations have been made with the aim of obtaining a unique set of phase shifts in the region below the threshold for meson production. Charge independence has been tested at successively higher energies. More recently, isobar models, final-state interactions, the concept of peripheral interactions, and π - π resonances have assumed prominence.

The further development of experimental techniques, e. g., polarized targets and beams, spark chambers, and higher magnetic fields, seems promising enough to indicate that the precise systematic measurements characteristic of low energy nucleon-nucleon interaction studies can be extended up to a BeV.

Nucleon-Nucleon Scattering. - It is possible to completely describe nucleon-nucleon scattering in terms of a scattering matrix. The initial and final spin-space density matrices each depend upon 16 independent real scalar parameters. This means that in principle 256 experiments could be performed on the nucleon-nucleon system at a single scattering angle for any given energy. Fortunately, the assumptions of invariances under rotations, space-reflection, and time-reversal, provide relationships between the observables which reduce the number of independent experiments to 9 for the p-p system and 11 for the n-p system (9 also if charge independence is assumed). With the unitarity condition for the scattering matrix, integral relationships are obtained that, for elastic scattering, reduce the number of independent angle-dependent functions at each energy to 5 for the p-p system and 6 for the n-p system. At energies where inelastic scattering is possible, the unitarity condition involves additional states, and the last reduction does not hold true.

In general, more than the minimum number of experiments are essential, chiefly because the dependence of phase shifts on S-matrix elements is not linear and consequently multiple solutions easily arise. Additional experiments are also desirable both to check the theoretical assumptions and to detect possible systematic errors in the measurements. The simplest measurements to make are the total and differential cross sections for an unpolarized beam. These have been made, up to several BeV, for the p-p, n-p (p-n), and n-n (n-d) systems.

Next in complexity are the so-called double scattering experiments in which the beam is polarized in the first scattering and analyzed by the asymmetry in the second scattering. The polarization parameter P thus obtained has been measured for the p-p and n-p systems at selected energies up to about 1.7 BeV. However, the precision of the data, particularly for the n-p scattering, could be considerably improved with either a polarized ion source or higher beam intensities.

Triple scattering experiments require a first scattering to polarize the beam and the third scattering to analyze the beam. It is the intermediate scattering involving the Wolfenstein parameters which is of interest. The depolarization parameter D occurs for coplanar scattering, the rotational parameters R and R' are obtained with the second scattering plane perpendicular to the first, and the longitudinal parameters A and A' are studied by precession of the spins in magnetic fields. These five measurements have been made for the p-p system at 90, 140, 210, and 310 MeV. Measurements on the n-p system are in progress at 140 and 210 MeV. This type of data should be extended in energy and precision.

Finally, the spin-correlation parameters involve the simultaneous measurement of the polarizations of both outgoing nucleons. Only the C_{nn} and C_{kp} parameters for the p-p system have thus far been measured (at 310 to 650 MeV), and only in a very small angular range. Spark chambers can greatly increase the detection efficiency, and a polarized target would greatly increase the effective angular range.

The scarcity of data, particularly above 400 MeV, makes clear the importance of further work at higher energies. Higher energy is an experimental advantage, for the slight decrease in efficiency of measuring polarization on the high energy side is overcompensated by the ability to go to larger angles before encountering the rapid fall off on the low energy side. The presence of inelastic scattering leads to the complication of complex phase shifts with a resultant increase in the number of parameters to be determined. Recent calculations indicate, however, that at 660 MeV the phase shifts for $J > 5$ are essentially real. It seems relatively certain that the usefulness of accurate determination of nucleon-nucleon scattering parameters extends throughout the energy range of the cyclotron.

It would be useful to perform complete sets of measurements at several energies at the same laboratory to systematically study the nucleon-nucleon interaction. Experiments thus performed should lead to greater consistency in the data than would be expected from measurements obtained from several locations. Of course, duplicating experiments should be done where possible to check on possible errors.

Single Pion Production Experiments. - A number of pion production experiments from nucleon-nucleon collisions have already been performed with protons in the energy range from 400 to 900 MeV. The total inelastic cross sections have been measured at several energies for the following reactions:

(1) $p + p \rightarrow \pi^+ + n + p$	(5) $p + n \rightarrow \pi^+ + n + n$
(2) $p + p \rightarrow \pi^0 + p + p$	(6) $p + n \rightarrow \pi^- + p + p$
(3) $p + p \rightarrow \pi^+ + d$	(7) $p + n \rightarrow \pi^0 + d$
(4) $p + n \rightarrow \pi^0 + p + n$	

In addition, the branching ratios (2):(1), (3):(1), and (3)+(5)+(6):(2)+(4) have been investigated in some detail. It is expected that further experimentation in the next few years will greatly reduce the uncertainties in many of the above cross sections and branching ratios.

Experiments measuring the energy spectra of mesons in the reactions (1), (2), (5), and (6) above have also been undertaken at several energies and pion production angles. Pion energy analysis of reaction (4) has not yet been studied nor has an attempt been made at the energy analysis of the outgoing nucleons.

Angular distributions integrated over energy have been measured for the neutral pion in reactions (2) and (4) at 660 MeV. Some experiments of this type have also been done with the outgoing nucleons and charged pions. However, angular distributions of the outgoing particles at a given energy have not yet been made. Such experiments would require high intensity beams even for p+p experiments, not to mention the p+n experiments.

Polarization of the deuteron in reaction (3) above has been measured at 670 MeV at several angles. Further work of this nature may be expected in the next few years, as it has become increasingly evident that polarization experiments aid in the resolution of certain ambiguities. However, due to their difficulty, slow progress can be expected with the presently available proton beams. Polarization measurements on the outgoing neutron and proton have not yet been attempted. In addition, pion production experiments with polarized nucleon beams are of great theoretical interest. Both the asymmetry of the pion production and the polarization of the outgoing nucleons should be examined.

In general, most of the experimental work on single-pion production agrees with Mandelstam's phenomenological theory. The resolution of some of the existing discrepancies will be aided by further experimentation. Almost all of the above-mentioned experiments would be expedited by a higher intensity beam than now available.

Pion-Nucleon Scattering. - Two complex functions of scattering angle are sufficient to specify the scattering matrix for elastic pion-nucleon scattering below the inelastic threshold. Allowing for an arbitrary overall phase, one concludes that three experiments at any angle completely determine the scattering matrix at that angle and energy. Unitarity implies that only two independent experiments need to be done for all angles. The simplest experiments are the measurement of the differential cross section and final proton polarization.

In the most comprehensive experiment to date, an attempt was made to obtain S, P, and D wave phase shifts at 310 MeV where the inelastic cross section is less than 1% of the elastic. Measurement of the polarization was limited, however, by the analyzing power of carbon to angles such that the proton energy was greater than 90 MeV. As a result four sets of phase shifts are in contention. The ambiguity could be eliminated by measurement of one of the triple scattering parameters which would be relatively easy with a high-intensity pion beam. Although the ambiguity might also be resolved by improvements in the technique for detecting polarization, it is expected that triple scattering data would

have considerable value. Because of the non-linearity of the phase-shift equations, and because of the large uncertainties in the data, it is desirable to over-determine the parameters where possible. In particular, it is noted that in some cases the phase shifts may be more sensitive to a triple-scattering parameter than to $P(\theta)$, especially in regions where $P(\theta)$ is small.

An improved method of phase-shift analysis, incorporating a peripheral interaction treatment of elastic and inelastic processes in the higher angular momentum states gives promise that π -nucleon scattering can be used quantitatively to determine the short range π -nucleon interaction. Since much of the inelastic cross section is expected to come from the peripheral-collision region, it should be useful to measure accurately the elastic scattering well into the π -production energy region.

A great variety of experiments on single-pion production would be made possible with a high-intensity machine. In particular, angular correlations and direction-polarization correlations with energy selection are necessary to go beyond the current interest in phenomenological resonance and isobar models. Careful studies of this process would furnish a quantitative tool for the investigation of strong interactions.

Only the simplest experiments on double-pion production have been done so far, e. g., branching ratios and total cross sections. With a high-intensity beam the difficult correlation measurements, which encompass a wider variety than for single-pion production, could be done. Although such experiments may seem rather far removed from present work, they may be essential for further progress in the meso-dynamics of the future. It is to be expected that analysis of the production processes using dispersion relations will eventually reach a high degree of usefulness.

Photon production may proceed through the reactions

$$\pi^- + p \rightarrow n + \pi^0 \rightarrow \begin{cases} n + 2\gamma & (1a) \\ n + \gamma + e^+ + e^- & (1b) \end{cases}$$

$$\pi^- + p \rightarrow \begin{cases} n + \gamma & (2a) \\ n + e^+ + e^- & (2b) \end{cases}$$

$$\pi^\pm + p \rightarrow \begin{cases} \pi^\pm + p + \gamma & (3a) \\ \pi^\pm + p + e^+ + e^- & (3b) \end{cases}$$

More precise measurement of the Panofsky ratio, $R = \frac{\pi^- + p \rightarrow \pi^0 + n}{\pi^- + p \rightarrow \gamma + n}$, is of continuing interest. Some recent values are 1.53, 1.56, 1.40, and 1.62, with error estimates ranging from 0.05 to 0.2. R can be used in calculations of internal conversion coefficients for reactions (1) and (2) above. These can then be compared to the very accurate values predicted from quantum electrodynamics.

Samios has recently obtained the form factor to first order of the $\pi^0 \rightarrow 2\gamma$ vertex for the virtual π^0 in reaction (1). This was obtained from the differential distribution for the Dalitz pairs in (1b). With higher intensity beams more precise data should be obtainable for investigating higher order terms.

Weak Interactions

The Mc² cyclotron will make possible thorough and precise measurements of the weak interactions of non-strange particles. The set of weak interactions among these particles is summarized by the Puppi triangle, with three pairs of particles (np), ($e\nu_e$), and ($\mu\nu_\mu$) at the vertices, and three interactions represented by the lines joining them.

For several years the investigation of these interactions has been spurred by the universal Fermi interaction (UFI) hypothesis according to which all three of the basic interactions are of the same form and have the same coupling constant. Explanations of the small experimental deviations from universality have been sought in renormalization effects arising from the structure of the nucleons produced by the strong interactions. In recent years thought has been given to the possibility that the weak interactions are not of the Fermi form, i. e., local interactions among four fermions, but rather of the non-local Yukawa form in which a

vector boson, W , is exchanged between pairs of fermions.* In this

Fermi

Yukawa

case the predictions of the Fermi theory would no longer agree with data at higher energies or with more precise measurements at low and medium energies. The Yukawa theory would be most convincingly demonstrated by the experimental discovery of W mesons. In any case the intermediate weak vector boson hypothesis has stimulated interest in the momentum transfer dependence of the weak interactions. One is now interested in measuring not merely coupling constants but rather weak interaction form factors.

Muon Absorption. - Of the three legs of Puppi's weak interaction triangle, muon capture by nuclei is the least well understood at present. Two avenues of progress are discernible. On the one hand, capture in pure hydrogen, deuterium, H-D mixtures, and He^3 promises to reveal the details of the weak capture interaction. As in the history of nuclear beta decay, refinements may be expected to continue to accumulate over the years with increasingly painstaking investigation. High intensity will greatly facilitate the more difficult polarization and angular correlation experiments. On the other hand, once the basic interaction is well pinned down, muon capture in complex nuclei can complement nuclear beta decay in providing information about nuclear structure through nuclear matrix elements, pair correlation functions, etc. The combined theoretical treatment of the nuclear structure effects and the strong interaction renormalization effects on the capture process should continue to propose challenging experiments for years to come.

*The tenability of the weak vector boson hypothesis in the face of the experimental absence of the decay $\mu \rightarrow e + \gamma$ requires that the neutrino paired with the muon in the Puppi triangle be different from the neutrino in beta decay. This exciting possibility was confirmed at Brookhaven in 1962.

The current theoretical description of the $\mu + p \rightarrow n + \nu$ reaction is in terms of a Fermi interaction involving four effective couplings, namely, axial vector, vector, induced pseudoscalar, and "weak magnetism". In contrast with nuclear beta decay the four-momentum transfer q^2 is appreciable. This complicates a test of the universal Fermi interaction (UFI) hypothesis, but on the other hand promises to provide information on the q^2 dependence of the weak interaction form factors, which is not obtainable from beta decay. Among the more interesting questions are: the extent to which the universality hypothesis is confirmed; the nature of the momentum dependence of the form factors; the detailed nature of virtual pion effects, in particular the sign of the pseudoscalar coupling constant (g_P); and the magnitude of the weak magnetism constant (g_M).

Muon capture in hydrogen is the basic reaction for unraveling the μ -capture interaction, similar to the decay of the free neutron for the beta process. Capture in hydrogen is complicated by strong hyperfine effects and by molecule formation. However, one is confident that it will soon be possible to obtain the desired information about the mu absorption interaction from the experiments, since the atomic effects are becoming better understood. It will be useful to have the results also for capture in pure deuterium, in H-D mixtures, and in He^3 , so as to determine the vector and effective Gamow-Teller coupling constants separately. These will be discussed below under mu-mesic molecules.

For capture rate experiments in hydrogen, the most important feature of the cyclotron facility would be the ability to obtain clean meson beams, and to use gas targets. The layout of experimental equipment including magnetic analysis, long flight paths, and sufficient shielding are very important. The μ^- beam must be very pure since π^- capture will simulate μ^- capture and neutrons in the beam will simulate neutrons from the capture reaction. The target must be of very carefully controlled isotopic content; either extremely pure H, or D, or of precisely known mixture. The rates of various atomic and molecular processes depend strongly on the mixture. The number of fusions, $p + d \rightarrow \text{He}^3$, can act as a convenient monitor of the deuterium concentration.

Much additional information is to be gained from more difficult experiments such as the following:

(1) The asymmetry of the emitted neutron relative to the polarization of the muon in its K orbit. The induced pseudoscalar interaction should show up strongly. A 40% asymmetry is expected.

(2) The neutron helicity. This gives the neutrino helicity independent of the sign or magnitude of the muon polarization. In view of the identification of two kinds of neutrinos it is of interest to determine the neutrino helicity independently for each process.

(3) Radiative capture $\mu^- + p \rightarrow n + \nu + \gamma$.

(a) The asymmetry of the γ distribution together with its circular polarization gives the muon polarization just before capture.

(b) The spectrum of the γ ray gives the momentum transfer dependent form factor of the pseudoscalar interaction, by which the induced pseudoscalar can be distinguished from a pseudoscalar bare coupling in the Fermi interaction.

(c) The (n, γ) correlation provides an analogue to the classical recoil-electron correlation in beta decay. It would distinguish between S and V Fermi components and between T and A Gamow-Teller components. While the universality of V-A is expected, it should be confirmed experimentally for μ capture.

(4) (n, n) correlation in $\mu^- + D \rightarrow 2n + \nu$ could give information on the n-n interaction. (Unfortunately, the simpler measurement of the neutron spectrum is relatively insensitive to the n-n force.)

Almost all the information on the μ -capture interaction has come, so far, from measurements of partial or total capture rates in complex nuclei. The results have shown that $g_A^{(\mu)}$ is within 30% of $g_A^{(\beta)}$ and that Primakoff's theory of nuclear structure effects is rather good. In addition, a measurement of the asymmetry of the emitted neutron distribution about the initial mu polarization direction has verified the non-conservation of parity and the existence of an effective pseudoscalar coupling with $g_P/g_A > 0$, in agreement with the UFI. Capture in hydrogen, deuterium, and He^3 should pin down the interaction. Experiments in complex nuclei can then be used primarily for information on nuclear structure, much as beta decay is being used since the "clarification" of the interaction.

Pi-mesic hydrogen has not yet been detected because nothing is transparent to the X-rays. With a sufficient intensity of pions one might use a proportional counter containing hydrogen gas. If atomic transitions to the 1S state are not prevented by the Day-Snow-Sucher effect, one would hope to measure the strong π -p interaction through the energy shift and width of the 1S level.

Rare Processes. - The high intensity of muon and pion beams will greatly help in the search for and investigation of rare decay modes. For example, the pion decay mode $\pi^+ \rightarrow \pi^0 + e^+ + \nu$, with an expected branching ratio of 10^{-8} is being looked for. One could go on to measure the (π^0, e^+) correlation which would distinguish the V and S couplings. Similarly the (e^+, γ) correlation in the rare mode $\pi^+ \rightarrow e^+ + \nu + \gamma$ (BR $\sim 10^{-6}$) is of interest because of terms dependent on the structure of the vertex. Spark chambers may make such experiments much easier to do. With the advance of understanding of the weak interactions such increasingly refined information will be required. For the study of the decay modes higher intensity will matter greatly whereas higher energy would be irrelevant.

The neutrino capture reaction $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ has been detected at Brookhaven and at CERN. It will be of interest eventually to obtain the energy dependence of the cross section. The Mc² cyclotron could provide an anchor point by using the nearly monoenergetic neutrinos from stopped π 's or μ 's.

Quantum Electrodynamics and Atomic Physics

Basic Properties of the Muon. - Increasingly precise values of the basic constants characterizing the muon will be needed as time goes on. The mass and anomalous magnetic moment are important for quantum electrodynamics. The parameters for mu decay have fundamental significance for the theory of weak interactions. These parameters also affect the precision with which other quantities can be obtained. A national laboratory is well suited to pursuing a program of such careful measurements.

In view of the recognized importance and the familiarity of the properties we merely list them: (1) mass, (2) magnetic moment anomaly, ($g/2 - 1$) (present data show agreement with the first radiative correction ($\alpha/2\pi$); it should be possible to test the α^2 term) (3) upper limit on electric dipole moment, (4) lifetime, (5) Michel's parameter ρ , and (6) the asymmetry parameter. Pure and intense beam of muons may enable more precise measurements of all or some of the above quantities.

Muonium. - Production of muonium ($\mu^+ e^-$) has been detected in dense argon gas by measuring the precession frequency of its magnetic moment in a magnetic field by microwave techniques. A preliminary measurement of the hyperfine structure intervals has been made. If the muon differs slightly from being merely a "heavy electron", the differences in its electromagnetic behavior should show up most easily in the precision measurements that are possible with muonium.

In analogy with $K^0 \rightarrow \bar{K}^0$ transitions, muonium ($\mu^+ e^-$) might convert into antimuonium ($\mu^- e^+$) if a direct weak interaction coupling the "neutral current" of $\mu^+ e^-$ with that of $\mu^- e^+$ exists. No example of any weak interaction involving a neutral current has been observed to date. Examples have been sought in K^+ and Σ^+ decays. Assuming the interaction exists with the "universal" value of the coupling constant, $g_V \sim 3 \times 10^{-49}$ erg cm³, Feinberg and Weinberg have concluded that conversion could be observed only in dilute inert gases where muonium cannot be easily formed. The problems involved in producing muonium in a solid and quickly getting it into the gas may resist solution for some time.

Mesic Atoms. - One can study the capture of the negative muon and pion into atomic orbits, the bound decay rate, depolarization, the mesonic X-rays and Auger electrons, and radiationless transitions of several kinds.

A negative mu behaves essentially as a heavy electron and can be captured by an atom into an orbit characteristic of its greater mass. After capture the μ^- passes by radiative transitions, Auger processes, and in the final stages also possibly by radiationless transitions (with the energy taken up by the nucleus) to its 1S orbit, where after a time it may decay or be absorbed by the nucleus. Negative pi mesons will also undergo similar processes, but because of their stronger nuclear interaction will often be absorbed from excited orbits.

Atomic physics is basically determined by the electromagnetic interaction, probably the best understood interaction in physics. By using mesons in place of electrons some effects become enhanced and some new effects occur. Several properties of the muon are primarily responsible for the special possibilities of mesic-atom physics: (1) The incident muon beam is strongly polarized, and consequently polarization measurements at every subsequent stage (decay electrons, X-rays, nuclear γ rays, etc.) provide useful information. (2) The heavy mass of the meson makes the lower orbits lie well inside the electronic K shell, implying (a) that screening of the nuclear charge by the electrons is negligible, so that accurate theoretical calculations can be made, (b) that the meson can perform as a useful probe of the nucleus (for example, above $Z \approx 45$ the K level is actually within the nuclear radius), and (c) that the hyperfine interaction, vacuum polarization, and K-capture interactions are enhanced relative to those of electrons. (3) The muon possesses a decay mechanism.

There are several anomalies in mesic-atom physics which have not been explained. For example, one of these which was revealed by the systematic measurements of Stearns and Stearns on the X-rays from μ and π mesic atoms indicated unexpectedly low yields in the K and L series in the light mesic atoms. Later measurements by several groups give yields which are higher but still are less than expected. Different theoretical assumptions about the relative frequency of capture into initial orbits would alter the expected number of X-rays. A radiationless transition mechanism has also been contemplated. The solution of the "problem of missing X-rays" will require further investigation.

Clarification of the problem could come from the direct measurement of the Auger electrons. Their measurement would require very thin sources and coincidence techniques, which in turn would also require a high-intensity meson beam. A group at this laboratory has special skills in this kind of measurement and has interest in the mu-mesic atom application.

The X-ray spectroscopy of mesic atoms has been for a long time of great interest, but many, if not most of the phenomena, that can be studied are limited by the resolution of the apparatus which may be used with the low intensity meson beams available. To quote from a review article by M. B. Stearns, "However, a real boon will be achieved in mesonic spectroscopy when and if the presently proposed high-intensity, high-energy accelerators are built (e. g., FFAG cyclotrons). This could increase the meson beams by a factor of 100 or more. Regular spectroscopic techniques (e. g., crystal spectrometers in the MeV range) could then be applied to the field and effects which are now impossible or difficult to measure could be readily investigated. All effects of vacuum polarization, spin and anomalous magnetic moment of the μ meson, static quadrupole moments, quadrupole moments of excited states of the nucleus should then be in the realm of easy measurability."

Mesic Molecules. - The present interest in mu-mesic molecules is mainly limited to hydrogen and deuterium, in which the detailed molecular properties have a strong influence on the rates of the $p + d$ fusion reaction and of mu-meson capture by P, D, and He^3 .

In isotopically pure hydrogen mu capture occurs both from the atom ($\text{P}\mu^-$) and from the molecular ion ($\text{P}\mu^- \text{P}^+$). One needs to know the relative amounts of ($\text{P}\mu^-$) and ($\text{P}\mu^- \text{P}$), the relative populations of the various hyperfine states, and the magnitude of the muon wave function at the proton in the molecular ion.

The absorption in liquid H_2 gives a measurement primarily of the capture rate in the singlet state (Λ_0). Measurements in the gas would also give only Λ_0 because of the Gerstein-Zeldovitch collisional exchange mechanism, $(P\mu^-)_{F=1} + H_2 \rightarrow (P\mu^-)_{F=0} + H_2$, which becomes more important as the density is increased. Use of the liquid is preferable because of the higher density. It has been suggested that by distinguishing between early and late neutron counts, Λ_0 and Λ_1 may be obtained separately.

In H-D mixtures, capture absorption of muons by He^3 atoms, present as reaction products, seriously complicates interpretation.

C. Biological and Medical Research

Biological Research

A vigorous biology program is necessary in connection with the Mc^2 accelerator. Its principal concern will be the fundamental investigation of the effects of radiation on biological systems, with concurrent programs oriented toward the treatment of cancer in humans and radiation effects of space travel. The fundamental part of this program exists in the Biology Division.

The problem of the relative biological effect, RBE, of high energy protons (≥ 20 MeV) is essentially solved for single cell organisms. Negligible data exists, however, for multicellular organisms. The RBE of protons as a function of energy should be measured for such systems as a problem in fundamental radiobiology as well as on account of the significance this measurement has for space travel. The Mc^2 accelerator, as it is currently conceived, will produce protons at only one energy. However, for low intensities such as are required in biophysics work, lower energies may be achieved by the following method. The full beam is scattered from a hydrogenous target in the corridor, protons scattered through various angles have different energies. These protons then must be magnetically analyzed and piped into one of the shielded rooms. With the addition of absorbers it should be possible to vary the energy from 400 to 800 MeV in at least four 100-MeV steps. Because dE/dx changes slowly with energy the values of RBE may be predicted to be independent of energy at these high energies.

High-energy protons have the advantage that dE/dx is practically constant for a small organism such as a mouse, which can thus be exposed to whole-body radiation. In addition to determining the acute effects of such radiation on 30-day survival, and on the blood-forming elements, gonads, and other radiosensitive organs, its effect on life span, tumor incidence, lens of the eye, and aging changes should also be studied. Such a program requires exposure of several hundred mice at varying dose rates from one to 50 rads/min. In addition to mice, other biological systems can be exposed to this radiation. These include groups of cells, simple organisms, plants, and animals.

The π^- beam which will be produced by the Mc^2 cyclotron provides a source of very high LET radiation at the end of the pion range where stars consisting of protons, alpha particles, and recoil nuclei result in very high localized ionization. Three lines of research can be pursued with the pions.

With monoenergetic pions it is possible to deposit a high LET dose in the interior of an animal without excessive damage to the rest of the tissue, see Fig. 3. 2. The RBE of such radiation can thus be studied for different organs, in a program which is closely related to the use of pions for cancer therapy. Large animals are required for this investigation.

When the range spectrum of the pions exceeds the thickness of the organism, uniform irradiation with high LET particles can be achieved. Here, again, the principal goal is to study the RBE of pion stars, this time in whole-body irradiation.

Finally, π^- stars can be used to destroy selectively organs which are not readily removed by surgery. The destruction of the pituitary in the treatment of certain tumors is an example. However, the method is a powerful one and can be used for other biological or medical investigations as well.

Experimental facilities required by the biology program do not differ significantly from those available for the physics work. It is proposed to include biophysics stations in the three large experimental rooms as the need for them arises. Much preparatory work in dosimetry and in the preparation and characterization of the beam is necessary before any work on biological materials can be done. Close cooperation with the experimental physicists and machine development group will be necessary for this phase of the program. Once this is achieved, the bombardment of mice will require fairly simple setups, and no special facilities. Again, great attention must be paid to the problem of reducing the background, so that the particle under investigation can safely be regarded as contributing the major part of the dose.

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Fig. 3. 2. Relative depth distribution of localized ionization in animal tissue, normalized to unit dose at surface.

Pion Irradiation for Medical Purposes (ORINS Medical Division)

The study of the medical uses of pion irradiation has as its ultimate aim the possibility of using a beam of negative pions for the treatment of cancer. Although much preliminary experimentation will be needed, involving work with inanimate objects and with experimental animals, it is thought that there is a good possibility of obtaining the desired goal--to irradiate human tumors more effectively with negative pions than with currently available sources of radiation.

The advantages to be expected depend on the fact that negative pions produce heavy ionization within a few millimeters from the site where the pion stops and the pion-nucleus interaction occurs.

From a radiobiological standpoint, pion irradiation can be discussed under three headings:

Radiation Distribution. - density of ionization inside the body. With X-rays or gamma rays the intensity of ionization decreases steadily as the beam of radiation passes through the body tissue, but with negative pions almost the opposite occurs. If the amount of ionization produced at the surface of the body is given a relative value of one, then for the major part of the pion's range the amount of ionization remains close to one, until, near the end of the range, it rises steeply to a value between five and fifteen. This means that if the end of the track of the negative pion is made to coincide with the depth at which the tumor is located (by selecting negative pions of a certain energy), it is possible to concentrate most of the irradiation in the tumor volume and thereby spare normal tissues.

Relative Biological Efficiency (RBE). - radiosensitivity as related to linear energy transfer. The highly energetic heavy particles and nuclear fragments that form the star at the end of a negative pion's track, have very short ranges; hence, will produce heavy ionization within a distance measurable in microns. A high LET will result in a high RBE per incident particle and should give a high RBE per rad for tumors as compared with normal cells (see the next section). Because of the complexity of pion star formation, the RBE for π^- irradiation is not well known. Theoretical estimates vary so widely (from 1 to 20) that this very important question can be answered only by experimentation.

It is anticipated that several RBE's are likely, depending on the end point used to determine them: i. e. , acute mortality, changes in the weight of certain organs, degree of radiation effect on different tissues and tumors, uptake of iron-59 by bone marrow, and other physiological functions. These and other experimental procedures that have been shown to vary proportionally to radiation dose will be investigated. It is expected that a biology research program will be established which will deal with this problem extensively.

Differential Radiosensitivity. - radiosensitivity as related to the "oxygen effect". Tumors vary in their sensitivity to radiation, some are more and others less resistant than surrounding normal tissue. Various, and largely unexplored, factors are important here. One of these factors which has been studied and quantitated is the "oxygen effect". Areas of poorly-oxygenated tumor, because of deficient blood supply, are about two to three times less radiosensitive than well-vascularized, well-oxygenated regions of the same tumor, when radiosensitivity is tested with X-rays or gamma rays with an RBE of about one. This relationship of oxygen and radiosensitivity has been reported, however, as being of little or no importance with high RBE radiation. It should be expected, therefore, that in the region of star formation in π^- irradiation, the tumor would be relatively more radiosensitive with respect to normal neighboring tissues. If this occurs, it probably would represent a method of overcoming the oxygen effect that is a handicap in gamma-ray therapy in some tumors. This hypothesis can be tested by irradiating tumor-bearing animals with negative pions and gamma rays.

Even though the use of negative pions in the treatment of cancer seems promising, it is to be realized that many questions will need to be investigated before an attempt may be made to start a clinical trial. In the course of these studies insight should be gained on the biological effects of this novel tool of irradiation. The program would proceed in three main stages which in chronological order are: Stage I. Studies of beam characteristics, dosimetry, and radiation protection. Stage II. Biological experimentation to determine relative biological efficiency and differential radiosensitivity. Stage III. Clinical trials.

Beam Intensity and Dosimetry. - It is estimated that useful dose rates for biological and clinical experiments could be obtained with a flux of about $5 \times 10^6 \pi^-/\text{cm}^2\text{-sec.}$ This flux would deliver about 20 rad/min at the end of the particle range. (This figure is very tentative; present theoretical estimates vary by a factor of 5, and this matter should be among the first ones to be studied.) High pion fluxes are not available anywhere at the present; for some time to come the Mc^2 cyclotron will be the only machine with which negative-pion irradiation can be studied.

Negative pions of 100 MeV have a range of about 30 cm in tissue; since no patient or biological system thicker than 30 cm is likely to be irradiated, 100 MeV is the maximum energy that will be required. For ranges of 1 to 2 cm in tissue, pions of very low energy are required. They will be obtained by attenuating more energetic negative pions through an absorber.

It may be necessary to vary the range of negative pions in tissue during irradiation. Heavy ionization occurs in a slice of tissue, the thickness of which is determined essentially by the energy spread of the π^- beam and the extent of the ionization region of the star. Beams with little energy spread deposit most of their energy in a layer of tissue less than 1 cm thick. Although it may be highly desirable in some type of experiments to be able to concentrate most of the irradiation within such close limits, in considering irradiation of human tumors that may measure several centimeters in thickness, this effect would prevent uniform irradiation of the tumor. It will, therefore, be necessary to vary rapidly and continuously the range of the negative pions either by sweeping their energy or by interposing variable thicknesses of an absorber.

In the irradiation of tumors the cross section of the beam should closely correspond to the cross section of the object to be irradiated. Although there will be a practical limitation to the maximum cross-section area that can be obtained, it is anticipated that cross-section areas of about 300 cm^2 could be achieved with little sacrifice of flux. Careful control and study of the beam will be required to ensure that it is reasonably uniform over its cross section.

Radiation Protection. - Because the primary proton beam and the target where negative pions are being produced would be outside the treatment room, protection from them and their associated radiation will be provided by adequate shielding. The matter of protection inside the treatment room is, however, of great concern to its users, experimenters, and possibly to patients. From the decay of negative pions and their interaction with absorbers and the object being irradiated, gamma rays, muons, and fast neutrons will be produced. This may constitute an annoying problem or a hazard, depending on their quantity and the protective measures instituted. Initial study indicates that the patients will not receive an excessive amount of total-body irradiation, but this will need to be carefully studied during the early stages of the program.

Clinical Trials. - After the problems of beam calibration, ranges in tissues, and other physical aspects of this project have been solved, and the preliminary biological experiments described in previous sections have been completed, π^- irradiation of selected human patients will be undertaken. Techniques of irradiation should not be difficult to master; the main problem probably would be the ever-recurring one in radiation therapy: tumor localization, which depends not on machines, but on human limitations.

Single fields should probably be adequate and ideal for treating small lesions. For large tumors, however, it may be necessary to use two or more fields. The reason is that if the lesion is thick, the energy spread of the π^- beam will need to be considerable; it may well be that under these circumstances the ratio between tumor dose and entrance dose is less than 1. Hence the tumor would have to be cross-fired from two or more portals of entry, as is done with X-ray and gamma teletherapy. If multiple fields are used, provision will be required to carefully align tumor and beam for each position, whether by rotating the patient or by bending the π^- beam.

The Mc^2 isochronous cyclotron being a large and complicated installation might have an unfavorable impact on patients. Aside from the psychological harm this might do, there is the practical consideration that a scared patient moves, and a patient that moves during treatment is the curse of radiotherapy. Rather than devising ingenious and draconian restraining devices, it seems more humane and practical to set the treatment room in such a way that it does not look threatening to a sick and bewildered person: painted walls, as little noise as possible, and most of the machine out of sight.

In the early stages of clinical trials, only patients with incurable cancers will be treated, because it would not be right to experiment with a patient who might have a lesser but certainly better known chance of being cured by some other means. During this time it should be possible to treat patients with multiple areas of malignancy with both gamma rays and negative pions to compare the effects of each type of radiation therapy. Patients with very advanced malignant diseases would not be treated with negative pions; because it is difficult to appraise what one has done with this group of patients.

As soon as the usefulness of π^- irradiation has been confirmed, potentially curable patients may be treated in a controlled clinical study. There is no better way of convincing oneself or others that something is curative, than curing with it.

D. Applied Physics

The Mc^2 cyclotron is designed primarily for the study of nuclear matter and the basic interactions of elementary particles. The various beams may prove very useful, however, for other kinds of research, such as the study of shielding in relation to manned space travel. The question whether neutrons could be produced more economically with accelerators than with reactors may bear reinvestigation. This machine will provide the means for such studies.

There are two additional topics which should be mentioned even if they are not developed here in any detail. One is the study of the solid state by means of radiation-induced damage, and the other is the basic problem of ionization losses of relativistic particles in matter. For both these purposes the cyclotron will furnish useful beams. In radiation damage what is wanted is controlled irradiation over a considerable depth of material. BeV protons have a range of hundreds of grams/cm^2 and a dE/dx which does not vary greatly for considerable energy losses. On the other extreme, if one wants very high damage in a layer deep inside a material, π^- stars would provide an excellent mechanism. High intensity and good energy resolution are of paramount importance.

Ionization losses for various mesons, as well as for protons, in matter constitutes a somewhat unfashionable and worked-over field right now. It may well be of great practical importance and of some theoretical interest when very high resolution meson beams become available, and have to be stopped in thin targets.

Shielding Studies for Space Flight

The existence of radiation belts around the earth, and intense proton radiation from the sun, greatly complicates the problem of manned space flights. The energy of protons in the radiation belts ranges from a few MeV up to 700 MeV, and the maximum intensity is about 4×10^4 protons/ cm^2 -sec. Most solar proton events have a maximum proton energy of 300 MeV, but a few events have been observed with energies up to 20 BeV. Except for low orbital flights and short excursions into space, considerable shielding will be necessary to protect the

astronaut from this lethal radiation. It is imperative that the weight of the required shield be held to a minimum. To accomplish this one must have detailed information describing the space radiations, the penetration of shields by these radiations, and the interaction of the radiation emerging from the shield with the biological system. Information can be gained on the last two items from cyclotron studies, but only shield penetration studies will be discussed here.

Calculations indicate that protons and secondary radiation from them pose the most difficult shielding problem, and it is expected that if the proper proton shielding is employed there will be more than adequate shielding for the electrons.

In thick shields, which are necessary, nuclear interactions give rise to secondary radiation. This becomes the principal source of the dose for protons above a few hundred MeV. No definitive theoretical calculations or experimental measurements have been completed which enable one to calculate the energy spectra, angular distribution, and intensity of the secondary radiation with sufficient accuracy to determine the protection afforded by a thick shield.

The important secondary radiation consists of protons, neutrons, and gamma rays, with the neutrons posing the most severe biological problem. Since the radiation belts around the earth contain protons with energies up to 700 MeV and since some solar emissions have high intensities of protons around 1 GeV, studies of the secondary radiation resulting from the bombardment of a shield by protons at the energy available from the proposed cyclotron would be valuable.

High beam intensity is important for shielding studies because the attenuation of the secondary radiation in thick shields leads to difficulties in obtaining neutron spectra and angular distributions. Besides the gross shielding properties of matter, the cross sections and the angular distributions for certain important reactions should be measured in detail. A high-intensity accelerator would facilitate these measurements and, in some cases, might make important measurements feasible which are not possible on present machines because of their lower intensity.

It should also be pointed out that these measurements would lead to more exact designs for future accelerator shields through the direct use of the data as well as providing a check on calculations to be used at higher energies. Experimental and theoretical programs which should give much of the desired information are now in progress; however, many studies that can be done on the proposed machine are well beyond the scope of the present programs.

Neutron Production

From time to time there has been considerable interest in developing an economical electronuclear process for large-scale production of neutrons. A high intensity neutron source could, for example, be used to fission depleted uranium. A neutron source plus depleted uranium might, in fact, provide a source of power competitive in cost with large reactors.

The two major units of such an electronuclear plant are an accelerator and a target. Both aspects were studied intensively on the MTA Project during the years 1950-1954. At the time the MTA Project ended, the most feasible and economical accelerator concept was believed to be a linear accelerator for accelerating deuterons to 500 MeV. The target problem was not as well developed, although it appeared that the best target configuration was a beryllium primary target, whose stripped neutrons were multiplied in a uranium secondary target through high-energy fission and spallation reactions. Production of Pu^{239} was achieved through neutron capture by U^{238} in the secondary target and in a surrounding subcritical lattice of depleted uranium.

Developments in radio-frequency engineering and electronuclear technology since 1954 indicate that a re-evaluation of accelerator economics might lead to a very favorable case for a cyclotron instead of a linear accelerator. The Thomas-type cyclotron was evaluated in the early 1950's as a possible MTA accelerator, but was rejected because of uncertainties about resonances which were expected to limit the attainable energy. Now that model tests have shown that it is quite feasible to build a cyclotron for 810-MeV protons, experience with such a machine should prove useful in evaluating the economics of high-energy, high-current cyclotrons of the AVF type.

Possible applications of this process will require new data on the neutron yield. This information is best obtained by direct measurement of the neutrons emitted from typical primary + secondary target configurations (the "external yield"), and the number of fission and capture events occurring within the target (the "internal yield"). The external yield can be determined by a manganese bath technique, which does not require a very intense beam of incident particles. On the other hand, the internal yield values must be measured by nuclear chemical methods, and hence require high beams. While the Mc^2 cyclotron is not proposed as a power producer, it would be useful for a study of this whole question, and especially so for the determination of internal yields from complex target assemblies.

4. BEAM OPTICS SYSTEM

The beam optics system proposed for the Mc^2 Cyclotron is illustrated by the plan view of Fig. 4. 1. This arrangement of beam optics elements resulted from studies in the following four areas:

1. Primary beam transport and shaping
2. Primary beam energy analysis
3. Pion beam formation
4. Mu-meson beam formation

Each of these areas is discussed below.

Transport and Shaping of Primary Beam

The general layout of the floor plan was determined mainly by the desire to confine the high radiation areas and to allow experiments to be set up in one area while experiments were in progress in another area. It is then necessary to provide for the transport of the beam from the cyclotron to the target areas with minimum beam losses. For this purpose, as well as for beam shaping, simple systems of quadrupole-doublet lenses were considered.

The nature of the beam to be transported was estimated from the beam-extraction experiments on the electron analogue (see Chapter 5). From these experiments, it was estimated that the energy spread in the 810-MeV proton beam would be about 1% and that the phase-space volume would be about 80 millimeter-milliradians in both the horizontal (radial) and vertical (axial) planes. In addition, the maximum divergence of the primary proton beam was estimated to be about $\pm 0.5^\circ$ in both directions. For purposes of these initial studies the phase-space distribution was taken to be shown in Fig. 4. 2. For designing an analyzing magnet system this distribution is more conservative than a more probable elliptical distribution because a smaller beam width at the object position of the analyzing magnet results in a larger usable energy dispersion at the image position.

Fig. 4.1. Plan view of cyclotron vault and experiment areas showing components of ion optics systems.

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Fig. 4. 2. Assumed phase-space distribution of extracted beam.

To transport and shape the beam with the initial phase-space distribution of Fig. 4.2, quadrupole-doublets consisting of 15-in. long elements with 5-in. apertures and separated by a 6-in. gap were considered. A peak operating pole-tip field of 10,000 gauss was assumed. It was found that the minimum focal length attainable with such quadrupole doublets was about 5 ft for 810-MeV protons. The maximum focal length which could accept the phase-space volume of Fig. 4.2 was found to be about 14 ft, and a system of two such lenses could transport and re-form the beam without significant losses over a distance of about 225 ft.

With a simple two-lens system, the horizontal and vertical magnification factors shown in Fig. 4.3 are possible. The results are for the case where lens Q_1 has a focal length of 12 ft; this is nearly the maximum focal length which can accept the beam phase-space volume. Note that when the first elements of both lenses are defocusing in the horizontal plane, the horizontal width of the object can be de-magnified by better than a factor of five if lens Q_2 has the minimum focal length of 5 ft. Therefore, this arrangement could be used to re-shape the beam phase-space distribution from that shown in Fig. 4.2 to the distribution shown in Fig. 4.4. The resulting small horizontal width (0.060 in.) is favorable for further energy analysis of the beam; it will be assumed that these beam conditions can be achieved at the object position of an analyzing magnet.

Energy-Analysis System for Proton Beam.

The high intensity of the primary beam of the Mc² Cyclotron will make it possible to obtain a proton beam of sufficiently small energy spread to be very effective as a probe of nuclear structure. For this use, an energy dispersion of about 1 MeV/in. is desirable. This energy dispersion was taken as the design goal for the simple energy analysis system shown in Fig. 4.5, which consists of an object slit, an analyzing magnet, and an image slit. For the analyzing magnet a non-uniform-field wedge magnet with a field index $n = 1/2$ and providing focusing in both horizontal and vertical planes is considered. ^(1, 2) Together with

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Fig. 4.3. Magnification for a two-lens system.

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Fig. 4.4. Phase-space distribution re-shaped for energy analysis.

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Fig. 4.5. Simple energy analysis system.

the system apertures, the important parameters are indicated in Fig. 4. 5. These parameters are determined by considerations of energy dispersion, acceptance, transmission, image size, space limitations, and, more than likely, by costs.

At the image position of this system, particles within an energy interval ΔT will be distributed over a horizontal width $\Delta X_{I, \Delta T}$ given by:

$$\Delta X_{I, \Delta T} = (\Delta X / \Delta T)_A \Delta T - M_X \Delta X_O \quad (1)$$

where $(\Delta X / \Delta T)_A$ is the energy dispersion produced by the analyzing magnet, ΔX_O is the width of the object, M_X is the horizontal magnification of the analysis system, and we are neglecting the contribution to the image size due to aberrations. The considerations that lead to the above relation are illustrated by Fig. 4. 6. A mono-energetic beam of energy T forms an image of width $M_X \Delta X_O$. Mono-energetic particles of energy $T + (\Delta T / 2)$ form an image of the same width but displaced an amount $(\Delta T / \Delta T)_A (\Delta T / 2)$ with respect to the image for particles of energy T . Mono-energetic particles of energy $T - (\Delta T / 2)$ are displaced an equal amount in the other direction. Particles with energies in the energy interval ΔT centered about energy T will be found in the region $\Delta X_{I, \Delta T}$ given by Eq (1). It is desired that $\Delta X_{I, \Delta T} = 1$ in. for $\Delta T = 1$ MeV.

For an $n = 1/2$ magnet the energy dispersion is given by:

$$(\Delta X / \Delta T)_A = [\gamma / (\gamma + 1)] 2 \rho [(1 + M_X) / T] \quad (2)$$

where ρ is the radius of curvature of the magnet, $T = M_O(\gamma - 1)c^2$, and M_O is the rest mass of a beam particle. Taking $T = 810$ MeV, $\Delta T = 1$ MeV, and $\Delta X_{I, \Delta T} = 1$ in., Eq (1) and (2) were used to determine the radius of curvature required to satisfy the energy dispersion criteria for various object widths. The results are shown in Fig. 4. 7. Note that, for a given object width, the required energy dispersion can be attained with a smaller radius of curvature (and therefore at a lower magnet cost) provided an increase in horizontal magnification can be tolerated. For a mean magnetic field of 8,000 gauss, which is a reasonable field for a non-uniform-field magnet, the radius of curvature for

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Fig. 4.6. Illustration of energy dispersion.

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Fig. 4.7. Conditions to achieve 1 MeV/in. energy dispersion with $n = 1/2$ magnet.

810-MeV protons would be fixed at 240 in. If the horizontal extent of the beam at the object position can be limited to 0.060 in. by beam optical means, then the desired energy dispersion can be attained when the analysis system is operated to produce a magnification of about 1.9.

The magnet gap required to accept and transmit the full beam depends on the object distance L_o and the vertical divergence as follows:

$$\delta y_{\max} = [1 + (2\rho^2/L_o^2)]^{1/2} L_o y'_{o \max} \quad (3)$$

where $\delta y_{\max}$ is the maximum vertical deviation of the beam from the optic axis and $y'_{o \max}$ is the maximum vertical divergence at the object position (about $\pm 0.4^\circ$, from Fig. 4.4). The point of maximum deviation occurs within the magnet at an angle of bend ψ given by:

$$\tan(\psi/\sqrt{2}) = \sqrt{2} (\rho/L_o) \quad (4)$$

and the angle is measured from the entrance edge of the magnet. With the magnet gap limited to 5 in. to match the quadrupole aperture, the full vertical beam width can be transmitted, provided the object distance is 3 ft or less. With a 3 ft object distance the maximum width of the beam in the horizontal plane would be about 35 in. The width of the magnet would thus be about seven or eight gap widths.

The remaining features of the analysis system are determined by the double-focusing condition:

$$\tan(\phi/2) = \sqrt{2} [(\ell_o + \ell_I)/(\ell_o \ell_I - 2)] \quad (5)$$

where ℓ_o and ℓ_I are object and image distances respectively, in units of radius of curvature. A plot of this equation in terms of normalized image and object distances is shown in Fig. 4.8. The magnification contours result from the relation:

$$M_X = M_Y = (L_I/\sqrt{2}\rho) \sin(\phi/\sqrt{2}) - \cos(\phi/\sqrt{2}). \quad (6)$$

Fig. 4. 8. Double-focusing condition for $n = 1/2$ magnet.

The normalized object distance required for 100% transmission through a 5-in. gap is 0.15. From Fig. 4.8, for a magnification of 1.9, the double-focusing condition is satisfied for a bending angle of about 165° and an image distance of $2.3 \rho = 46$ ft.

Because of operation at a magnification of 1.9 the beam would still be about 30 in. wide in the horizontal plane at the exit end of the magnet. At the image position the horizontal beam extent would be determined by energy resolution requirements (1 in./1 MeV energy spread) and the vertical extent of the beam would be about 1.1 in. Thus, if aberrations can be made unimportant by magnet design and by final shimming, the above system would provide the desired energy dispersion within a reasonable spot size and with high transmission.

Placement of the energy-analysis system is indicated in Fig. 4.1. This arrangement is intended to minimize the background from the object slit. A 25° bending magnet following the object slit together with 35 ft of concrete shielding should do much to reduce both the neutral and the charged particle background from the slit. For a one-inch slit opening, the slit should be no more than one-inch thick. A tungsten slit of this thickness is enough to reduce the energy of 810-MeV protons by 50 MeV.

The availability of a high-intensity primary-proton beam is provided by a 60° bending magnet (see Fig. 4.1). This beam path is designed to produce a minimum of energy dispersion with a single bending-magnet system. Minimum energy dispersion is achieved with a uniform-field magnet which has a high magnetic field intensity and is operated to produce zero magnification. For a magnetic-field intensity of 17,500 gauss, such operation would form an image about 5 ft from the end of the magnet with a horizontal spread of about 0.6 in. due to a 1% energy spread in the beam. It is felt that this amount of dispersion probably does not justify the complications of a triple-focusing system.

Formation of Pion Beam

Pion production from a complex-nucleus target is characterized by both a wide energy distribution and a wide angular distribution. The large acceptance of an Enge-type double-focusing analysis system,⁽³⁾ illustrated in Fig. 4.9, is therefore attractive for forming a pion beam from such a source. The wide angular distribution of the pions permits the formation of pion beams at backward angles, where these beams will presumably be freer from background contamination. As seen from Fig. 4.1, formation of such pion beams is provided for in both the pion room and in the medical facility.

Another characteristic of pions is their short rest-frame half-life ($\tau_0 = 2.56 \times 10^{-8}$ sec). Figure 4.10 shows the half-decay flight-path for pions as a function of pion energy. After a flight path of 40 ft, the initial intensity of a 210-MeV pion beam would be diminished by one-half. To shorten the flight path from the beam corridor to the pion room to a minimum, the pions are routed perpendicular to the shield, and the shielding thickness is reduced by the use of steel rather than the usual concrete (see Fig. 4.1).

In the Enge-type analysis system, vertical focusing is provided by a vertically-focusing quadrupole element located between the object slit and the analyzing magnet, as shown in Fig. 4.9. The vertical focusing condition is given by the relation:

$$(\tan \theta) / \theta = (L_1 + L_I + g + \rho \phi) / \ell \left\{ [L_I + \rho \phi + g] [L_1(\theta/\ell)^2] - 1 \right\} \quad (7)$$

With the exception of θ , all quantities are shown in Fig. 4.9. The quantity θ is a property of the quadrupole element and is related to the quadrupole field gradient, dB/dr, and the beam momentum P by:

$$\theta^2 = \ell^2 (dB/dr) / 1.313 P, \quad (8)$$

where ℓ is in inches, dB/dr is in kilogauss/in, and P is in MeV/c. In the horizontal plane, the quadrupole element is defocusing and the bending magnet is focusing, resulting in the following focusing condition:

$$\tan \phi = \frac{[(L_1 + L_I + g)/\rho] + \left\{ [(\ell/\theta) + gL_1(\theta/\ell) + L_1 L_I(\theta/\ell)]/\rho \right\} \tanh \theta}{\left\{ [(L_1 L_I + L_I g)/\rho^2] - 1 \right\} + \left\{ [L_I(\ell/\theta) + gL_1 L_I(\theta/\ell) - L_1(\theta/\ell)]/\rho \right\} \tanh \theta} \quad (9)$$

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Fig. 4.9. Enge energy-analysis system.

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Fig. 4.10. Half-decay flight path for pions as a function of pion energy.

Both Eq (7) and (9) must be satisfied simultaneously to achieve double focusing. The complexity of the double-focusing condition for an Enge-type analysis system does not admit display in the form of a universal graph such as Fig. 4.8. Figures 4.11 and 4.12, however, show the double-focusing condition for a few selected values of the parameters.

The energy dispersion of this system is due to the uniform-field bending magnet and is given by:

$$\Delta T/\Delta X = [(\gamma + 1)/\gamma] T/\left\{\rho[1 + (L_I/\rho)\sin\phi - \cos\phi]\right\} \quad (10)$$

The image conditions are determined by the horizontal and vertical magnification factors which are given by the following relations:

$$M_X = [(L_I/\rho)\sin\phi - \cos\phi] [\cosh\theta + (g\theta/\ell)\sinh\phi] \\ - [(\theta/\ell)\sinh\theta] [\rho\sin\phi + L_I\cos\phi] \quad (11)$$

$$M_Y = (\theta/\ell) (L_I + \rho\phi + g) \sin\theta - \cos\theta. \quad (12)$$

A bending magnet with a radius of curvature of 100-in. is used to develop a pion beam near the forward beam direction (see Fig. 4.1). With this large magnet operated at 19.4 kG it will also be possible to direct 810-MeV protons into the pion room. The particular arrangement shown in Fig. 4.1 is for the following values of the parameters which satisfy the double-focusing conditions:

$$\begin{array}{ll} L_I = 70 \text{ in.} & \theta = 0.49 \\ \ell = 15 \text{ in.} & \phi = 90^\circ \\ g = 40 \text{ in.} & L_I = 124 \text{ in.} \end{array}$$

These parameters would then produce horizontal and vertical magnifications of $M_X = 0.55$ and $M_Y = 3.7$ and an energy dispersion of 1.8-MeV/inch. A variety of other double-focusing conditions which could provide other image conditions and energy dispersions are, of course, possible.

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Fig. 4.11. Lens strength, θ , vs normalized gap width g/p , for $\phi = 90^\circ$.

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Fig. 4.12. Normalized image distance L_I/ρ , vs normalized lens distance L_1/ρ , for $\phi = 90^\circ$.

Mu-Meson Beams

One of the main features of the ion optics system proposed for the Mc^2 Cyclotron is the availability of a high intensity mu-meson beam. The design of the facilities for such a beam must rely on the properties of the $\pi \rightarrow \mu$ decay characteristics. Pions with a rest-frame mean-life of $\tau_\pi = 2.56 \times 10^{-8}$ sec decay to muons. A pion of velocity v_π will travel a mean distance of $v_\pi \gamma_\pi \tau_\pi$ before decaying, where $\gamma_\pi = (1 - v_\pi^2/c^2)^{-1/2}$ and c is the velocity of light. Thus, the mean-flight path for pions of 420-MeV kinetic energy (near the highest pion energies that can be produced by the Mc^2 Cyclotron) would be about 100 feet.

In their own rest frame, pions give rise to monoenergetic muons with an isotropic probability distribution in space. If the pions decay while moving in the laboratory system, the angular distribution of emitted muons becomes peaked about the pion's direction; for sufficiently energetic pions the muon directions will be restricted to lie within a cone about the pion direction. The half angle θ for the cone is given by:

$$\tan \theta = 1/\gamma_\pi [(v_\pi/v'_\mu)^2 - 1]^{1/2} \quad (13)$$

where v_π is the pion velocity in the laboratory system and v'_μ is the velocity of the muon in the rest frame of the pion. Fig. 4.13 shows a plot of the cone half angle with respect to pion kinetic energy. The spread of the muon directions from the parent pion direction, as typified by Fig. 4.13, compounds with whatever spread is inherent in the original pion beam to produce a very divergent muon beam.

Another important feature of the $\pi \rightarrow \mu$ decay kinetics is that a monoenergetic beam of pions gives rise to a flat energy distribution for the resulting muons in the laboratory system. The muon energy distribution extends from $(\gamma_\pi \gamma'_\mu - 1) m_\mu c^2 - v_\pi \gamma_\pi P'_\mu$ to $(\gamma_\pi \gamma'_\mu - 1) m_\mu c^2 + v_\pi \gamma_\pi P'_\mu$, where m_μ is the muon rest mass and P'_μ is the muon momentum in the rest frame of the pion. By suitable momentum analysis, the above feature allows easy separation of pions and muons.

Fig. 4.13. Muon cone half-angle as a function of parent pion kinetic energy.

Muon beams have been constructed at existing cyclotron facilities in two distinctly different arrangements. One arrangement, the so-called "mu-meson channel", consists of a string of identical and equally spaced quadrupole magnets.⁽⁴⁾ The channel is designed to trap and to transmit muons arising from the in-flight decay of pions travelling down the channel. As a result, the channel has rather poor transmission properties with respect to particles produced at a point source before the entrance.

Another arrangement for forming a mu-meson beam consists of a simple system of two quadrupole doublet lenses and a bending magnet.⁽⁵⁾ Operation of this system is based on collecting the mu mesons produced in the neighborhood of the pion source and focusing them to an image. Such a system can have a sizeable transmission for particles produced near the source but essentially no trapping properties with regard to particles produced by in-flight decay beyond the target. This system is also quite momentum selective and can easily be "tuned" to a variety of particle momenta.

A precise comparison of the above two methods for producing mu-meson beams is difficult because of different primary beam conditions, different targets, and different geometries. Roughly, the mu-meson intensities available from the two facilities appear to be of the same order of magnitude; however, the CERN channel design has several orders of magnitude smaller pion contamination in the mu-meson beam than does the Berkeley two-lens system. To be sure, the latter beam could be further purified by various methods but at the sacrifice of muon intensity. As the high purity feature of the channel design is necessary for many types of experiments, the channel design is preferred for a versatile mu-meson facility.

Design of a mu-meson channel has been studied by the CERN group.⁽⁴⁾ The main channel parameter expected to be affected by the availability of higher-energy pions is the channel length. To contain a mean-flight path of pions with energies near the upper limit available in the Mc² Cyclotron, the channel would need to be about 100 ft long.

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5. BEAM EXTRACTION FROM CYCLOTRON ANALOGUE II

The primary goal in the electron cyclotron studies has been to provide an experimental evaluation of the beam extraction system for the Mc^2 Cyclotron. The Analogue was designed so that the orbit dynamics of the accelerated electrons closely match those expected in the large proton cyclotron. The maximum electron energy achieved (limited by axial focusing) is about 530 keV, which is equivalent to 970 MeV for protons. The integral resonance $\nu_r = 2$ is at an electron energy of 445 keV, which corresponds to a proton energy of 810 MeV. The results of these beam extraction experiments, described below, demonstrate that for the Mc^2 Cyclotron an extraction efficiency in the 80 to 90% range can be anticipated. A description of the Analogue, along with a review of the observed characteristics of the internal beam, is given in Appendix A.

Extraction Method

The energy of the Mc^2 Cyclotron is well beyond that at which an electrostatic extraction system is tenable; therefore, a magnet channel system is needed. To obtain a sufficient decrease in magnetic field (some thousands of gauss) a channel entrance thickness of perhaps 0.5 to 1 cm will be required. Since, at maximum energy, the turn separation in the Mc^2 Cyclotron is only about 2 mm, and in the Analogue about 0.11 mm, some means to increase the turn separation coherently is essential.

The system here used to obtain additional turn separation is a modification of the Tuck, Teng, LeCouteur deflection scheme as applied in several frequency-modulated cyclotrons. The basic idea of the system is to make use of some suitable naturally occurring resonance. An appropriate point for extraction in a high-energy cyclotron is at the resonance $\nu_r = 2$, where there are exactly two radial oscillations per revolution. In an eight-sector cyclotron this is the $8/4$ resonance, a cubic essential resonance.

Gordon ⁽¹⁾ has worked out the main details of the motion in the resonance. There are two important features. First, motion along an asymptote in the phase plot, the change in radius per revolution, is proportional to the cube of the displacement from the equilibrium orbit. Second, as a consequence of first, the growth rate is exceedingly small for small amplitudes; ions can actually be accelerated through the resonance with only a modest increase in amplitude if the initial radial amplitude is small.

To use the 8/4 resonance effectively in an extraction system, the small-amplitude stability must be destroyed. This is accomplished by use of the 2/1 resonance, an imperfection resonance in an eight-sector cyclotron. The addition of a $\cos 2\theta$ component to the magnetic field causes a shift in the location of the equilibrium orbit, a shift which increases rapidly as $v_r = 2$ is approached. The small-amplitude stability is destroyed before the resonance is reached, and, depending on the orientation of the bump, one or two corners are opened in the otherwise closed phase contours.

The computed location of an accelerating particle in the r, p_r plane on successive revolution illustrates, Fig. 5.1, the rapid growth of radial amplitude that occurs in the resonance. The particle was started on the equilibrium orbit at an energy of 410 keV in the Analogue magnetic field, with an added $\cos-2\theta$ term, 0.2% of the mean field. The energy gain per turn is $0.001 m_0 c^2$. The optimum phase of the $\cos-\theta$ component is such that its maximum is 22.5° forward of the hill on which maximum radial growth occurs.

The Extraction Mechanism

A mechanism must be provided to permit the particles to leave the cyclotron after the turn separation is magnified by the resonance. The magnetic field must be made to decrease sharply along the intended path (by use of a magnetic channel) or an electrostatic force must be provided to counteract the magnetic field, as in

Fig. 5.1. Location of accelerated particle on successive revolution in r , p_r plane.

an electrostatic deflector. In the Analogue experiments an electrostatic channel was used; it may be regarded as model of the magnetic system to be used with the Mc^2 Cyclotron.

The Analogue extraction mechanism, Fig. 5.2, consists of two 0.125-mm thick tantalum strips spaced about 3 mm apart. The inner strip (the septum) is at ground while the outer (the deflector) is maintained at a positive potential of several kilovolts. The channel is supported at five equidistant points, each of which can be moved radially by means of a screw adjustment to shape the channel to match the path of the beam. An additional screw permits precise adjustment of the entrance angle of the channel, without changing the entrance position. The complete assembly is positioned azimuthally by means of a rack and pinion mechanism. The several adjusting screws are controlled from outside the vacuum chamber with a multi-headed screwdriver, the shaft of which moves through a ball and socket vacuum seal on the faceplate.

The $\cos-2\theta$ magnetic field perturbation is provided by coils wound symmetrically to produce two hills and two valleys in the magnetic field, without changing the average field. The coils are attached to the top and bottom lids of the vacuum chamber approximately 40 cm from the median plane and are movable in azimuth to optimize the phase of the field perturbation. The radial dependence of the $\cos-2\theta$ component is shown in Fig. 5.3.

Performance of the Extraction System

An extraction efficiency of 90% has been consistently achieved. This was with the entrance of the extraction channel located 2.5° forward of the point of maximum turn separation. The beam impinging on a phosphor-coat target at the extractor exit, Fig. 5.4, is a well defined spot, 1×5 mm. The electric field gradient used in these experiments, 6.6 kV/cm, would be equivalent to a magnetic field reduction of 3000 gauss for the magnet channel of the Mc^2 Cyclotron.

The septum of the Analogue electrostatic channel is too thin to model accurately the thickness required for a magnet channel in

Fig. 5. 2. Analogue II beam extraction mechanism.

Fig. 5.3. Radial dependence of magnetic field perturbation.

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Fig. 5.4. Beam spot at extractor exit. Spot is 1 x 5 mm.

the Mc^2 Cyclotron. The scale factor between the two machines is approximately 17, the ratio of their respective cyclotron unit lengths. Accordingly, the 0.125 mm septum of the Analogue corresponds to a thickness of about 2.1 mm for the Mc^2 Cyclotron, but a thickness of probably 5 to 10 mm will be needed to produce the required 3000-4000 gauss reduction in magnetic field. To study the effect of septum thickness on extraction efficiency, the septum of the Analogue extractor was thickened in successive steps by the addition of thin strips of metal. The efficiency was thus measured for each thickness at two azimuthal positions of the entrance, 2.5° and 8° forward of the point of maximum turn separation. The results are shown in Fig. 5.5. With the entrance located 8° forward of the point of maximum turn separation, the extraction efficiency extrapolates to zero at approximately half the channel aperture; this shows the channel is not filled at the entrance. A plot of the radius vs azimuth of a particle on successive revolutions, Fig. 5.6, shows why this is so. With the channel entrance 8° forward of maximum turn separation only about $1/2$ the maximum separation is achieved. With the channel entrance moved nearer the point of maximum turn separation the performance is much improved; the efficiency extrapolates to zero at nearly the full channel width with correspondingly less dependence on septum thickness. A septum thickness of 5 mm for the Mc^2 Cyclotron corresponds to a thickness of about 0.3 mm in the Analogue, which according to the 2.5° curve of Fig. 5.5 would give an efficiency of about 80%. Further adjustment of the entrance location and the use of a larger channel aperture can be expected to increase the efficiency further.

The extraction efficiency was measured as a function of several additional parameters to characterize the performance of the system. As shown in Fig. 5.7, the dee voltage is not a critical parameter. The abrupt drop in efficiency at 170 V is a result of loss of injection. The internal beam current shows a similar abrupt decrease because the minimum voltage for the beam to clear the source is approximately this value. Fig. 5.8 illustrates that the dependence

Fig. 5.5. Dependence of extraction efficiency on septum thickness for two locations of entrance.

Fig. 5.6. Calculated trajectory of accelerated particle on successive revolutions. The approximate path of the extracted beam is shown.

Fig. 5.7. Extraction efficiency vs dee voltage.

Fig. 5. 8. Extraction efficiency vs amplitude of field bump.

of extraction efficiency on field bump amplitude is only moderately critical, the optimum being about 0.3% of the mean field. These results indicate that the nonlinear 8/4 resonance dominates the particle motion in the extraction region.

The performance of the extraction system was also tested with an uncollimated filament as the electron source. The highest efficiency obtained was only 30%. This illustrates the great importance of injecting with suitably small radial amplitude. The radial amplitude in the Analogue beam was estimated from shadow measurements obtained with two probes at 90° and just inside the $v_r = 2$ point. With the electron injector the radial amplitude is about 0.2 mm, whereas with the filament source it was found to be two to three times larger.

Emittance measurements await bringing the beam completely out of the fringing field. The emittance calculated from the radial amplitude measurements is 20 mrad-mm, which is probably a lower limit. For estimating the Mc^2 Cyclotron ion optics system requirements, an emittance of 80 mrad mm was used.

The measurements on the Analogue demonstrate that a resonance extraction system based on the 8/4 resonance is indeed a practical one. Continued work will be required, however, to optimize the system and to convert the results of the Analogue studies to the design of a suitable magnet channel system for the Mc^2 Cyclotron.

An extraction efficiency in the 80-90% range can reasonably be expected with the Mc^2 Cyclotron.

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6. RESIDUAL RADIATION STUDIES

An essential part of the ORNL study of the Mc² Cyclotron designed to accelerate 100 μ A of protons to an energy of 810 MeV is a realistic appraisal of residual radiation levels that will result from operation of the machine. This study includes calculations made at Oak Ridge, the results of which are compared with experimental activation data obtained from colleagues at the CERN Synchro-Cyclotron. The calculations were made by using a derived formula that gives the dose rates outside slabs of material irradiated by a beam of fast particles incident normal to the surface of the slabs. The calculation was modified to take into account oblique incidence and then used to estimate the radiation levels to be found between the pole faces of the cyclotron. Activation of the atmosphere in the cyclotron vault and in the experiment rooms by spallation reactions and by thermal neutron capture was determined. Radiation damage to non-metallic components by the proton beam and by the induced radioactivity was also considered.

Comparison of Calculated and Experimental Decay Curves

A general formula was derived for calculating the γ -ray dose rates outside slabs of materials irradiated with fast particles. It is assumed that a collimated beam of particles impinges normal on the slab. The incident beam intensity I_0 is attenuated in the material by the macroscopic geometric cross-section Σ_t . Thus, at a depth X in the slab,

$$I(X) = I_0 \exp(-\Sigma_t X).$$

The production rate of spallation product j at position X is

$$R_j(X) = I(X) \Sigma_j,$$

where Σ_j is the macroscopic cross section for the reaction. After bombardment time t_B and cooling time t_c , the concentration of product j , as a function of X , is

$$N_j(X) = \{R_j(X) [1 - \exp(-\lambda_j t_B)] \exp(-\lambda_j t_c)\} / \lambda_j,$$

where λ_j is the radioactive decay constant for product j . The activity A_j of j , as a function of X , is

$$A_j(X) = N_j(X) \lambda_j.$$

At a point p a distance d outside the slab, the flux $\varphi_j(X)$ of photons resulting from $A_j(X)$ is

$$\varphi_j(X) = [A_j(X) \exp(-\mu_j X)] / 4\pi(X+d)^2,$$

where μ_j is the absorption coefficient for the radiation. The radiation dose rate $D_j(X)$ due to $A_j(X)$ is⁽¹⁾

$$D_j(X) = \text{const. } \varphi_j(X) E_j,$$

where E_j is the energy of the photons. The total dose rate at a point p due to all activity from product j distributed along the incident beam path is obtained by integration:

$$D_j = \{ \text{const. } I_0 \sum_j E_j [1 - \exp(-\lambda_j t_B)] \exp(-\lambda_j t_C) \} \int_0^{X_{\max}} \{ [\exp(-\Sigma_t + \mu_j) X] / (X+d)^2 \} dX,$$

where $X_{\max}$ is the smaller quantity of the slab thickness and the range of the incident protons in the slab material. In actual calculations, the integration does not need to extend to the range of several hundred MeV protons because of the exponential attenuation of the γ -radiation in the material. The analytical evaluation of the integral yields a slowly converging infinite series; therefore, numerical integration is used to evaluate D_j . For the total dose rate at a given point p the D_j 's for all the spallation products must be evaluated. Since the amount of computation is enormous, the calculation was programmed for the IBM-7090 computer.

Cross sections for the production of radioactive products in the material were taken from published studies of spallation reactions induced by protons of this energy range. The IBM-7090 computation determines the dose rate, for specific bombardment and cooling times, at the slab surface, at 10 cm, and at 1 meter. Buildup of intensity due to the production of secondary fast particles is not included in the computer calculation. Buildup, in the case of normal incidence, does not contribute significantly to the dose rate detected outside the irradiated material. Because of the exponential attenuation of the γ -radiation inside the slab only the activity produced in the first few centimeters of material need be taken into account. An allowance for this must be made in the case of oblique incidence of the primary beam, because the activity is now produced near the slab surface all along the beam path.

Barbier⁽²⁾ placed samples of C, Al, SiO₂, Ti, Mn, Fe, Co, Ni, Cu, Mo, Cd, and Pb, in the cyclotron vacuum tank for a period of three months. He then removed the samples and measured decay curves for the γ -radiation emitted. As a test, a calculation was made for a 3-mo bombardment by a 1- μ A 600-MeV proton beam on samples of C, Al, Fe, and Cu 1 mm thick. These samples were selected because they are the common materials to be used in the construction of the cyclotron and supporting equipment, and because spallation reactions in these materials have been studied extensively.⁽³⁻⁷⁾ For comparison the experimental and calculated decay curves, shown in Fig. 6.1, were normalized where the aluminum curves flattened out (this is where Na²² is the dominant activity in aluminum). The shapes of the two sets of curves are very similar. It should be pointed out that the experimental data are in counts/g-sec, while the calculated curves are in units of radiation dose rate. Since dose rates are dependent on gamma energy, the normalization factor for a particular material is not a priori the correct normalization factor for other materials, nor for a large range of cooling times. Table 6.1 lists the ratio, (calculated dose rate)/(experimental dose rate), at several decay times. The ratios are in most cases unity, within a factor of two. It is believed, therefore, that the calculation can be used to determine residual dose rates to within a factor of two.

Another problem to consider is the determination of dose rates induced by fast neutrons. The usual assumption is that fast neutrons produce the same type of spallation reactions as fast protons. Barbier⁽²⁾ has placed samples of fifteen materials, C, H₂O, Mg, Al, SiO₂, Ti, Fe, Co, Ni, Cu, Mo, Ag, Cd, W, and Pb, outside the CERN Synchro-Cyclotron in the path of neutrons emitted when the internal meson-producing targets are struck by the proton beam. The beam loses energy in the target and spirals back into the machine, while the fast neutrons produced by the protons are forward-peaked and emerge from the cyclotron, mainly at small angles. Thus, Barbier's samples were activated by only the fast neutrons. The γ -ray decay curves were compared with the decay curves obtained from other samples activated by the proton beam. Since the two sets of curves were similar in shape, it is assumed that fast neutrons

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Fig. 6.1. Calculated and experimental residual radiation decay curves for carbon, aluminum, iron, and copper activated by proton-induced spallation reactions.

Table 6.1. Ratio of calculated to experimental dose rates.

	Days of Cooling				
	0.4	2.1	21	100	210
Carbon	1.03	1.03	1.27	1.06	0.67
Aluminum	1.93	1.57	normalized	normalized	normalized
Iron	0.83	0.74	0.58	0.49	0.61
Copper	1.29	1.02	0.82	0.74	0.69

Table 6.2. Comparison of proton and neutron activation.

Sample	Proton (Counts/g-sec)	Neutron (Counts/g-sec)	Ratio
C	165	4	41
Al	1600	21	76
Fe	5500	75	73
Cu	4200	80	53
Pb	420	12.5	34

and protons induced essentially the same spallation reactions. If the counting rates for similar samples are compared by determining the ratio of proton-induced activity to neutron-induced activity, it is apparent that, aside from different particle fluxes, the cross sections for the reactions induced by fast neutrons and fast protons are essentially equal. The counting rates, for C, Al, Fe, Cu, and Pb, after 100 days of cooling time, are summarized in Table 6.2. If it is assumed that there were approximately 40 times more protons hitting the samples placed inside the cyclotron than neutrons striking the samples situated outside the machine, then these ratios become unity within less than a factor of two. The determination of dose rates due to fast neutrons can thus be calculated after making the appropriate assumptions concerning the fast neutron flux.

The neutron and proton activation data discussed above provide a valuable check on the validity of the dose rates calculated by using the formula for D_j derived above. Figure 6.1 indicated that relative to the normalized aluminum curves the other experimental and calculated decay curves agree within a factor of two. These data do lack one important feature, however, and that is an absolute normalization. Barbier⁽²⁾ has exposed thin samples of various materials to a monitored proton beam (1.06×10^9 p/cm²-sec) for a period of three hours at the CERN Synchro-Cyclotron. By using the counting efficiency of the NaI crystal, measured by Barbier, his γ -ray counting rates were converted to absolute dose rates. The IBM-7090 computation was made for the irradiation of C, Al, Fe, and Cu samples by a proton beam of the same intensity for a period of 3 hours. The calculated decay curves and the experimental points obtained by Barbier are compared in Fig. 6.2. The calculated curves match quite well the shapes of the experimental decay curves. In addition, good agreement is found between the calculated and experimental dose rates for the C and Al samples. For Fe and Cu samples, the disagreement between the calculated and experimental dose rates is found to be in the range of a factor of two or three. This disagreement is not surprising, especially if one bears in mind the experimental errors involved in a bombardment of short duration by a beam of low intensity.

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Fig. 6.2. Calculated decay curves along with experimental points for samples irradiated in the CERN Synchro-Cyclotron.

As an example of the application of this IBM-7090 program, dose rates were calculated for a 100- μ A beam of 810-MeV protons striking 4-cm thick copper and 5-cm thick aluminum targets for a period of 100 hours. The residual radiation dose rates at a distance of 1 meter from the targets were plotted as a function of cooling time, see Fig. 6.3. The high radiation levels indicate the necessity for either handling these targets remotely or shielding them. Targets shield designs are discussed in the following section of this report.

Estimated Radiation Levels to be Found Between the Cyclotron Pole Faces

The calculations discussed above are for the special case of a collimated beam of particles impinging normal to the surface of a block of material. The calculations can be used, however, to estimate the residual radiation levels from distributed fluxes of particles and for oblique angles of incidence on the stopping material. The residual radiation level between the pole faces of the Mc² Cyclotron was estimated as follows.

If the beam is of high quality, such as the electron model (Analogue II) indicates, the principal source of activation will be from beam lost during extraction. For a 100- μ A beam and 90% extraction efficiency about 10 μ A would be slowed and scattered by the extraction system. The magnetic field will cause the charged particles to move to smaller radii and they will impinge on the pole faces at oblique angles. Barbier⁽²⁾ has obtained data which shows that the specific activation decreases with depth X in the pole face approximately as $\exp(-0.5X)$, where X is in cm.

Computer runs were made in which the incident beam was attenuated by a factor $-0.5/\text{cm}$ instead of by the geometric macroscopic cross section. This calculation predicts the residual radiation level where all activity is concentrated in a small area. The computed value was increased by a factor of 4 (this factor is based on the data of B. J. Moyer⁽⁸⁾) for fast-particle buildup in the stopping material, and by an estimated factor of 10 to account for the oblique incidence. It was then assumed that the activity is uniformly distributed over the pole face area. Except near the periphery of the poles the gamma flux in the gap may be computed by assuming the pole tips to be infinite plane slabs of activated material;

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Fig. 6.3. Calculated residual radiation dose rates at one meter from copper and aluminum targets after 100-hr bombardment with 100- μ A of 810 MeV protons.

standard solutions are readily available.⁽⁹⁾ The gamma flux for the case in which all of the activity is concentrated in a small volume (the assumption used in the computer calculation) is obtained by an inverse square calculation. The ratio of the flux due to the distributed activity to the flux due to the concentrated activity is multiplied by dose rate due to the latter to give the dose rate due to the distributed activity.

This method of estimating the residual radiation level was applied to the CERN data. A 1- μ A beam of primary protons was assumed. The curve in Fig. 6.4 is the computed residual radiation level after 1000 hr of cyclotron operation; the experimental points shown were measured by Barbier⁽²⁾ 15 days after a cyclotron shutdown. They were obtained at over 30 widely distributed locations throughout the cyclotron. For the detector used, 10^6 counts/sec for 0.5-MeV gammas corresponds to about 1 R/hr. In an actual case the activity is not uniformly distributed on the pole faces; thus, the distribution of the experimental points is not surprising.

The agreement of experimental and calculated radiation levels for the CERN machine suggests that estimates based on the same assumptions are valid for the Mc² Cyclotron. The estimated ranges thus obtained are shown in Fig. 6.5. The upper curves are for pole faces of iron and copper (sector coils). The lower curves show the residual radiation levels if the pole faces are covered with 4 cm of carbon. The results indicate that residual radiation levels can be reduced by more than an order of magnitude by covering the pole faces with a few cm of carbon.

The curves shown in Fig. 6.5 do not include activation due to evaporation neutrons. For the pole faces in the Mc² Cyclotron the evaporation neutrons are estimated to contribute ~ 50 mR/hr to the radiation levels encountered between 1 and 10 days after machine shutdown.

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Fig. 6.4. Residual radiation levels in CERN Synchro-Cyclotron gap. Solid curve is calculated. The experimental points were measured 15 days after cyclotron shutdown. For the detector used, 10^6 counts/sec of 0.5 MeV gammas corresponds to ~ 1 R/hr.

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Fig. 6.5. Calculated residual radiation levels in the Mc^2 Cyclotron after 1000 hr operation with $10 \mu\text{A}$ of protons being scattered into the pole faces by the beam extraction apparatus.

The radiation levels in the cyclotron vault result from several contributions. The activity produced on the pole faces will be shielded by the cyclotron itself; the radiation levels outside the cyclotron due to this activity should not exceed a few percent of the radiation level in the cyclotron gap. There will be local hot spots, however, where any beam is stopped in the external beam optics. For example, if 1 μ A of 810-MeV protons impinge on a thick slab of iron until saturation, the radiation level one meter away (with no shielding) one hour after shutdown will be between 1 and 2 R/hr. Thus, the external beam optics system must be designed to avoid stopping an appreciable fraction of the beam in unshielded locations.

One local area of above average radiation level in the cyclotron vault will be the region of the cyclotron vacuum tank that is irradiated by the forward peaked spallation neutrons produced in the beam extraction apparatus. If 10 μ A of protons impinge on the extraction apparatus and produce an average of one fast neutron per proton, a 20 x 50 cm area of the vacuum tank in the forward direction will be bombarded with $\sim 10^{12}$ fast neutrons/sec. The residual radiation level one meter away, due to the induced activity in the vacuum tank wall, is estimated to be ~ 100 mR/hr one hour after machine shutdown.

Activation of the Atmosphere

Activation of the atmosphere in the cyclotron vault and beam rooms will result from both spallation reactions and thermal neutron capture. Activities of greater than 1-min half-life that can be produced in the atmosphere are listed in Table 6.3. Thermal neutron absorption contributes to the production of H^3 and Ar^{41} only. The H^3 and other activities (except Ar^{41}) are produced in air by spallation reactions. A calculation of each type of reaction will illustrate the atmospheric activation levels for the Mc² facility.

Table 6. 3. Activation of atmosphere.

Activity	Half-life	Radiation	Method of Production	Cross Section (mb)	Maximum Permissible Concentration 40/hr week, whole body ($\mu\text{C}/\text{cm}^3$)
H^3	12.26 y	β^-	H^2 thermal capture (p, t) on oxygen and nitrogen	0.57 ~ 5	5×10^{-6}
Be^7	53 d	0.48-MeV γ	Spallation on O and N	3 - 10	6×10^{-6}
C^{11}	20.5 m	β^+	Spallation on O and N	3 - 10	
N^{13}	10.0 m	β^+	N^{14} (p, d) O^{16} spallation	~ 7 ~ 6	
C^{14}	5770 y	β^-	N^{14} (n, p) O^{16} spallation		0.01
F^{18}	111 m	β^+	O^{18} (p, n)	1.5	4×10^{-5}
Ar^{41}	1.83 h	β^- , 1.29-MeV γ	Ar^{40} thermal capture	530	2×10^{-6}

Thermal Neutron Capture. - H^3 is produced by thermal neutron capture of H^2 and Ar^{41} by thermal neutron capture by Ar^{40} . Both the atmospheric concentration and the thermal neutron absorption cross section of H^2 are a few orders of magnitude lower than for Ar^{40} , so Ar^{41} is the only important activity that can be produced in the atmosphere by thermal neutron absorption.

If 800-MeV protons are stopped in material of $A \sim 60$, the evaporation neutron yield is ~ 4.0 neutrons/protons. (It is assumed that the spallation neutrons will produce nuclear reactions without becoming thermalized.) Thus, $1 \mu A$ of beam results in a production rate of 2.5×10^{13} n/sec. The thermal neutron flux in the room φ_{th} is given by⁽¹⁰⁾,

$$\varphi_{th} = 1.25 Q/S$$

where Q is the production rate and S is the wall surface area. S for the proton room of the Mc^2 installation is $\sim 40,000 \text{ ft}^2$ or $4 \times 10^7 \text{ cm}^2$. Therefore,

$$\varphi_{th} = \frac{1.25 \times 2.5 \times 10^{13} \text{ n/sec}}{4 \times 10^7 \text{ cm}^2} = 7.8 \times 10^5 \text{ n/cm}^2 \cdot \text{sec}$$

is the thermal neutron flux in the volume of the room. This does not allow for any thermal neutron absorption in the walls and assumes that all evaporation neutrons are thermalized.

The production rate R of Ar^{41} for each cubic centimeter is

$$R = \Sigma_{\text{th}} \varphi_{\text{th}},$$

where Σ_{th} is the macroscopic cross section for Ar^{40} in the atmosphere. The value of Σ_{th} is $1.3 \times 10^{-7}/\text{cm}$; therefore,

$$\begin{aligned} R &= (1.3 \times 10^{-7}/\text{cm}) (7.8 \times 10^5 \text{ n/cm}^2\text{-sec}) \\ &= 0.103 \text{ Ar}^{41} \text{ atoms/cm}^3 \text{ sec.} \end{aligned}$$

If there were no ventilation and the beam were maintained until saturation of the Ar^{41} activity prevailed, the level would be $0.103 \text{ dis/cm}^3\text{-sec}$ or $2.8 \times 10^{-6} \mu\text{C/cm}^3$. This is 1.5 times the maximum permissible concentration for 40 hr/week whole body exposure (National Bureau of Standards Handbook No. 69). With a 1.83-hr half-life the activity level will decay by about four orders in magnitude during the first day after shutdown. Thus, if a few hours of cooling time after cyclotron shutdown are allowed before personnel enter the beam rooms, Ar^{41} activation of the atmosphere does not present a serious problem.

There will of course be ventilation of the cyclotron vault and beam rooms. This reduces the saturation level of a specific airborne activity. A calculation based on one air change per hour indicated that the saturation level of Ar^{41} in the proton room will be at the maximum permissible level for 40 hr/week whole body exposure only if the proton beam intensity is 20 μA of 800-MeV protons.

Spallation. - Spallation reactions in the atmosphere will be induced by both fast protons and fast neutrons. If target shields and shielded beam stops are used it is reasonable to stop all of the protons and to reduce the number of neutrons by a factor of 100 in the shield.⁽¹¹⁾ The production of spallation neutrons in the target or beam stops is ~ 2.5 neutrons/proton. Thus, the number of fast particles emerging into the atmosphere does not need to be more than 4% of the number of particles in the beam.

Cross sections for production of various spallation products in air are generally $\lesssim 10$ mb. Thus, the macroscopic cross section is $6 \times 10^{-7}/\text{cm}$. If we consider a $1 \mu\text{A}$ beam of protons in a 10-meter path in air, the production rate R of an activity for which the cross section is 10 mb is

$$\begin{aligned} R &= \Sigma I X \\ &= (6 \times 10^{-7}/\text{cm}) (6.25 \times 10^{12}/\text{sec}) 10^3 \text{ cm} \\ &= 3.74 \times 10^9/\text{sec}. \end{aligned}$$

If these diffuse uniformly throughout the volume of the room (for the proton room volume $= 4.5 \times 10^5 \text{ ft}^3 = 1.13 \times 10^{10} \text{ cm}^3$) the production rate in the air of the room is $(3.7 \times 10^9)/(1.13 \times 10^{10}) = 0.33 \text{ atoms/cm}^3\text{-sec}$. At saturation (with no ventilation) this corresponds to $10 \times 10^{-6} \mu\text{C/cm}^3$. Thus, if the beam is kept in a beam pipe and shields are used to attenuate spallation neutrons by about two order of magnitude, the saturation activity with no ventilation will be less than $10^{-6} \mu\text{C/cm}^3$. With one air change/hr the level will be somewhat less. The maximum permissible concentration for 40 hr/week whole body exposure as shown in Table 6.3 is more than $10^{-6} \mu\text{C/cm}^3$ for all activities. Thus, with one air change/hr the air activation levels at the cyclotron vault will be maintained within tolerable levels.

Radiation Damage

One problem to be encountered with the Mc^2 Cyclotron is the radiation damage to certain components caused either by the primary or scattered proton beam or by the dose rates due to the activities induced in materials situated close to these components. The damage to a particular type of component by a given integrated dose rate can be found in various publications. For example, a comprehensive table, too long to reproduce here, on radiation damage to plastics is shown in Chapter 6 of a forthcoming book edited by R. O. Bolt and J. G. Carroll.⁽¹²⁾ The table presents a summary of changes in mechanical properties resulting from irradiation of commercial plastics. From such available information decisions can be made as to what type of insulator to use at a given location. These decisions, of course, must be based in part on the dose rates estimated for each specific circumstance.

The above-described IBM-7090 program can be used to calculate induced dose rates in materials situated close to a given insulator. As an illustration, let us consider an insulator placed 10 cm from a meson-producing 4-cm-thick copper target. At the end of a 100-hr bombardment by a 100- μ A proton beam, the calculated dose rate is $\approx 10^4$ R/hr. Most of this dose rate is due to activities whose half-lives are on the order of several hours or less. These activities will have achieved saturation levels in the course of the 100-hr bombardment. The insulator, therefore, has been irradiated by an integrated dose of about 10^6 R. According to the table in Ref. 12, teflon retains only 10-50% of its tensile strength and elongation properties after an irradiation of 5×10^6 R; it should not be used as an insulating material at this location. Some other materials, such as clear polystyrene, could be employed; this material retains 80% of its properties for an integrated dose of 10^{10} R.

Dose rates from induced activities can be calculated for the radioactivity due to only those isotopes whose production cross sections have been measured experimentally. Cross sections for short-lived isotopes (less than 5-min half-lives) are generally unavailable. It is imperative to know the contribution these short-lived isotopes will add to the dose rates. Barbier⁽²⁾ has recently measured radiation levels in the CERN Synchro-Cyclotron vault two minutes after machine shutdown. His measurements showed these levels to be a factor of two greater than those he had previously measured 30 min after shutdown. This factor of two resulting from short-lived nuclides must be taken into account when radiation damage due to induced activities is considered.

Non-metallic components can also be damaged if they are exposed to the direct or scattered proton beam. A 1- μ A/cm² beam of 810-MeV protons corresponds to a dose rate of about 10^9 R/hr. Therefore, the radiation damage can be determined if the amount of beam striking the components is known.

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7. TARGET SHIELDS AND BEAM STOPS

The interaction of high-energy nuclear particles with matter results in the production of neutrons, mesons, and other charged particles and in residual radioactivity. To achieve the maximum research capabilities of high beam intensity accelerators, such as the Mc^2 cyclotron, careful consideration must be given to the important sources of radiation, and steps must be taken to minimize and contain the residual radioactivity. Two important sources of radiation are targets and beam catchers. Some ideas on the design of target shields and shielded beam stops were presented at the 1963 International Conference on Sector-Focused Cyclotrons and Meson Factories.⁽¹⁾ The discussion below is based in part on that paper.

Target Shields

A thick target used for meson production will become very radioactive. During bombardment it becomes an intense source of both high energy spallation neutrons and low energy evaporation neutrons. The target shield should protect the surrounding equipment, floors, and walls from the high neutron flux from the target. At least the outer part of the shield should consist of materials that produce predominately short-lived radioactivities; also, it should provide high absorption of the residual radiations. The volume and cost of the shield are, of course, important factors.

The cross section for removal of high-energy neutrons by a shielding material is the total reaction cross section, which may be assumed to be approximately the geometric cross section of the nucleus $\sigma = \pi r_0^2 A^{2/3}$, where A is the atomic weight of the shielding material. The neutron flux is attenuated by the macroscopic cross section, $\Sigma = N\sigma$, where N is the number of nuclei per unit volume, i. e. $N = \text{const.} (\rho/A)$, where ρ is the density of the material. Thus, $\Sigma \propto A^{2/3} \rho/A = \text{const.} (\rho/A^{1/3})$ is a

criterion to be used in selecting a material for spallation neutron shielding. This value for several materials is listed below:

<u>Material</u>	<u>$\rho/A^{1/3}$</u>
Carbon	0.87
Aluminum	0.90
Iron	2.06
Lead	1.92

Another, but less important consideration, is the production of evaporation neutrons; these must be removed by being thermalized and absorbed in material of large thermal neutron cross section, such as boron or cadmium. In general the evaporation neutron production increases with atomic weight of the material. The yield of both evaporation and spallation neutrons produced by 800-MeV protons is shown as a function of atomic weight of target material in Fig. 7.1. The yield of evaporation neutrons produced by spallation neutrons is similar to the yield of protons of the same energy.

The other main considerations in the selection of materials for the design of a target shield are the residual radioactivity induced in the shielding material and the shielding properties of the material for gamma radiation.

Recent experiments at the CERN Synchro-Cyclotron with 600-MeV protons⁽²⁾ yielded information that is pertinent to the selection of shield materials. These studies indicate that lead is better than medium weight materials, such as iron, because the residual radiation is less intense and shorter lived in the case of lead. Lead also has excellent shielding properties for the residual radiation.

A criterion for determining the thickness of the target shield is the maximum acceptable neutron flux at the exterior surface of the shield. If it is assumed that the activation of lead is similar to that of tantalum, the work at CERN⁽²⁾, based on long-term exposure to neutron fluxes, indicates that where the neutron flux is $\sim 2 \times 10^7$ n/cm²-sec the residual radiation dose rate will be ~ 100 mR/hr at one day after shutdown, ~ 30 mR/hr one week after shutdown, and ~ 10 mR/hr one month after shutdown.

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Fig. 7.1. Neutron production as function of atomic weight of target material. These curves were extrapolated from the data of Moyer⁽³⁾.

An illustrative design of a target shield is shown in Fig. 7.2. It is desirable to keep the dimension along the beam exit direction as small as possible in order that a quadrupole lens may be effective in converging the charged mesons emitted from the target and for effective collection of the multiply scattered proton beam. For neutron attenuation (discussed above) iron appears to be the best choice of shielding material since it has the largest macroscopic reaction cross section, and consequently the smallest relaxation length of the readily available materials. Surrounding the iron part of the shield, an outer layer of a few centimeters of lead should be included for shielding against residual radiation. The beam exit channel is conical because of multiple scattering of the proton beam in the target.

When target materials are bombarded with intense beams of protons, the targets become very radioactive. For thick targets in an intense beam it is important to have remotely controlled facilities for removing the target from the beam position to a shielded cooling area. The lateral channel shown in Fig. 7.2 provides access for target installation, removal, and cooling.

The target shield shown in Fig. 7.2 is suggested as adequate to provide minimum shielding for a 100- μ A beam of 800-MeV protons bombarding a target sufficiently thick that 1/4 of the incident particles produce spallation reactions in the target. In this situation 1/4 of the incident protons would each produce about 2 to 3 spallation neutrons, depending on the atomic weight of the target material. Thus, total spallation neutron production would be about 4×10^{14} n/sec. If the angular distribution is similar to that for 6.3-GeV spallation reactions in copper⁽⁴⁾, the fast neutron flux at points A and B (in Fig. 7.2) will be about 2×10^7 n/cm²-sec. Without the target shield the fluxes at A and B would be $\sim 10^{10}$ and 1.2×10^9 respectively. These fluxes would, during an extended period of operation, induce radioactivities in the neighboring equipment, floors, and walls that would result in residual radiation levels severely limiting access of personnel to the area. In principle the target can be placed far enough from the walls for geometric attenuation to reduce the residual radiation to a tolerable level. In practice, however, this is often difficult to achieve, especially for the floors.

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Fig. 7.2. Illustrative design of target shield.

As was discussed above, the residual radiation level near the outside surface of the target shield will be ~ 100 mR/hr one day after shutdown if the fast neutron flux at the outside surface is $\sim 2 \times 10^7$ n/cm²-sec for a long exposure. It will decay to ~ 30 mR/hr in one week and ~ 10 mR/hr in one month. These values do not include contributions to the radiation levels from other sources in the area. In practice the time average of the beam intensity will be somewhat lower than the maximum of 100 μ A. If the target shields are designed to provide the minimum required shielding for the maximum beam intensity they will, of course, provide more than the minimum for the average beam intensity.

The target shields will contain the residual radioactivity that would have been distributed in the walls, floors, and equipment if the shields were not used. The specific activation of the target shield will be highest in the materials nearest the target position; therefore, during a shutdown shielding plugs should be used to cover the channels in the target shield. The residual radiation level in the area can be further reduced by removing the target shield during a shutdown, if personnel access to the area requires it.

Beam Stops

For beam stops one must consider three effects that are not included in the above discussion of target shields. These are neutron production, heat removal, and the range of the protons in the stopping material. The ranges of 800-MeV protons in several materials are:

<u>Material</u>	<u>Range (cm)</u>
Air	2.4×10^5
Water	260
Beryllium	151
Carbon (density = 2)	133
Aluminum	111
Iron	45
Lead	41
Copper	39

Neutron production as a function of the atomic weight of the stopping material is shown in Fig. 7.1. The best choice of material from the standpoint of proton range, fast neutron attenuation, evaporation neutron production, and cost appears to be iron for both the proton beam stop and the shielding around it.

The proposed beam stop for up to 100 μA of 800-MeV protons is shown in Fig. 7.3. To facilitate heat removal (up to 80 kW) the iron that stops the proton beam is laminated and water is circulated through the space between the iron sheets and around the central iron region. Iron is also suggested for the region surrounding the water volume. An outer layer of a few cm of lead should be included because of its lower residual radioactivity level and its favorable shielding properties for the residual radiation of the iron.

If 100 μA of 800-MeV protons are stopped in iron, the spallation neutron production rate is estimated (see Fig. 7.1) to be about 1.5×10^{15} n/sec. The beam stop and surrounding shield should reduce the neutron flux at the surface of the shield to the same level as that of the thick target shield that was discussed above. This criterion and choice of materials determine the size of the beam stop shield.

For the beam stop shown in Fig. 7.3 the fast neutron flux at the outer surface will not exceed 2×10^7 n/cm²-sec for 100 μA of 800-MeV protons.

The evaporation neutrons produced in the beam stop will be thermalized in the water. The thermal neutron flux will be attenuated by neutron capture in the outer region of iron. Further reduction of thermal neutron fluxes can be easily achieved by a small thickness of cadmium or other material of large thermal neutron absorption cross section.

The requirements of beam stops will vary with the experiment. For thick-target bombardments, such as would be employed for meson production, the beam stop may be located a short distance away from the target. In this situation the main requirement of the beam stop shield is to maintain residual radiation levels at a tolerable level for personnel access during shutdown. For other experiments such as thin-target proton experiments or neutron experiments the requirements of the beam

stop is to keep neutron background levels tolerable for the experiment in progress. In this situation the beam stop would be located at greater distance from the experimental target, and additional shielding such as stacked concrete blocks or sand bags would be used. The beam stop illustrated in Fig. 7.3 is movable and adaptable to a variety of experimental requirements.

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8. CYCLOTRON DESIGN AND SPECIFICATIONS

This section describes the mechanical design of the magnet, the rf cavities, the ion injection system, the beam extraction system, and the vacuum system. The detailed magnetic field and the rf system design considerations are described in Chapters 9 and 10 respectively. A summary of the principal cyclotron specifications are given in Table 8.1.

The Magnet

The magnet is composed of eight identical "C" shaped sectors that spiral out from the center of the machine. They are spaced at equal angles azimuthally and are symmetrically disposed above and below the horizontal midplane, see Fig. 8.1 and 8.2. Each sector is composed of an upper and a lower pole joined by a vertical yoke located outside the maximum radius of the beam. Each pole consists of two horizontal yoke pieces supporting a pole tip and two attached coils, see Fig. 8.2. An average-field coil is wound around the vertical sides of each pole tip. The radial gradient coils are wound around the outer arc of the pole tip but pass across the pole tip face at selected radial intervals. All coils are encased in stainless steel to exclude the insulation from the vacuum space. The leads are directed downward and penetrate the lower vacuum tank head for connection to the dc current leads.

Magnet Yoke and Pole Pieces. - The mechanical design of the magnet presented many unusual problems because of its size and weight, and because of the large magnetic forces which are developed. Representatives of the steel industry were consulted to determine the size of forging of the required shapes that could be practicably produced. It was found that the sectors would necessarily have to be constructed by assembling several large forged plates. Both horizontal and vertical plates were considered as possible types of construction. Vertical plates introduce difficult fabrication problems

Table 8.1. Specifications of the Mc² Cyclotron.

<u>General</u>	
Energy, internal, max	900 MeV
At maximum orbit radius, av	240 in.
Energy, extracted beam	810 MeV
Extraction radius	230 in.
Internal beam current, peak	200 μ A
Internal beam current, normal	115 μ A
Extracted beam current	100 μ A
Orbit frequency	6.86 Mc/s
<u>Magnet</u>	
Maximum field	18,000 gauss
Central field	4,500 gauss
Spiral law	$\theta = r^2$
Tan γ at extraction radius	1.41
Magnet gap	8 in.
Number of sectors	8
Maximum diameter	53 ft
Height	14 ft
Pole diameter	41 ft
Gap tolerance	± 0.004 in.
Main field coils	8 pairs
Magnet power, total	7-8 MW
Weight, cyclotron analysis steel	4,800 tons
Copper	150-190 tons
<u>Radio-Frequency System</u>	
Operating frequency of coaxial cavities	13.72 Mc/s
Number of accelerating gaps	4
Mode of cavity operation	TEM
Q (unloaded)	30,000
Peak gap voltage	250 kV
Energy gain per turn	1.0 MeV
Beam aperture	4 in.
Cavity half-height	10 ft
Power coupling	capacitive
Total power input	1,200 kW
Total RF power	872 kW
Power loss to cavities	500 kW
Beam power, max	160 kW
Contingency losses	200 kW
Amplifier operation	push-pull
Power tubes, two	RCA 6949
Frequency determined by	master oscillator

(contd.)

DC Injector

Energy	1 MeV
Current	1 mA
Inflector radius	8 in.
Inflector field	6,700 gauss
Orbit radius at inflection	12 in.

Beam Dynamics

v_z	0.2 - 0.3
v_r	1.0 - 2.0
Oscillation amplitude	0.5 in.
Radial amplitude, max	4.5 - 9.0 mm
Phase lag permissible	30°

Accelerator Vacuum Tank, mild steel

Inside diameter	62 ft
Overall height	44 ft
Gross volume	3.2×10^6 liters
Pumped volume	2.6×10^6 liters

Vacuum System

Design pressure	1×10^{-6} torr
Operating pressure	5×10^{-6} torr
Pumping time, to 0.05 torr	40 min
Pumping time, to 5×10^{-6} torr	17 hr
Number of 32 in. diffusion pumps	20
Type of oil	DC-705
Baffle temperature	-50°C
Total pumping speed	1×10^6 liters/s
Effective pumping speed	2.5×10^5 liters/s
Forepumps	Roots and mechanical
Maximum roughing speed	42,000 cfm

Fig. 8.1. Plan view and section of Mc^2 Cyclotron.

Fig. 8. 2. Vertical section of Mc^2 Cyclotron.

due to the curvature of the poles. Horizontal plates appeared more economical in comparison. Consequently, the design is based on this concept.

An initial problem to be investigated was the deflection of the pole faces. The magnetic forces were calculated; subsequently, the calculations were verified, to within about 10%, by the model magnet measurements. It was also determined by estimate and verified by the model that a stanchion located near the central tip of each sector would be necessary.

A vertical section through a magnet sector is shown in Fig. 8.3, along with data used in calculating the deflection of the upper half of the "C." The effective radial distribution of the dead-weight load of the iron and of the load imposed by the magnetic field are shown along the top of the section.

The stanchion is centered at about 8.5 in; this is inside the first beam orbit. The force of 242,000 pounds at the stanchion is the force required to maintain zero deflection at the sector tip. Cantilevering the sector from the outside yoke is regarded as impractical.

The deflections were calculated by the "area-moment method" which uses the displacement of the moment curve from a zero axis to give vertical deflections of a beam. In computing the moment of inertia of the layered yoke, the total moment of inertia at each cross section of the beam was assumed to be the sum of the moments of inertia of each layer. This approach does not credit the layers with acting as a composite or unified beam. Thus, since in practice all parts will be doweled and bolted together, the actual deflections will be less than shown. The maximum bending stress encountered is only 3850 lb/in^2 .

With the present design, the entire magnet will require 72 machined forgings. The layout of the nine forgings which comprise each of the eight sectors is shown in Fig. 8.4. Due to the spiral configuration, the forgings in the upper and lower halves mirror each other. The largest piece weighs somewhat less than 70 tons, finished. Parts B_2 and E_2 of each sector require very large ingots and also require use of one of the largest forges available in the steel industry.

Fig. 8. 3. Section of magnet sector showing forces on and deflection of upper pole.

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PLAN VIEW OF SECTOR

ELEVATION VIEW OF SECTOR

Fig. 8.4. Steel plates required for magnet sector.

It is suggested that these large pieces can be flame cut to rough shape from large flat rectangular forged slabs. To complete each piece, the flat sides can be planed and the curved surfaces can be machined with a traveling mill. The large bolt holes for assembly can be drilled with a horizontal boring mill, or with a traveling crane drill. The above procedures are all common in present day industrial practice.

It has been found that excellent magnetic properties, and good forging and machining properties are provided by steel having the following analysis:

<u>Trace Element</u>	<u>Maximum Allowable</u>
C	0.15%
Mn	0.50
P	0.04
S	0.05
Si	0.20
Ni	0.08

The above composition is generally known as cyclotron analysis steel. The Oak Ridge National Laboratory and other groups have found this type of steel to be very satisfactory for use in large magnets.

Magnet Support. - The support structure must provide a stable base for mounting the magnet and still allow clearance for the removal of the lower halves of the rf cavities, see Fig. 8.2. Since the cavities divide the magnet into four areas, the support system is also in four sections. The two sectors in each section are supported by six columns, three for each sector. These six columns are braced to give a stable platform; they are connected to the other sections by tie beams which can be removed to permit the bottom half of an rf cavity to be lowered and removed from the vacuum tank. This system of supports places the median plane of the magnet 21 ft above the vault floor.

The height of the columns was reduced by about 13 ft from the design shown previously (ORNL-3324). This was achieved by designing the vacuum tank with a flat lower head so that the columns rest on the

head and on concrete piers, Fig. 8.2. This design also eliminates the necessity for the columns to penetrate the lower head.

The RF Cavities

The cost of the magnet would be increased unreasonably if a gap suitably large for conventional dees were provided. For this reason, a system for acceleration with vertically oriented resonant cavities was adopted. Two cavities are inserted vertically in the 16 in. space between alternate magnet sectors, see Fig. 8.1 and 8.2. Each cavity encircles two sectors of the magnet. The two cavities intersect at the center, thus dividing the magnet into four parts. The cavities are supported from the sectors with mounts which can be adjusted to obtaining proper alignment with the magnet gap. To facilitate installation and servicing, the cavities are divided into sections. Since the rf currents flow in a vertical direction, all mechanical joints are also vertical. All of the cavity sections can be removed from overhead except the lower sections that are within the 16 in. wide space between sectors. These sections can be lowered to the tank bottom and moved out through side openings provided at four places in the vacuum tank wall.

Under the present concept the cavities can be constructed of copper sheet, with attached copper tubing for water cooling. Since a total of 10,000 ft² of copper sheet is necessary, furnace brazing of the tubing to the sheet can be employed economically for those areas where annealed copper (soft) is acceptable. Rigidity of these portions can be achieved by using an interconnected system of stainless steel reinforcing channels and beams and by connecting the cavities to the magnet sectors. Other areas where soft copper is undesirable can be fabricated by a Heliarc welding process using BT solder. This relatively new technique was employed on the new Oak Ridge Isochronous Cyclotron with excellent results.

Assembly and Maintenance

Because of the very great complication associated with a small vacuum tank that would fit inside the magnet gap and yet also contain the rf cavities, the alternate approach of enclosing the entire magnet in a large vacuum tank was adopted. The top head of the tank (62 ft in dia) is removable for assembly and for major servicing of the cyclotron.

For the initial assembly of the magnet the lower half of the sectors with attached coils can be assembled on the support platform. These units can be carefully aligned and leveled. The outer yokes can be lowered into place and aligned. Then the upper half of the sectors with coils can be lowered, aligned, and bolted into place. Next the upper inner sections of the cavity can be installed. The lower section of the cavity, due to its cross section, will not pass through the 16 in. space between magnet sectors; however, it can be installed from below the magnet. These units can be moved through openings in the tank wall under the magnet and be lifted into position and connected to the other cavity sections. Finally the outer "wrap around" sections of the cavity are installed. Disassembly for servicing of the machine can follow the reverse of this procedure.

For work not requiring the use of the overhead crane, maintenance personnel can enter the vacuum tank through a number of access ports.

Ion Injector System

The ion injector system planned for the cyclotron consists of a 1-MeV dc accelerator located external to the cyclotron vault. The beam is injected into the cyclotron by means of a lens system and a magnetic inflector. This arrangement provides a beam of high phase-space density, and a degree of operating flexibility unique for cyclotrons: the microscopic duty factor can be varied over wide limits; the phase of injection can be adjusted; and single-pulse operation over a wide range of repetition rates, variable pulse width, is easily achieved. This latter feature will be of particular value for time-of-flight experiments.

Beam Emittance Requirements. - The beam emittance requirements for the Mc^2 Cyclotron injector were estimated from measurements made in Cyclotron Analogue II. In the Analogue the radial amplitude of the internal beam is 0.25 mm at extraction radius. The equivalent value for the Mc^2 Cyclotron is 4.25 mm. The corresponding beam emittance (assuming uniform radial oscillation phase distribution) is 21 mm-mrad. The required emittance at injection is larger than the final energy value by the ratio of the momenta at the two energies. At 1 MeV the required emittance is 720 mm-mrad. This value is easily achievable with modern ion sources; for example, McKeever and Yokosawa⁽¹⁾ have reported an emittance of 250 mm-mrad for a 0.2 MeV, 80 mA beam from the ZGS injector ion source. The corresponding emittance at 1 MeV is 112 mm-mrad.

The injection energy also has an important bearing on the performance of a dc injection system for a cyclotron. Because the point of injection is fixed in the machine, the location of the ion orbit center will depend on the energy gain per turn, and therefore on the rf phase. If the point of injection is optimized for one phase of transit of the acceleration gaps then ions which traverse the gap at other phases will have displaced orbit centers. The radial amplitude that results from this effect depends on the injection energy and phase, as illustrated in Fig. 8.5. The choice of 1 MeV injection for the Mc^2 Cyclotron will result in a radial amplitude of only 2.1 mm. for 30° phase acceptance.

Although higher injection energy would result in smaller radial amplitudes or, conversely, a larger phase acceptance at the same amplitude, the smaller turn spacing at higher energy and the increased power requirement for the inflector magnet make the design of the system more difficult. It is believed that the choice of a 1-MeV system represents a reasonable compromise.

Choice of DC Accelerator. - The dc accelerator chosen for the Mc^2 injector system is a 1-MeV tandem unit into which a neutral beam is injected. Units employing either the ICT* or Dynamitron**

*Insulated Core Transformer, High Voltage Engineering Corp., Burlington, Mass.

**Radiation Dynamics, Inc., Westbury, N.Y.

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Fig. 8.5. Radial amplitude vs injection energy, with phase acceptance as parameter, for 4500 gauss central field, 250 kV peak accelerating gap voltage, and optimized injection radius.

power supply concepts are well suited for this application. Beam is formed initially at 30 keV, an energy favorable for neutral beam production and subsequent stripping at the high voltage terminal of the tandem. Injection of neutral particles has the chief advantages that the ion source and associated beam programming equipment are at ground potential. Also, by replacing the gas stripper in the terminal with an ionizer assembly, polarized proton beams can be accelerated. Several more ordinary systems have been investigated, including open-terminal units, single-ended pressurized units, and conventional Van de Graaff machines. All suffer from one or more of the following defects: excessive space requirements, lack of terminal space, lack of terminal auxiliary power, and lack of flexibility for future uses. The injector system selected is shown schematically in Fig. 8.6.

Beam programming can be provided by deflection pulsing at a proton energy of 30 keV. With this system, the deflection plates are driven at one-half the cyclotron rf frequency from a source synchronized with the master oscillator of the cyclotron rf system. The phase of injection relative to the cyclotron rf can be easily varied; by changing the sweep amplitude, the length of injected pulses can be adjusted.

Counting circuitry can be used to trigger a deflection voltage to provide single bursts variable in length in the range of 1 to 15 nanoseconds and separated by an integral number of rf cycles. For pulsed operation, much higher instantaneous currents than would be customarily used in continuous acceleration can be accelerated without exceeding the capacity of the dc injector or the cyclotron radiofrequency system. Peak currents of tens of milliamperes are easily achievable.

Beam Transport and Inflection into the Cyclotron. - The dc accelerator and ion source equipment are both located outside the cyclotron vault. Maintenance of the units is not complicated by background radiation and the components are free from any limitations imposed by radiation damage. In particular, there is no need to preclude the use of solid state electronics components, as might be the case if the injector were located inside the vault.

Fig. 8.6. Schematic of system for injecting 1-MeV protons.

The arrangement of the inflector and beam pipe system is shown in the elevation view of Fig. 8.7 and in the median plane sections Fig. 8.8. The beam enters the cyclotron vacuum chamber below the magnet assembly. At a point below the cyclotron center, the beam is bent vertically, passes between the poles, and enters the inflector magnet. The inflector magnet bends the beam into the median plane of the cyclotron at a radius of about 12 in. The inflector magnet has a radius of about 8 in. and a field strength of 6,700 gauss. Although magnet shimming and compensating windings should compensate the field perturbation caused by the inflector, the requirements are not critical because of the large turn spacing. The second orbit is separated from the injection point by 5 in., thus, the beam expands rapidly outward away from the inflector region.

Beam Extraction

The design of the beam extraction system is a direct application of experience with electron beam extraction in Cyclotron Analogue II, see Chapter 5. A magnetic channel extractor will be required, however, in place of the electrostatic system used in the Analogue. This is because electric fields are relatively ineffective at high particle velocities, but the force on an ion due to a magnetic field is proportional to velocity. The electric field used in the Analogue extraction experiments, 6.6 kV/cm, scales to 700 kV/cm for the Mc² Cyclotron, but the equivalent magnetic flux density is only 2,800 gauss. Although a channel field of 2,800 gauss could be used, a slightly higher field will extract the beam more quickly and minimize distortion from the nonlinear magnetic field gradient of the fringing field. The beam trajectory for a 10 ft long 4,000 gauss channel is shown in Fig. 8.9. As shown in the figure, the beam passes through the magnet yoke, where quadrupole elements are provided to focus the beam.

The magnet channel is similar to units now in use in other cyclotrons at ORNL. These are based on the combined effect of iron and current sheets in a magnetic field, as illustrated in Fig. 8.10. The iron reduces the magnetic field locally on both sides; the current

Fig. 8.7. Injector system, elevation view.

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Fig. 8. 8. Inflector arrangement at center of Mc^2 Cyclotron.

Fig. 8. 9. Arrangement of beam extraction system.

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Fig. 8.10. Effects of iron and current sheets in magnet gap.

sheet cancels the effect of the iron on one side and further decreases the field on the other. A pair of such elements are used to form a channel with a radial aperture of 2 to 2.5 in. Additional conductors are placed at the gap faces, both inside and outside the channel aperture, to control gradients and to cancel any residual field perturbation in the region of the circulating beam. About 50,000 A are required in the channel; the linear power density is approximately 40 kW/ft for a 3/8 in. thick channel wall. The required power can be rapidly reduced, however, by increasing the conductor thickness as the extracted beam is separated further from the circulating beam.

Magnet channels for more sophisticated designs could be used to realize a much smaller effective wall thickness for the channel entrance section, although at the expense of additional power. An example is the coaxial unit now in use at Oak Ridge.⁽²⁾

To block out that portion of the beam, 10 to 20 μ A, which would normally strike the entrance to the magnetic channel, a narrow beam stop located diametrically opposite the extractor entrance is used to shadow the inner-radius element of the magnetic channel. This is possible as a consequence of the fact that at $v_r = 2$, the turn separation grows coherently on two opposing hills. During cyclotron maintenance the beam stop can be moved by remote control into a shielded enclosure so that the induced radioactivity will not contribute to the radiation background. The use of the beam stop will reduce the current striking the extraction system to the 1 to 5- μ A level, of the same order as in frequency-modulated cyclotrons.

The magnet channel can be designed to preclude appreciable radiation damage to the insulating materials. This requirement suggests the use of stable inorganic insulating materials, such as aluminum or magnesium oxide.

Accelerator Tank

As indicated above, the vacuum tank encloses the entire magnet and rf system. The magnet coils are "canned" to separate the insulation from the vacuum system. All of the other cyclotron components are exposed to vacuum.

The tank, although very large, is clearly within conventional design and construction practice. It has an inside diameter of 62 ft and is 44 ft high, see Figs. 8.1 and 8.2. It is constructed of 1/2 in. thick carbon steel plate and is reinforced with vertical beams between ring girders.

An unusual feature of this tank, in addition to its size, is the flat lower head. It is constructed of 1-in. steel plate anchored into the concrete foundation with steel rods on 48 in. centers. In addition to this restraint, twelve steel columns supporting the 4,800 ton magnet rest on the head at points which are in turn supported by twelve concrete piers. A clearance of 4 ft to the floor is provided for utilities piping.

The upper head of the tank is 62 ft in dia. and is removable for servicing the accelerator. Four large openings in the side wall of the tank are large enough, 11 ft high and 4 ft wide, to pass sections of the rf cavity.

Metallic seals are used in regions of high radiation intensity, such as in the median plane near the extraction mechanism, and in regions where replacement is difficult. As a general rule, elastomer seals are used only where the predicted 10-yr radiation dose is less than 10^8 rad and where the seal is easily changed. The tank head gasket is a double elastomer seal with provision for pumping out the volume between gaskets.

Since both the head and tank flanges are too large to transport, they will be assembled in the building. The gasket groove and gasket surfaces can be machined by a traveling mill erected on the tank. This technique was used successfully on a number of the large chambers built in the recent past for space simulation.

The Vacuum System

The basic requirements of the vacuum system are to provide a pressure between 1×10^{-5} and 1×10^{-6} torr and to achieve it in a reasonable length of time. The large volume of the tank, 2.6×10^6 liters, does not pose a serious problem because the free air can be

quickly removed. A more serious problem arises from the slow release of the large amount of gas trapped on and in the surface of the materials exposed to the vacuum. This outgassing plus leakage determines, of course, the base pressure for a given pumping capacity. A flow diagram is shown in Fig. 8.11.

High Vacuum. - The high vacuum system is designed to use standard components and to employ well established vacuum techniques.

The number of diffusion pumps was determined by the outgassing load and the time required to achieve a given pressure. The data of Blears et al⁽³⁾ was selected for calculating the outgassing load. This data represents a reasonable average of the published data, which contains wide variations. A pressure vs time curve was calculated for twenty 35-in. dia oil diffusion pumps, see Fig. 8.12. The net speed of these pumps was assumed to be 25% of the speed at the mouth of the pump, because of the usual losses in baffles and valves. This leaves a total net speed of 250,000 liters/sec for removing gas from the tank.

At the new Oak Ridge Cyclotron it was found that Blears' data predicts a gas load considerably in excess of the load actually measured by the rate of rise method. This difference amounts to a factor of 20 after one hour of pumping; it drops to approximately a factor of 2 after 20 hrs. It seems reasonable to expect, therefore, that the performance will be substantially better than shown in Fig. 8.12.

In this machine protons are injected from outside the tank and differential pumping is used on the injection pipe; consequently, the ion source gas load usually experienced in cyclotrons is eliminated. Other pumping methods, such as cryogenic pumping, may be investigated as a possible supplement to the diffusion pumps.

Forevacuum. - The forevacuum system is designed to evacuate the tank to a pressure low enough to permit opening the diffusion pump valves in about 40 min under average conditions. The system, Fig. 8.11, includes the following pumps:

Fig. 8.11. Cyclotron vacuum system.

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Fig. 8.12. Pumpdown curve calculated for Mc^2 vacuum system.

<u>Stage</u>	<u>Pumps</u>	<u>Pump Speed (cfm)</u>	<u>Total Speed (cfm)</u>
1st	2 Roots blowers	14,000	28,000
2nd	1 Roots blower	14,000	14,000
3rd	1 Roots blower	7,000	7,000
4th	1 Roots blower	3,500	3,500
5th	4 Mechanical pumps	500	2,000

When the roughing valve is open, all stages operate in series until the pressure in the tank reaches 2 torr. Stages one and two are then paralleled for a total speed of 42,000. When a pressure of 0.05 torr is reached the diffusion pump gate valves are opened, and the forevacuum system is used for backing the diffusion pumps. Shortly after this, when the initial heavy gas load is removed, the first stage is turned off and the remaining stages continue as a backing system.

This system is located outside the vault shield wall on the second floor of the cyclotron building. It is connected to the tank through a 30-in. dia. pipe with suitable automatic valving, Fig. 8.11.

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9. MAGNETIC FIELD DESIGN

In principle, the proven magnetic field of Cyclotron Analogue II, obtained without iron, could be scaled up to accelerate protons to the same ratio of kinetic energy to rest energy that is obtained for electrons. The values of average field and flutter would be correct for the heavier particles, and would, in fact, have to be achieved within a rather small tolerance. A close examination of the azimuthal variation of the Analogue field suggests, however, that such a magnetic field shape would be difficult to obtain with iron pole tips of simple rectangular cross section. It could be obtained with pole sectors of a more complicated shape, but this would increase the cost unnecessarily. A magnet with a rectangular azimuthal pole contour, the pole width varying with radius, can be constructed to give a magnetic field with the correct values of average field and flutter.

Three basic requirements for the Mc^2 Cyclotron are: the average field must have the proper value at all radii for isochronism, the spiral angle and flutter must give the proper focusing forces, and the field must be achievable with reasonable power. Beyond these requirements the advantages and disadvantages of various magnet configurations that might be used become more subtle and must be weighed against such factors as the cost, ease of beam extraction, and maintenance requirements.

Two methods of obtaining the required magnetic field for the Mc^2 Cyclotron have been investigated. Mc^2 Model Magnet I, a 0.15-scale model of three of the eight sectors, see Fig. 9.1, was fabricated and tested to determine the feasibility of constructing a magnet with characteristics similar to Analogue II, but using a uniform gap between iron poles driven by main coils and radial-gradient coils. This technique had been developed for and used in the construction of the ORIC magnet. The design of a magnet with this configuration can readily be calculated, and the measurements made with the model have demonstrated the reliability of these calculations. A second design study, now modeled

Fig. 9.1. Mc^2 Model Magnet I, 0.15 scale.

in only a rough approximation, has a non-uniform gap and makes use of controlled saturation of the poles. This design is attractive because it provides more flexibility in handling the problems, evident in Model I, of high power density in the outer conductors, radiation damage in insulation, and requirements for precision placement of windings.

Mc² Model Magnet I

In Model I the magnetic field goes to zero at large radii between sectors, and the flutter in this region depends only on the relative width of hills and valleys. This ratio can be readily determined for a required value of flutter. At smaller radii, where the field does not go to zero, the solution for hill width and peak field is more complex, but obtainable. The maximum field on a hill at any radius can be determined from the required average field and flutter.

The pole geometry of the 0.15-scale model was determined by using a trapezoidal approximation for the field shape; the distribution of currents in the radial-gradient coils on the pole faces was determined by a simple computation. The azimuthal variation of the field measured at several radii is shown in Fig. 9.2. The average field, Fig. 9.3, and peak field measurements, Fig. 9.4, agree with the desired curves to within the experimental error. The flutter is larger than required at all radii, see Fig. 9.5, but is very similar in shape to the required curve over the outside 50% of the machine, where most of the beam orbits lie. At smaller radii the azimuthal gradient was larger than anticipated, and the field in the valley approached zero at smaller radii than originally estimated. The flutter was, therefore, larger than expected. This discrepancy can be easily corrected by widening the hill and reducing the peak field on the hill to maintain the correct average field. The flutter at the 16-in. model radius can be decreased about 50% by increasing the hill width 5 degrees. The power required for the full-scale magnet of this design would be 10 MW.

Fig. 9.2. Magnetic field vs azimuth in 0.15-scale model.

Fig. 9.3. Average field vs radius.

Fig. 9.4. Peak field vs radius. Fig. 9.5. Flutter vs radius.

An appreciable reduction in power in the radial-gradient coils for Model I can be made by widening the iron gap and increasing the volume of copper in the coils. The number of ampere turns must be increased as the gap is increased but in a large gap there is a larger proportion of the gap available for conductors, since it is assumed that the beam space remains fixed. The relative power in this portion of the magnet as the iron gap varies from 8 in. is shown in Fig. 9.6 for two efficiencies. The 100% efficiency condition, or a condition fairly close to it, applies over the central region out to about the 200-in. radius. At the outside the efficiency falls very rapidly as the hill field increases above 10,000 gauss until the efficiency drops to 50% or less at the maximum radius. A maximum iron gap of about 12 in. would require a minimum power in the radial-gradient coils. Over 50% of the ampere turns in the system are confined to the outside 20% of the machine. Since the relative current density in the copper is low out to 80% of maximum radius, fairly wide variations in the volume of copper can be used without an appreciable increase in overall magnet power. About 3/4 in. of graphite can be placed on each side of the gap over all the machine without increasing the magnet power if the iron gap is increased from 8 in. to 12 in. and the copper is increased from 1 in. to 2.25 in. on each side of the median plane. If the graphite shielding were not used the magnet power in this section of the magnet could be reduced 25%.

Further Magnet Studies

Although the Mc^2 Magnet Model I satisfies the basic requirements of average field, flutter, and reasonable power, further preliminary studies indicate that an entirely different approach may provide a magnet having some desirable features that are difficult to obtain in a magnet in which the radial gradient is largely achieved by high power density coils on the pole surfaces. Since the radial gradient coils lie only a few inches from the median plane, the field is quite sensitive to errors in the position of the conductors. The insulation for the coils at large radius is also in a most vulnerable location from the standpoint of radiation damage caused by beam loss at the deflector septum. A magnet design as shown in Fig. 9.7 would help reduce

Fig. 9.6. Power required in radial-gradient coils as a function of magnet gap.

Fig. 9.7. Section through a sector of a magnet design under study.

these fairly serious problems. The gap is a minimum at small radii so that the desired flutter can be obtained in this region; it is reduced again to a minimum at large radius so that relatively high fields can be achieved with reasonable power. The gap over the remainder of the machine can be fairly wide and still provide the desired flutter and average field. The gap space thus gained can be used for graphite shielding, if needed, and for trimming coils operated at relatively low power. The main driving coils are in a location that provides some shielding by the pole tips. The useful working gap is nominally 4 inches.

To achieve the required field variation with radius, two altogether different techniques must be used. Steep gradients are required at the outside of the machine, along with a sharp cutoff, as the beam approaches the pole edge. These high gradients can best be achieved by a radial variation of the gap between the poles. Since for minimum power the gap must be small at the outside where the field is high, the gap is necessarily rather large in the mid-radius region. The field must rise, however, from the center to the mid-radius region, but a wide gap cannot be tolerated near the center because of flutter requirements. The field gradient out to the mid-radius region is, therefore, controlled by varying the amount of iron in the pole, and hence the saturation, so that the field increases with radius even though the gap also increases with radius.

This design has been crudely modeled in two sections. The first was a 1/16-scale test in the ORIC model magnet to determine the feasibility of obtaining the desired radial gradients near the outside radius of the machine by varying the pole gap with radius. Although the test was made with a peak field of 22,000 gauss, where 18,000 gauss now appears more desirable, and the model was out of scale radially, the data indicate that the desired gradients can readily be achieved in the outer 20% of the magnet. Figure 9.8 shows the required field and the measured values after the scale factor is corrected. The minimum pole-to-pole gap is set at 8 in. so as to provide room for 2 in. of graphite over the entire surface and still maintain a 4 in. useful gap.

Fig. 9.8. Field vs radius obtained by varying magnet gap with radius.

A second series of measurements of the field between Mc^2 Model I pole tips was made while they were clamped between flat poles in the ORIC model. These studies were concerned with the feasibility of controlling the field gradient in the gap by pole-tip saturation. Some typical results of these studies are shown in Fig. 9.9. The slowly changing gradient at small and intermediate radii are very close to those required for Mc^2 .

In Fig. 9.10 the desired peak field is shown along with the calculated field for two regions of the magnet, at small and large radii. The model data does not cover the intermediate region, but it appears that the combination of the two systems will provide the desired field. Further model studies will be necessary to establish detailed geometry and power requirements for the magnet.

A magnet of this design places all the critical dimensions on the iron geometry and minimizes the sensitivity to errors in coil placement. It is reasonable to expect that the final magnet would have to be shimmed after construction to achieve the desired field accuracy, although this can be minimized by providing sufficient variability in the design of the trimming coils. Low power trimming coils may be constructed with an inorganic insulation so that radiation damage would be negligible.

The model tests to date have been directed at determining the gross characteristics of various configurations and as a result have been relatively crude. The equipment and the measurements will need to be refined to determine the details that must be resolved before construction of the full-scale magnet. Future models will include one very accurate version on which measurements suitable for orbit calculation can be made. Automatic data acquisition devices will, of course, be used on this model and on the full-scale machine.

Fig. 9.9. Field gradient out to $R = 140$ in. obtained by pole tip saturation.

Fig. 9.10. Model magnet results obtained for regions of inner and outer radii.

10. THE ACCELERATING SYSTEM

The basic requirement of the RF accelerating system for the Mc^2 Cyclotron is that it provide an energy gain of 1 MeV/turn for particles having a cyclotron frequency of 6.86 Mc/s. The internal beam current would be about 120 to 200 μA ; this represents a beam load of 100 to 160 kW. An energy gain of 1 MeV/turn in conjunction with the large radial dimensions and small magnet gap effectively precludes the use of a conventional dee-type of accelerating system. Thus, since its inception, the machine design has been based on the use of cavities placed in the spaces between magnet sectors.

RF Accelerating Cavities

Cavities operating in either the TE_{011} or TEM mode are applicable to the Mc^2 Cyclotron. A cavity operating in the TEM mode has been chosen for the final design since this is the ordinary "coaxial" cavity and is more amenable to design than the TE cavity. A sketch of the proposed cavity is shown in Fig. 10.1. The computed characteristics of this cavity for a peak accelerating gap voltage of 250 kV are as follows: power loss, 500 kW; stored energy, 180 joules; and an unloaded Q of about 30,000. The computed power is based on the use of copper cavity walls; the use of aluminum would increase the power by about 25%.

The cavity shown bears scant resemblance to the usual coaxial cavity due to its peculiar cross-section and to the fact that its circumference is considerably greater than its length. It will, however, support a TEM mode and may be analyzed to a reasonable degree of accuracy as a three-step transmission line. The resonant frequency of a model cavity, which will be considered later, was calculated by this method to within 4% of the measured value.

It can be shown that the condition for $\lambda/4$ resonance in a three-step line is as follows:

Fig. 10.1. Proposed design of cavities to operate in the TEM mode. (Spiraling of cavity walls to fit magnet configuration is omitted to simplify presentation.)

$$1 - (Z_2/Z_1) \tan \beta l_1 \tan \beta l_2 - (Z_3/Z_2) \tan \beta l_3 [(Z_2/Z_1) \tan \beta l_1 + \tan \beta l_2] = 0 \quad (1)$$

where Z_1 , Z_2 , Z_3 are the characteristic impedances of the uniform sections and l_1 , l_2 , l_3 are the lengths of the uniform sections.

The above equation contains a total of six variables, aside from the frequency variable contained in β . For the Mc^2 cavity several of the variables are fixed by other machine parameters. For example, Z_1 (the characteristic impedance of the cavity near the median plane) is determined primarily by the 4-in. cavity wall-to-wall spacing which, in turn, was chosen as a compromise between voltage-holding ability and transit-time effects. The slots between magnet sectors have a width of 16 in.; this permits a maximum spacing of 12 in. (S_2) inside the cavity, thereby partially determining Z_2 . The spacing in the circular section of the cavity (the portion "outside" the magnet) completely specifies Z_2 . This spacing is again a compromise between the power loss and the volume of the vacuum system. The trimmer plates in the circular section permit a small variation in Z_1 to provide adjustment of the resonant frequency. The length, $l_1 + l_2$, is determined by the height of the magnet (~ 7 ft) above the median plane. Design of a cavity is thus a cut-and-try process using the fixed lengths and spacings and adjusting the free variables to obtain a reasonable compromise between cavity height and power loss.

The power loss in a three-step $\lambda/4$ line can be expressed as

(2)

$$P_{\lambda/4} = \left[\frac{R_1}{4\beta} \left(\frac{V_0}{Z_1} \right)^2 \right] (\beta l_1) \left\{ \begin{aligned} &1 - \frac{\sin 2\beta l_1}{2\beta l_1} + \frac{R_2 l_2}{R_1 l_1} \left(\frac{Z_1 \cos \beta l_1}{Z_2 \cos \theta_2} \right)^2 \left[1 - \frac{\sin 2(\beta l_2 + \theta_2) - \sin 2\theta_2}{2\beta l_2} \right] \\ &+ \frac{R_3 l_3}{R_1 l_1} \left(\frac{Z_1 \cos \beta l_1}{Z_3 \cos \theta_2} \right)^2 \left[\frac{\cos(\beta l_2 + \theta_2)}{\cos \theta_3} \right]^2 \left[1 + \frac{\sin 2\theta_3}{2\beta l_3} \right] \end{aligned} \right\}$$

where R_1 , R_2 , R_3 are resistances per unit length.

V_0 is the peak voltage across the open-circuit end

$$\theta_2 = \tan^{-1} [(Z_2/Z_1) \tan \beta l_1]$$

$$\theta_3 = \tan^{-1} [(Z_3/Z_2) \tan (\beta l_2 + \theta_2)]$$

The above equation neglects the discontinuity capacitances associated with the abrupt junctions between the three uniform sections of line and assumes a uniform spacing (as a function of radius) between coaxial conductors. In calculating power loss for the cavity in Fig. 10.1, the discontinuity capacitances, non-uniform spacing, and losses in the "short-circuit" were considered. The main attribute of Eq (2) is that the latter portion of it is a normalized expression relating total line length to power, if certain assumptions are made. Two families of curves obtained from Eq (2) are plotted in Fig. 10.2. The effect of non-uniform spacing around the cavity on power loss can be considered approximately by assuming the current density in the walls to be inversely proportional to the wall-to-wall spacing. This should be a good assumption for cavities such as that in Fig. 10.1 whose peripheral dimensions are much greater than the spacing between walls. The discontinuity capacitances between the uniform line sections can be approximated from published data⁽¹⁾.

The energy stored in the cavity, U , can be calculated in a manner similar to that described above. The cavity Q can then be obtained from the relationship $Q = \omega(U/P)$.

A photograph of a 1/12 scale model cavity is shown in Fig. 10.3. This is actually a model of only 1/2 of the cavity shown in Fig. 10.1; it was constructed primarily to check the design technique. The model was designed to have a resonant frequency of 165 Mc/s, and the Q was calculated to be about 11,000. Measurements on the model indicated a resonant frequency of 145.6 Mc/s and a Q of about 7000. Checking of the model dimensions revealed a construction error of several percent in the spacing near the median plane of the cavity. After the dimensions were revised a resonant frequency of 151.3 Mc/s was calculated for the model; this is within 4% of the measured value. The Q value was not re-calculated; however, the dimensional error was in the direction to reduce Q .

A factor which caused some concern during the early design of the cavity was its large peripheral dimension. Since this dimension is considerably greater than a wavelength (at 13.72 Mc/s) it might be

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Fig. 10.3. Test model of coaxial cavity.

possible for modes other than the TEM to be excited. For example, in a strictly uniform coaxial cavity having a circumference ℓ_c much greater than its length b it can be shown that

$$f_1/f_0 = [1 + (2b/\ell_c)^2]^{1/2},$$

where f_0 is the frequency of the TEM mode and f_1 is the frequency of the first TE mode. Thus, there is only 10% separation between the two frequencies when the circumference of a cavity is about four times its length. This problem was checked on the model cavity and found to be less severe than indicated by the above analysis. The first higher order resonance occurred at about 200 Mc/s, so it appears that the non-uniform spacing inside the cavity aids materially in separating the modes.

RF Amplifiers

The total rf power requirements for the Mc^2 accelerating system may be summarized as follows:

Computed power loss in cavity	500 kW
Beam power	160 kW
"Contingency"	<u>200 kW</u>
total	860 kW

This amount of power could be supplied by two RCA-6949 tubes operating in push-pull under the following conditions: dc plate voltage = 17.5 kV, plate current (per tube) = 34.8 A, grid bias = -1 kV, grid current (per tube) $\approx$ 0.5 A, peak rf plate voltage = 14.5 kV, peak rf grid voltage = 2.4 kV, rf output power = 872 kW, plate dissipation (per tube) = 175 kW, drive power $\approx$ 2.4 kW, and plate-to-plate load = 480 ohms.

A block diagram of the proposed rf system is shown in Fig. 10.4. The system is somewhat similar to that used in the ORIC. The power amplifier is coupled to the cavity through a matched 75-ohm line and a drive capacitor. At resonance the equivalent input admittance at the drive capacitor consists of a resistance in parallel with a capacitance. The resistance can be matched to the 75-ohm line by

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Fig. 10.4. Diagram of radio-frequency system for Mc^2 Cyclotron.

proper adjustment of the drive capacitor, and the shunt capacitance can be "tuned out" with the matching stub. If the drive line is matched then its length is unimportant; however, if sparking in the cavity is considered the length becomes of considerable importance. If the drive line is inductively coupled to the plate tank circuit of the power amplifier, the plate load resistance is inversely proportional to the cavity shunt resistance for a line length of $n \lambda/2$. Thus, when a spark occurs in the cavity a large resistive load is reflected to the plates of the power amplifier and the tube plate current would decrease. The main disadvantage of this type of coupling is the increase in rf plate voltage which would occur during a spark. It has been shown that a class-C amplifier may develop peak rf plate voltages far in excess of the dc plate voltage when the amplifier is unloaded⁽²⁾, thereby causing voltage breakdown of components in the plate tank circuit. This situation could be alleviated by over-rating of components and the use of fast protective circuits to remove the drive from the power amplifier. Alternatives to the above coupling scheme would, in general, produce high plate currents in the power amplifier tubes during sparking in the cavity.

Both the input and the output tank circuits of the power amplifier would consist of balanced coaxial lines, and tuning would be accomplished by variable capacitors connected from the ends of the lines to ground. As stated previously, the driving power required by the RCA-6949's is about 2.4 kW. There would be available, however, at least 10 kW from the driver stage. The excess power would be dissipated in "swamping" resistors and parasitic suppressors and would provide an adequate reserve for higher output.

The driver amplifier would be operated essentially as a linear amplifier since this stage would act as a controller for the rf voltage regulator and as a switch for removing excitation from the power amplifier.

The power, driver, and second buffer amplifier would be located just outside the shielding wall, with the drive line entering the cyclotron vault through the maze. Power supplies for these stages.

would also be located in the same area. The low power stages (oscillator and first buffer amplifier) would be located in the control room. This arrangement should provide convenient servicing of all rf equipment.

Protection of the rf equipment would be provided by two basic systems aside from the normal circuit-breaker and overload devices. The power amplifier tubes would be protected by a "crowbar" on the plate power supply. This system could also be employed to provide protection for the drive line and power amplifier plate circuit components; however, it would be more desirable to remove the rf excitation in most cases. Switching of the rf excitation would occur in the driver stage by pulsing the grid bias of the driver amplifier to cut-off. This system would be somewhat slower in operating than the crowbar, but would recycle in a very short time as compared with the crowbar. It may also be necessary to crowbar the cavity because of the large amount of stored energy therein. This possibility will be given further consideration.

Future Developmental Studies

The next step in the development of the Mc^2 rf system should be the construction of a large scale (1/3 or 1/4), exact model of an accelerating cavity. This model would be employed to check assembly procedures, the effect of dimensional and alignment errors, variations in accelerating gap voltage and general design procedure. A model of the power amplifier and coupling network should also be developed in conjunction with the cavity model.

References

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- (2) L. E. Dwork, "Maximum Tank Voltage in Class-C Amplifiers," Proc. I. R. E., 38, 637-644 (1950).

11. SHIELDING

Historically, the shielding initially provided for high-energy accelerators has later proved to be inadequate. This has been for a variety of reasons, including inadequate initial assumptions, increases in the energy and current of the accelerators, and the need for experimental arrangements not considered in the original design. The experiment areas are now too small in almost every installation; this is one of the problems we hope to avoid in the facilities for the Mc² Cyclotron.

During the past several years the understanding of the basic shielding problems for high-energy accelerators has improved considerably. There is, however, a notable lack of precise experimental data on most aspects of the problem, for example: the attenuation length of neutrons as a function of energy, the spectrum of particles emerging from the shield, and the flux-to-dose conversion for high energy neutrons and protons. Nevertheless, estimates of accelerator shielding requirements can now be made with reasonable assurance that they will not be grossly in error.

In this chapter the shield requirements for the Mc² facility are outlined, beginning with a brief statement of the permissible dose regulations now in effect at the Laboratory. This is followed by a calculation of the attenuation of high energy neutrons, a discussion of the buildup of soft radiation, the shielding required for π and μ beams, and finally a review of the access provisions through the thick shield walls for personnel, equipment, instrument cables, utilities piping, and electrical power conduits.

Permissible Radiation Limits

The personnel radiation exposure limits in effect at the Oak Ridge National Laboratory, Table 11.1, are those recommended by the National Committee for Radiation Protection. The exposure limits are based on the MPD Age Proration Total, that is 5 rem/year or 100 mrem/week. This value applies to radiation workers. The

Table 11.1. Maximum permissible dose (MPD)

Organ	MPD per Calendar Quarter (rem/13 wk)	MPD per Year (rem/yr)	MPD Age Proration Total (rem)
Total body, head and trunk, lens of eyes, gonads, or blood forming organs	3	12	5 (N - 18)
Skin of whole body, thyroid	10	30	30 (N - 18)
Hands and forearms, feet and ankles	25	75	75 (N - 18)
Bone	30/4 n	30/n	(30/n) (N - 18)
Other single organs	5	15	15 (N - 18)

N = age of worker

n = "relative damage factor"; n = 1 for radium isotopes
and for gamma radiation, otherwise, n = 5 for all
radionuclides in bone.

recommended exposure limit for the general population is a factor of ten lower. Although there is no general population exposure problem at the proposed site, we have designed the shielding so that the limits for general population are observed in the regularly inhabited work areas adjoining the accelerator and experiment rooms.

Attenuation of Neutrons

The attenuation of neutrons in thick shields has been extensively investigated only for nuclear reactor shields, where the energy spectrum of interest does not extend beyond about 20 MeV. Only a few measurements of high-energy neutron attenuation in thick shields have been made. Moyer and co-workers at the Lawrence Radiation Laboratory measured the half-value thickness in ordinary concrete for 90- and 300-MeV neutrons and reported values of 9.5 and 18.0 in. respectively. For the purpose of this calculation we have used a curve published by Panofsky,⁽¹⁾ Fig. 11.1, which gives the half-value thickness as a function of energy up to 1 BeV. These data apply strictly only for broad beam attenuation; their use in the narrow beam sense, as in the following calculation, leads to a slight overestimate of the shielding requirements.

Energy Spectrum and Angular Distribution. - Nuclear emission in high-energy nuclear reactions consists of two parts, the emission of one or more high-energy particles (cascade particles) in the forward direction, which occurs before the excitation energy is distributed throughout the target nucleus, and second, the emission of several "evaporation nucleons", which occurs as thermal equilibrium is achieved. N. Metropolis, et al.,⁽²⁾ have investigated the cascade and evaporation process theoretically, using a Monte Carlo method.

The thickness of shielding required for a high energy accelerator is established chiefly by the cascade nucleons. These high energy nucleons are removed largely by inelastic collisions, hence exhibit long attenuation lengths. The evaporation particles have a Maxwellian energy distribution which peaks at a few MeV; they are rapidly attenuated

Fig. 11.1. Half-value thickness of ordinary concrete for fast neutrons.

by the shield and need not be taken into account in determining the shield thickness. The evaporation particles must be taken into account, however, in determining the activation of materials within the shield, as seen in Chapters 6 and 7, and in estimating the biological dose at the outer surface of the shield from secondaries produced in that region, as discussed later.

Metropolis has calculated the energy spectrum of cascade particles emitted when 460- and 1840-MeV protons are incident on aluminum and uranium. In the following calculations, the aluminum data is used for copper; the spectrum is not sensitive to target element. As suggested by H. B. Knowles,⁽³⁾ the energy spectrum of the cascade particles can be fitted by an exponential

$$\frac{dN(E)}{dE} \sim e^{-kE/E_0},$$

where E_0 is the energy of the incident proton. A value of $k = 4$ fits the Metropolis data at $E_0 = 460$ MeV, while a value of 6 would be more appropriate for the 1840-MeV data. In our calculations we have used $k = 4.0$ for the energy range to 800 MeV. Metropolis also calculated the ratio of neutrons emitted to incident protons, f_n/f_p . A value of $f_n/f_p = 1.0$ is appropriate for medium weight elements.

For the results in this section, a copper target is assumed. For protons impinging on a thick copper target, the number surviving to depth x in a target of thickness at least equal to the ionization range is

$$N = N_0 e^{-x/\lambda},$$

where λ is the inelastic removal length, i. e., $\lambda = 1/N$. The reaction rate, the negative of the removal rate, is

$$\frac{dN}{dx} = -\frac{N_0}{\lambda} e^{-x/\lambda}.$$

If a cascade particles are produced per inelastic event, the secondary particle production S is

$$S = \frac{N_0}{\lambda} \int_0^{x=R} e^{-x/\lambda} a(x) dx$$

$\alpha(x)$ is computed from $\alpha(E)$ (Metropolis, et al.) and the range energy relation for protons in copper. Of these secondaries, half are neutrons. The function $S_n = \frac{1}{2}S$, obtained by numerical integration of the above equation, is plotted in Fig. 11.2 as a function of the incident proton energy.

The energy spectrum of the neutrons produced in a thick target may be obtained by summing the contributions, to each energy group, from neutrons produced at each proton energy in the target. The distribution in neutron energy, the number of neutrons per 100-MeV energy interval produced by 100 μ A of protons on a thick target, is shown in the histogram of Fig. 11.3.

Knowles has carried the process a step further and included the cascade neutrons produced by the secondary protons, which adds another 20% to the total neutron production; however, the substantial attenuation of the neutrons in the target is neglected. In subsequent calculations we have neglected both the secondary production and target attenuation; this results in a conservative estimate still within the precision of other data.

The results of Metropolis show that the angular distribution of the cascade particles is relatively independent of energy (for particles $T = 90$ MeV) and target element. The angular distribution assumed for the cascade neutrons is that computed for aluminum. The angular distribution of flux density at a distance of one meter from a target with an incident proton beam of 100 μ A is shown in Fig. 11.4.

Attenuation in the Shield. - For a point source, the flux density at distance R , after passage through a shield of thickness T may be calculated as follows:

$$\frac{d\phi}{dE} = \frac{d\phi_1}{dE} \frac{1}{R^2} e^{-T/\lambda(E)},$$

where $d\phi_1/dE$ is the flux density per unit energy at unit radius. The above equation has been evaluated numerically with the attenuation curve of Panofsky. Fig. 11.5 shows the flux density distribution of 0° neutrons through 35 ft of ordinary concrete, or equivalent.

Fig. 11.2. Cascade neutron yield as a function of proton energy, for thick copper target.

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Fig. 11.3. Cascade neutron yield and energy distribution for 800-MeV protons on thick copper target.

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Fig. 11.4. Angular distribution of neutrons for 100 μ A of 800-MeV protons on thick copper target.

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Fig. 11.5. Energy distribution of 0° neutrons from 100 μ A of 800-MeV protons on thick copper target - after attenuation by 35 ft of concrete.

Secondary Particles. - The high energy neutrons from the target which penetrate the shield will be accompanied by lower energy secondaries produced in the outer layer of the shield. These secondary particles are produced by the inelastic collisions of the primary neutrons. To estimate the number of secondaries produced, we use the method of Moyer⁽⁴⁾. Briefly, the method consists in determining the number of secondaries produced in an outer layer of shielding of thickness λ , the removal length for the primary neutrons. The numbers of secondary particles produced are determined from Table 11.2 and the neutron spectrum of Fig. 11.5. Assuming that one-half the secondaries emerge from the shield, we estimate that each primary neutron will be accompanied by 1.5 cascade neutrons, 1 cascade proton, and 1 evaporation neutron. The evaporation protons are not included because of their short range. A few gamma rays and thermal neutrons will also accompany the primary radiation but are neglected because they will not contribute appreciably to the radiation dose.

Dose Estimates. - The neutron flux densities which result in weekly radiation doses of 100 and 300 mrem are shown in Fig. 11.6. The value at 10 MeV is equivalent to 4×10^{-8} rem per n/cm². The calculations of G. J. Neary⁽⁵⁾, AERE, Harwell, show that the dose per particle increases monotonically with energy to a value of 6×10^{-7} rem per n/cm² at 1000 MeV. For the primary spectrum of Fig. 11.5, we estimate that the appropriate mean value is 3×10^{-7} rem per n/cm². For secondary cascade neutrons we assign the same value, although it overestimates the dose because the energy spectrum of the secondaries will be more like that shown in Fig. 11.3. For cascade protons we use the recent results of J. E. Turner and J. Neufeld⁽⁶⁾ which give a value of 5×10^{-7} rem per proton/cm² at peak ionization.

The particle flux densities and dose rates which are predicted at the surface of 35, 40, and 15 ft shield walls are enumerated in Table 11.3. The tabulated data illustrate that 35 ft of ordinary concrete is insufficient if a target is near the shield wall. It is for this reason that we have provided 40 ft of shielding on the forward direction for the proton room and in addition 5 ft of concrete blocks at the back of the beam stop area to give an overall shielding thickness of 45 ft. For

Table 11. 2. Estimate of neutron and proton emission from cascade and evaporation processes induced by inelastic collisions of neutrons of energy E_n with nuclei of atomic number near 20. From Moyer⁽⁴⁾.

E_n (MeV)		50	100	200	500	1000
Cascade	n_p	0.4	0.6	0.9	1.2	1.5
	n_n	0.7	1.2	1.5	2.0	2.4
Evaporation	n_p	0.7	0.8	0.9	1.0	1.0
	n_n	1.0	1.0	1.0	1.1	1.2

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Fig. 11.6. Flux of neutrons to deliver the stated dose as a function of neutron energy.

Table 11.3. Predicted flux and dose rates at outer surface of shield wall when 100 μ A beam of protons strikes a thick copper target 1 meter from inner surface of wall.

Shield thickness	35 ft		40 ft		45 ft	
	Flux	Dose	Flux	Dose	Flux	Dose
Particle	(/cm ² - sec)	(mrem/hr)	(/cm ² - sec)	(mrem/hr)	(/cm ² - sec)	(mrem/hr)
Primary neutrons	11	12	0.9	1.0	0.07	0.075
Cascade neutrons	16	17	1.4	1.5	0.11	0.11
Cascade protons	11	20	0.9	1.6	0.07	0.13
Evaporation neutrons	<u>11</u>	<u>1.5</u>	<u>0.9</u>	<u>0.1</u>	<u>0.07</u>	<u>0.01</u>
Total		50.5		4.2		0.325

thin targets in the middle of the experiment room the additional distance attenuation, the target shields, and the lower neutron emission will result in dose rates outside the shield wall below tolerance.

Other Shielding Requirements

Shielding against radiation other than neutrons must also be considered. In the proton room, the cyclotron vault, and in the corridor π^0 mesons and a resulting intense flux of 70-MeV γ -rays will be produced. Positive and negative pions, muons from their decay, and low energy γ -rays must also be contained. It was found that the shielding required by the neutrons is more than sufficient to render all the other radiation harmless.

A maximum of 10^{11} pions/s will enter the two more lightly shielded experiment rooms. The average pion energy is about 300 MeV. The pion-induced cascades can be treated as the proton-induced ones in the previous section, except that the energy is decreased and the intensity lower by a factor of 6×10^3 . At these energies it is again the neutrons in the cascade which determine the shielding; the muons are stopped completely by the shield. For these considerations the shielding required in the π and μ experiment rooms is a minimum of 15 ft of concrete, or equivalent, in the forward direction, and 12 ft on the side walls and roof. As a result of structural considerations, 20 ft of concrete is provided in the forward direction for the pion room.

Summary of Shield Thicknesses

The following table lists the shielding provided for the various areas:

	<u>Cyclotron vault</u> (ft)	<u>Beam corridor</u> (ft)	<u>Proton room</u> (ft)	<u>π and μ rooms</u> (ft)
Walls, adjacent to occupied areas	40 conc.	--	40 conc.	20 conc.
Walls, general	35 conc.	35 conc.	35 conc.	15 conc.
Roof, min.	25 conc.	35 earth	30 earth	14 earth

As mentioned previously, an additional 5 ft of concrete in the form of blocks is planned for the back of the beam stop area to give a total thickness of 45 feet of concrete in the forward direction. The roof shield is substantially thinner than the main shielding because of the low emission at large angles and because of the softer spectrum of the large angle particles. In the proton room an additional 10 ft of concrete shielding over the beam stop area will reduce the flux transmitted through the roof to negligible levels. In the cyclotron vault the magnet structure provides additional shielding.

Shield Penetrations

Several types of access to the interior of the heavily shielded areas must be provided in a large accelerator installation. These include means for rapid access by personnel, large openings to permit installation or removal of bulky and heavy equipment, and passages for all instrument, utilities, and electrical power connections. In the Mc^2 Cyclotron facility rapid personnel access is provided by mazes. Similar but much smaller labyrinths or mazes are used to carry the water and electrical connections through the shield. Access to the shielded areas for heavy equipment is gained by removable shield plugs. The design considerations for the shield penetrations are described in the following paragraphs.

Maze Design. - References to maze design for high energy accelerator shields are almost completely absent from the literature. We have based our design on the methods used for nuclear reactor shielding. As a guide we have used the book by Price, Horton, and Spinney,⁽⁷⁾ which summarizes the experimental work up to 1957, in both the United Kingdom and the United States. All material presented here is from that reference.

The radiation which is transmitted through ducts in reactor shields consists of neutrons with near-thermal energies. Line of sight analysis is considered adequate for high energy neutrons. The same analysis method should apply for accelerator shields, because the high energy neutrons that penetrate the shield are practically

undeviated from their original directions. Also, the high energy secondary particles produced in the shield have a strongly forward peaked angular distribution.

The experimental measurements of the transmission of low energy neutrons in long circular ducts are well represented by the equation

$$\phi(z) = \phi(0) \left\{ 1 - \left[1 + (a/z)^2 \right]^{-\frac{1}{2}} \right\} \left\{ 1 + \frac{4(a/z)\beta}{1 - \beta} \right\}$$

$\phi(0)$ = flux density at duct mouth ($z = 0$)
 $\phi(z)$ = flux density at z along duct
 z = distance along duct
 a = duct radius
 β = albedo (fraction of incident neutrons reflected from the duct surface)

A plot of ϕ/ϕ_0 as a function of (z/a) for $\beta = 0$ and $\beta = 0.8$ is shown in Fig. 11.7. It illustrates clearly that near the entrance to a duct the attenuation is very slight.

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Fig. 11.7. Neutron transmission through ducts, with albedo as parameter.

At bends in ducts a new source of neutrons is formed via scattering. The equation above applies equally well for the continuing leg of a bent duct if z is measured from the bend. It has been shown experimentally that the attenuation at a bend is approximately $1/3 \csc \phi$ where ϕ is the angle of deviation from the original direction. The imperical constant $1/3$ takes into account both the angular distribution and albedo for the reflected neutrons. An additional factor of 3 attenuation at bends may be gained by extending the entering leg beyond the bend as in Fig. 11.8. The overall transmission for 90° bends of this design is about 0.1.

The attenuation of the personnel maze entering the proton experiment room is calculated as an illustration. For the purpose of this calculation we have assumed that the maze is circular in cross section with the same area as the 5 ft wide by 10 ft high passage. Fig. 11.8 shows the maze geometry in detail. The attenuation of the various sections is tabulated below.

Section	Length, z (ft)	Equivalent Radius, a (ft)	z/a	Transmission (ϕ/ϕ_0)
Leg 1	27	4	6.75	3.5×10^{-2}
Bend 1 - 2		"		0.1
Leg 2	25	"	6.25	4.4×10^{-2}
Bend 2 - 3		"		0.1
Leg 3	38	"	9.5	1.5×10^{-2}
Bend 3 - 4		"		0.1
Leg 4	15	"	3.75	1.5×10^{-1}
Total (product of transmission of individual elements)				4.8×10^{-9}

The above calculation applies for low energy neutron, such as constitute the neutron atmosphere within the experiment room. According to Moyer⁽⁸⁾ the thermal flux in a concrete enclosure is given approximately by the expression $\phi_{th} = 1.25 Q/A$ where Q is

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Fig. 11.8. Maze entering proton experiment room.

the number of high energy neutrons emitted in the enclosure, and A is the surface area of the enclosure in cm^2 . The proton room has a surface area of approximately $3.5 \times 10^7 \text{ cm}^2$. If we assume a beam of $100 \mu\text{A}$ (0.625×10^{15} p/sec) and the emission of 10 neutrons per proton, the thermal flux density will be about $2.2 \times 10^8 \text{ n/cm}^2 \cdot \text{sec}$. The flux density at the maze exit will be about $1 \text{ n/cm}^2 \cdot \text{sec}$ for the transmission factor of 4.8×10^{-9} calculated previously. These neutrons are of near thermal energy, and will contribute negligibly to the radiation dose in comparison with the high energy particles that penetrate the shield.

Should the maze design shown prove inadequate because of the propagation of high energy particles, the attenuation can be greatly improved by the addition of plugs at the bends. The extension of the leg beyond the corner offers a convenient location for a plug door which can be readily withdrawn. It might also be mentioned that no account has been taken of the attenuation by the beam stops discussed in Chapter 7. Their use will reduce both the neutron atmosphere flux density and the high energy neutron flux density by at least a factor of ten.

Utilities Penetrations. - The slow neutron transmission by circular ducts of various diameters and several simple geometries for the shield thicknesses used in the Mc^2 facility is shown in Fig. 11.9. Acceptable choices for the cyclotron vault and proton rooms (35 and 40 ft walls) should have a transmission factor of less than 10^{-8} while a transmission factor of 10^{-5} , or less, is adequate for the 12 and 20 ft walls of the π and μ rooms. To avoid reducing the effective shield thickness for high energy particles, the ducts should be installed so that the legs are not in line with potential intense sources of high energy neutrons. Also, the ducts in an array should be spaced several diameters apart to prevent an appreciable local reduction in the shield density.

Shield Plugs. - Access to the experiment rooms for the transfer of heavy equipment is provided by moveable shield plugs. The plug assembly is mounted on a carriage structure similar to that used in

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Fig. 11.9. Neutron transmission through ducts of simple geometries.

the railroad industry. Figure 11.10 shows the design of the 800-ton plug for the proton room. Inevitably the effective thickness of the shielding is reduced somewhat by the space for the wheels. In this design the reduction of thickness is compensated by the inclusion of higher density materials in those regions. To minimize misalignment errors and to achieve equal weight distribution on the wheels, the unit is divided into four sections. The steps provided at the top and sides minimize the dimensional accuracy required. With 12 in. steps, $\frac{1}{2}$ in. wide cracks between the plug and the wall are easily tolerable.

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Fig. 11.10. Roll-out plug for shielding door.

12. BUILDINGS

This section describes the buildings and utilities systems for the proposed Mc^2 Cyclotron and the plans for additional facilities for medical research and for neutron time-of-flight studies. A structural analysis of the shielding and an analysis of building space are also included.

Before the building complex was designed, the requirements for the research programs were formulated, for both initial and future experiments, see Chapt. 2 and 3. With these criteria established, the ion optics system and the shielded experiment area were designed, as described in Chapt. 4 and 11. As the central core, these designs provide for maximum utilization of various beams, for both initial and long range versatility, and for personnel safety in close proximity to intense radiation sources. The office and laboratory building and the accelerator building, described below, were then designed around the shielded area. Architectural drawings of the building complex are shown in Fig. 12.1, 12.2, 12.3, and 12.4. Additional drawings showing more structural details of the building are included in Appendix E.

The Cyclotron Building

The building containing the accelerator and the associated utilities, shops, and staging areas is constructed of reinforced concrete, structural steel, and masonry. The building is in a sense built adjacent to and over the cyclotron vault. The vault, extending upward to the third floor level, is described below as part of the shielded experiment area.

At the levels of the basement and the first two floors, the areas adjacent to the vault are 97 ft long by 60 ft wide; the ceiling heights are 25 ft for the basement and 16 ft for the first and second floors. The third floor, extending over the vault, is 104 by 202 ft; the ceiling clearance is 68 ft at the north end and 58 ft over the vault area. All floors are serviced by a 10-ton freight elevator, which also connects with the maze for entering the vault below the basement level. At each floor level removable hatches provide for handling large or heavy loads with a 150-ton gantry crane on the top level.

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Fig. 12.1. First floor plan and north elevation.

Fig. 12.2. Experiment level and basement floor plans, with sections A-A and B-B.

Fig. 12.3. Second floor plan and elevations, east and west.

Fig. 12.4. Third floor plan and plan of medical building.

The basement floor contains the power supplies for the cyclotron magnet, switch gear, and the ion injector room. This latter room is entirely shielded with 2 ft of ordinary concrete; access to the injector is through a rolling door 2 ft thick.

The first floor is at grade level, and is provided with a truck entrance. This level contains the forevacuum system, the rf oscillator and power supply, and the demineralized water cooling system for the cyclotron.

On the second floor is located the motor control center, the vault air conditioning, the building air handling system, the change rooms, and the rest rooms.

The third floor provides a high bay general staging and access area and contains a machine shop, a servicing and assembly area, and the opening in the roof of the cyclotron vault. This floor is serviced by the 150-ton two-hook gantry crane; it operates on tracks located over the side walls of the vault and extending through the south end of the building. When the cyclotron is being serviced, the vault-roof beams, vacuum tank head, and other large components can be moved with the crane through a large canopy door, 42 x 100 ft, and stored on an outdoor pad which extends 148 ft south from the building.

The following table shows the distribution of space in the cyclotron building, not including the cyclotron vault and roof hatch.

	Gross Area (ft ²)	Gross Volume (ft ³)
Basement	6,900	171,640
First floor	5,670	93,600
Second floor	5,670	93,600
Third floor	14,520	1,329,680
Subtotal	32,760	1,688,520
Foundation		22,260
Total	32,760	1,710,780

The Laboratory and Office Building

The laboratory and office building is a three-level structure adjoining the north shield wall of the three experiment rooms. The lower level of this building provides space for truck access to the experiment rooms and for the rolling shield doors in the open position. The basement also contains the demineralized water cooling equipment for the ion optics system, the air conditioning system, and the building utilities, as well as change rooms.

The first and second floors provide a total of 38 laboratories and 50 offices. There are also a drafting and reproduction room, conference room, instrument shop, staff shop, dark room, and a lunchroom. Approximately 7000 ft² of space on the first floor is occupied by the counting and control room.

Analysis of Building Space. - The building plans have been reviewed with respect to AEC building criteria. The ratio of net space to gross space is within the suggested norms. After the machine is completed and in operation, the number of scientific, technical, and clerical persons working on research programs is estimated to be approximately 85 requiring office space. This provides an average of 120 ft² of office space per person for the scientific, technical, and clerical people assigned to the building. The space utilization in the laboratory and office building is summarized as follows:

	<u>Net Usable (ft²)</u>	<u>Service and Wall Area (ft²)</u>	<u>Gross Area (ft²)</u>	<u>Gross Volume (ft³)</u>
Basement				
Floor			28,580	662,180
Truck tunnel			1,090	16,320
Shielding space			<u>3,270</u>	<u>76,390</u>
Subtotals			32,940	754,890
First floor	22,200	9,320	31,520	445,750
Second floor	21,030	10,850	31,870	425,210
Elevator room			<u>140</u>	<u>1,440</u>
Totals	43,230	20,170	96,470	1,627,290

The service designation includes such areas as stairs, halls, elevators, rest rooms, and passages for utilities. The above tabulation indicates that on the two main floors of the office and laboratory building space utilization is about 68%.

The Shielded Experiment Area

The heavily shielded experiment area includes the cyclotron vault, the beam transport corridor, and three large experiment rooms. These rooms are designed for experiments with high intensity proton, pion, and muon beams. The beam corridor is used for transportation of the primary beam, for beam analysis, and for the production of secondary particles. The arrangement of the rooms is based on the requirements of experiments and on economy of shielding construction.

Cyclotron Vault. - The vault is of reinforced poured concrete construction; the internal dimensions are 90 x 100 x 56 ft. The roof of the vault is formed by 200 beams 3 x 3.5 ft in cross section and an average length of about 72 ft. These beams are stacked to a depth of about 25 ft. Two of the vault walls are of counter fort construction and are about 4 ft thick; 40 ft of earth provides the additional shielding required. The wall in common with the proton room is concrete 35 ft thick. The wall between the vault and the utilities area of the cyclotron building is 40 ft thick. Access to the vault is either from the utilities area by way of a maze through the base of this shield wall or, from the third floor through the vault roof. The vault roof beams can be removed and stored outside of the building when access through the vault roof is necessary. The maze is for personnel, small equipment, control cables, and some utilities lines. Utilities penetrations requiring more space, such as the dc bus, water, and vacuum lines, are cast in the shield, as has been the practice on other accelerator projects requiring tight, heavy shielding.

Beam Corridor. - The 30 ft wide corridor contains the ion optics equipment which transports the beam from the cyclotron to various target positions, and directs the primary proton beam and product beams into the various experiment rooms. The corridor is about 300 ft long and is closed at the far (east) end by a rolling plug door 40 ft thick. This door provides for passage of

experimental equipment and for personnel access. In the 35-ft thick wall between the corridor and the proton and muon rooms, slots 10 ft high are stacked with concrete blocks which can be fitted around the beam pipes into these rooms. The pion beam is directed into the pion room through a steel plug 12 ft thick and surrounded by barytes concrete blocks, as shown in Fig. 4.1. The outside wall and the roof of the corridor are of concrete 4 ft thick; the corridor is covered with about 30 ft of earth. There are two 50-ton overhead service cranes in the corridor. With remote control handling equipment they can also be used for transporting irradiated targets and equipment to storage pits in the floor.

Proton, Pion, and Muon Rooms. - The proton room provides approximately 11,200 ft² of floor area. It is shielded by 35-ft thick walls adjacent to the vault and to the pion room. The wall adjoining the office building is 40 ft thick. Within the room is a large cave with concrete block walls 15-ft thick which serves to reduce the background from the enclosed beam stop.

The pion and muon rooms each contain 8,000 ft² of experiment area. The walls for these two rooms are about 15 ft thick on the sides and 20 ft thick in the forward direction.

Overhead, shielding for all three experiment rooms is provided by an earth cover that varies from 15 to 30 ft thick. This earth load is supported by concrete arched roofs over each room, as shown in section BB of Fig. 12.2. A "mezzanine" level, under the arch and above the crane level, is provided in the pion and muon rooms for the location of power supplies for the ion optics system. Forty-ton capacity bridge cranes are provided in each room; remote target handling equipment is mounted on these cranes. Shielded pits are provided for storage of hot targets and components.

Personnel access to these rooms is through mazes which also serve as utilities tunnels. The large rolling concrete door into each room permits the transfer of large equipment by truck.

Analysis of Shielded Space. - While space utilization in the laboratory and office building is comparable to similar existing buildings, the unique shielding requirements of the cyclotron building and of the experiment areas preclude meaningful comparisons. About 55% of the gross area occupied by the shielded areas is available experiment space, as tabulated below:

	Experiment Area (ft ²)	Gross Area (ft ²)	Gross Volume (ft ³)
Proton room	11,200		
Pion room	8,000		
Muon room	8,000		
Balcony, pion room	4,500		
Balcony, muon room	4,500		
Beam corridor	11,100		
Cyclotron vault	9,000		
	<hr/>	<hr/>	<hr/>
Subtotals	56,300	100,500	4,225,600
Foundation			555,000
	<hr/>	<hr/>	<hr/>
Totals	56,300	100,500	4,780,600

Analyses of Shielding Structures. - The efficient application of a large accelerator to a varied program of research requires several large independently shielded rooms. As outlined in Chapter 11, the high beam intensities of the Mc² Cyclotron require that the shielding be unusually thick. Consequently, the total shielding requirements are much greater than is found in other accelerator installations. Since the shielding represents an unusually large fraction of the total cost of the facility, several studies of structural design and cost analyses have been made.

A preliminary design study for the roof of the shielded area was described in the progress report of June 1962 (ORNL-3324). The findings of that study were since verified by additional structural and cost analyses. A system of concrete arches to support a deep layer of earth over the three experiment rooms is specified. The topography of the site favors the use of earth shielding.

Since the facility is built into a hillside with the cyclotron and experiment rooms below ground level, the external walls need meet only structural specifications. A very large volume of shielding is required, however, for the thick internal walls between experiment rooms, and between experiment areas and normally occupied areas. The use of concrete retaining walls filled with compacted crushed rock was investigated as an economic alternative to solid concrete construction.

Preliminary studies had indicated that the concrete walls cored with crushed rock would be the more economic design for thick shield walls. This type of construction was suggested in the preliminary status report of June 1962. After a comprehensive study of shield wall stresses, it became apparent, however, that the earlier conclusion in favor of cored-wall construction should be re-evaluated. The original assumption with respect to the amount of reinforcing steel required proved to be low for the stresses actually calculated.

For the comparison of cored-wall versus solid concrete construction a typical wall section 11 yd high and 11 yd wide was selected, see Fig. 12.5. The volume of this typical shield wall is, then, 121 yd^3 per yard of wall length. The re-evaluation of the two types of construction is summarized in Table 12.1; the assumed estimating factors and the requirements are detailed. The estimated cost of the cored-wall shielding is $\$35/\text{yd}^3$ while the solid wall costs only $\$20/\text{yd}^3$. The additional cost of the reinforcing steel required in the cored walls is, of course, the determining factor.

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Fig. 12.5. Typical section of shield wall used for comparison of solid and cored wall construction.

Table 12.1. Comparison of costs for cored wall and solid concrete construction of shielding.

	Estimating Factor	Cored Wall		Solid Wall	
		Required	Cost	Required	Cost
Concrete, 3000 psi	\$13/yd ³	58 yd ³	\$ 754	----	----
Concrete, 2000 psi	\$12/yd ³	----	----	121 yd ³	\$1450
Concrete, placement	\$4/yd ³	58 yd ³	232	121 yd ³	484
Reinforcing steel, placed	\$210/ton				
Vertical sections of bent		2% by vol	1000	----	----
Horizontal section of bent		4% by vol	1220	----	----
Reinforcing mesh	\$0.05/ft ²	----	----	200 ft ²	10
Forms	\$2/ft ²	360 ft ²	720	200 ft ²	400
Finishing	\$0.10/ft ²	200 ft ²	20	200 ft ²	20
Crushed rock fill, placed	\$5.25/yd ³	63 yd ³	331	----	----
Total Cost, for a section 11 yd high by 11 yd wide			\$4,277/linear yd	\$2,364/1-yd	
Unit Cost			\$ 35/yd ³	\$ 20/yd ³	

Utilities Systems

To reduce the length of lines the utilities should, of course, be located as close as possible to the area to be served. In a number of cases, however, this is made difficult by the very thick shielding required. To penetrate the thick shield walls most of the utilities lines are cast into the walls; some pass through the mazes. Most of the water, compressed air, and all of the dc bus lines are cast in the walls. Control cables and ventilation ducts pass through the mazes. This arrangement allows ample room in the mazes for future additions to the system. The mazes and shield penetrations are described in Chapter 11.

Demineralized Water System. - The cyclotron and the ion optics system are served by separate closed-loop demineralized water cooling systems. The system for the cyclotron, Fig. 12.6 is located on the second floor of the cyclotron building; the system for ion optics, Fig. 12.7, is in the basement of the office and laboratory building. This separation is advisable for maintenance and economic reasons. The two systems are similar, differing only in capacity.

Each system has a mixed resin bed demineralizer with a monitor which automatically shuts the unit down when a pre-set level of conductivity is reached. The make-up water supplied to the closed loops passes through these units.

Each loop consists of the head load, pumps, filters, heat exchangers, two storage tanks, and associated valves and piping. The second storage tank provides a standby supply whenever the water supply in use exceeds the limits of conductivity. Both of these water systems are continuously monitored; any off-limit condition gives an alarm.

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Fig. 12.6. Demineralized water system for cooling the cyclotron.

Fig. 12.7. Demineralized water system for cooling the components of the ion optics system.

Both loops contain 3-micron filter banks, plus spares to allow uninterrupted operation during filter maintenance. The heat exchangers have about 15% greater capacity than needed to allow for growth, or for limited operation if one exchanger is inoperative. Each system has a spare pump to provide for uninterrupted operation. There is a pressure control valve in each system. To maintain a nearly constant water temperature a diverter valve in the return line provides for bypassing the heat exchangers when necessary. Its operation is controlled by a temperature sensing element in the line at the output of the pump.

The cyclotron water system includes two 1200-gpm pumps, two 3000-gal unpressurized storage tanks, four 600-gpm filters, and two heat exchangers rated at 25×10^6 Btu/hr. The piping and valves are mild steel specified to operate at 175 psi.

The ion optics system requires three 1200-gpm pumps, two 7000-gal unpressurized storage tanks, six 600-gpm filters and two heat exchangers rated at 25×10^6 Btu/hr. Specifications for the piping and valves are the same as for the cyclotron.

The shell side of each heat exchanger is connected with a 30,000-kW cooling tower adjacent to the cyclotron building. This cooling tower also serves the cooling requirements of the office-laboratory building. The equipment size for both cooling systems is the same wherever possible. This minimizes the stock of maintenance parts and permits interchangeability.

Heating, Ventilating, and Air Conditioning. - The air handling equipment is designed to maintain 76°F at 50% relative humidity, while outside conditions may range from 0°F dry bulb in the winter to 77°F wet bulb temperature in the summer. There are 22 different air supply systems delivering a total of 538,000 cfm of air to the buildings. Nine of these systems provide temperature and humidity control for the first and second floors of the office and laboratory building and for the experiment areas, see Fig. 12.8 and 12.9.

One 10,000-cfm system delivers conditioned air to the cyclotron vault. Within the vault four recirculators are fitted with cooling coils to maintain the temperature and humidity control. All other areas receive 100% make-up air.

Fig. 12.8. Heating, ventilating, and air conditioning for first floor and basement.

Fig. 12.9. Heating, ventilating, and air conditioning for second and third floors.

All input air systems with temperature and humidity control include preheat steam coils, roll type filters, electrostatic filters, chilled-water coils, and blowers. The systems used for ventilation and heating only are equipped with steam preheat coils, automatic 80% efficient filters, and the usual blowers.

Two 1250-ton water chillers supply chilled water for the entire facility; partial cooling is possible in the event of failure of one of the units. Chilled water is piped to the chill coils in the air input systems, where the temperature of the air is lowered to 58° F. The air is then transported and distributed to each room or area. Hot water coils at the input vent to each room reheat the air to the desired temperature.

All of the experiment areas operate at a negative pressure, 0.1 in. of water, to prevent the release of airborne contamination to the other areas. The rate of air change varies from one change per hour in the proton room to five changes per hour in the beam corridor.

Electrical. - A 30,000-kVA, 161,000/13,800-V, three-phase, 60-cycle transformer will be provided at an existing area substation. A new 13,800-V power line, approximately one mile long, will be constructed from this substation to the Mc² building site. The power distribution lines at the site are shown schematically in Figs. 12.10 and 12.11.

The power for the cyclotron and cyclotron building is supplied through 13.8-kV switchgear supplying a 2000-kVA, 13,800/460-V transformer; a 2000-kVA, 13,800/2400-V transformer; and three motor generator sets with a total of 17,250 kVA.

The basement of the laboratory and office building contains the 13.8-kV switchgear for supplying power both to this building and to the shielded experiment area. The basement also contains one 2000-kVA, 13,800/460-V and one 2000-kVA, 13,800/2400-V transformer; these units supply the air handling, pumps, and other equipment. A 500-kVA, 460/120-240-V transformer provides for lights, small motors, and other equipment. Instrumentation power is provided by a 75 kVA, 13,400/120-240-V shielded secondary transformer.

Fig. 12.10. Electrical one-line diagram for cyclotron building and cooling tower.

Fig. 12.11. Electrical one-line diagram for laboratory and office building and for shielded experiment rooms.

A 60-kVA emergency power source for the buildings and a 5-kVA emergency power source for a Civil Defense fallout shelter are provided.

There are four 2000 kVA, 13, 800/460-V transformers in the muon room and two similar transformers in the pion room. These transformers supply 460-V service to the solid-state power rectifiers for the ion optics system. All of the magnet and quadrupole power supplies for the ion optics system are located overhead in the pion and muon rooms, on a floor above the room cranes; the floor thickness provides ample shielding. This location permits the shortest runs for dc bus to components of the optics system. Since only portions of the system are operated at any given time, switches permit multiple use of the power supplies. These dc supplies for the optics system are of the solid-state type and are regulated to within 0.01%. This is also a possible alternate type of supply for the main magnet.

Medical and Time-of-Flight Facilities

The medical facility and neutron-time-of-flight facility are presented as important possible future additions to the proposed research complex. Their treatment as separate items is primarily because of a combination of scientific, organizational, and historical reasons. The medical facility stems largely from the interest of the ORINS Medical Division in radio-therapy with pions. The neutron-time-of-flight facility is an optional plan to be considered if the now pending consideration of the Laboratory's electron linac proposal is not resolved. Although described and cost estimated separately, the medical facility is included in the architectural drawings. The neutron-time-of-flight facility, because it is a recent addition to the plans, is shown only in a single drawing which depicts the manner in which it is incorporated into the main installation. The two facilities are described below.

Medical Facility. - Facilities for bio-medical research include an underground room for irradiation experiments and, directly above, at the surface, a laboratory and office building, as shown in Fig. 12.2. The two areas are connected by an elevator with a 62-ft lift.

The well shielded irradiation room, located adjacent to the beam corridor, is constructed of reinforced concrete and covered with 30 ft of earth. The wall in common with the corridor is constructed of steel plates and barytes concrete. The lower level is for beam entry and transport; the upper level contains the target area and control station. This arrangement provides for irradiating the target from two directions, 90° apart. In addition to the elevator to the building above ground there is a horizontal access tunnel about 150 ft long.

The medical building provides space for laboratories, offices, rest rooms, recovery room, and for special equipment. The building is a one-floor structure of structural steel, concrete block, and brick veneer.

This facility contains its own air handling system and is temperature controlled year-round. Other utilities, such as water, steam, and power, are supplied from the main systems.

Neutron-Time-of-Flight Facility. - This facility includes a neutron source room, six flight stations, and an office and laboratory building, see Fig. 12.12. In the beam corridor the proton beam needs to be deflected only 2° to enter a bending magnet which then directs it upward to a target in the neutron source room. This room, located directly over the east end of the corridor, is shielded with concrete and a mound of earth; access is through an underground passageway.

Two horizontal flight tubes 30° apart extend radially outward from the neutron source and provide flight stations at 15, 30, 50, 70, and 150 meters. The shorter tube can be extended when necessary. A 5-meter station is directly above the source. This particular physical arrangement was chosen for a number of reasons: the location of the flight tubes largely above ground is the least expensive, the system can be more easily modified, and finally, the system can be installed after completion of the main facility with a minimum disruption of the existing research program.

The one-story laboratory building is of reinforced concrete, structural steel, and masonry construction. The building contains offices, laboratories, analyzer rooms, and space for mechanical equipment.

13. REVIEW OF COSTS AND ESTIMATING PROCEDURES

A cost estimate for the Mc^2 Cyclotron project has been prepared based on use of all the available data from the Mc^2 design studies. Our aim in this estimate has been to obtain realistic costs for a complete project; to accomplish this aim it was necessary to prepare a substantial amount of detailed work sheet material. A file document, ORNL CF 63-5-85, containing this material is much too voluminous for this report. A summary of the results is included in this section, however, and some typical supporting details are shown in Appendix F.

The data, arranged in six main phases, represents logical segments of the project. The cost of any particular item was assigned to the segment to which it made its major contribution. A summary of the costs arranged in these six comprehensive phases is given in Table 13.1.

The basic cost includes the costs of materials, construction, equipment, installation, and direct costs for these six phases, as itemized in subsequent tables. In addition, costs must be included for engineering, for contingencies, and for escalation. The engineering costs are estimated at approximately 15% of basic costs. The contingency factor reflects the precision of the estimate on particular phases or items. As a whole, the average contingency for the project is approximately 20%, but it varies on specific items from 15% to 40%, depending on the accuracy with which the estimate could be made. Many items, such as standard equipment and building materials, have small contingencies. Items for which design is incomplete, such as the rf cavity, have larger contingencies. Because of the long-term nature of the project, escalation must of course be included; the AEC accepted rate of 4% per annum is used. The escalation sum shown in Table 13.1 is based on 1963-64 dollar values and assumes that project is authorized in FY 1965 with commitments spread, according to a proposed schedule, over about 5 years.

Table 13.1. Cost Summary: Mc^2 Cyclotron Facility

Outside construction	\$ 1,386,000
Cyclotron building	1,636,000
Office-laboratory building	2,045,000
Shielded area	8,288,000
Cyclotron	10,097,000
Ion optics	5,167,000
<hr/>	
Basic cost	\$ 28,619,000
Engineering	4,293,000
Contingency	5,902,000
Escalation	3,875,000
<hr/>	
Total project cost	\$42,689,000
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These cost estimates are based on known market prices, quotations, and catalog price lists for standard items; on recent experience at the Laboratory in comparable construction and equipment procurement; on specific consultation with prospective suppliers; and on preliminary bids obtained from several representative vendors. Every effort was made to obtain realistic estimates of current, 1963-64, costs for construction in the Southeast area. The sources of specific quotations and preliminary bids for items totaling some \$11 million are tabulated in Appendix F. In the same appendix is a further example of the estimating technique used. A table of specifications for all the beam optics magnets is given, along with the individual computed costs.

The time schedule assumes the availability of the cyclotron vault and the beam corridor at about the halfway mark in overall physical construction. This allows assembly of the cyclotron magnet iron, coils, cavity, etc., during the general contractor phase, thus shortening the total time for the project. It is planned to use a cost-plus-fixed-fee contractor for assembly of the cyclotron and the ion optics systems. The labor for this work is included in the project cost; the current wage scales are used. The principal years of commitment for escalation projection are FY-1966-68 in which approximately $\$35 \times 10^6$ would be obligated to vendors.

In determining unit costs for the building portion of the project, the cost of equipment necessary to the functional operation of each building area is included in the total cost. The cost of equipment chargeable to the Mc^2 cyclotron and to the ion optics system is not included. The unit costs for the buildings are as follows:

	<u>Total Cost</u>	<u>\$/gross ft²</u>	<u>\$/gross ft³</u>
Laboratory and office bldg	\$1,944,000	20.15	1.19
Cyclotron bldg	1,266,000	38.17	0.73
Shielded area	7,909,000	79.03	1.66

Outside Construction

Outside construction includes land improvements, power transmission lines, substation equipment, the cooling tower, and all utilities piping to within 5 ft of the buildings. The largest portion of this cost is assignable to the 30,000 kVA, 161,000/13,800-volt transformer located at the building substation. These costs are summarized in Table 13. 2.

In sizing the water, steam, and drain lines for the project, consideration was given to the long range requirements for these services for future programs of the Laboratory. The cooling tower is a major item; it is sized to handle some 30,000 kW of heat load. This load is particularly large because all cyclotron and beam optics components are water cooled. The air conditioning compressors of the building complex are also cooled by this tower. The tower costs were obtained from preliminary quotations received from two manufacturers. The total tower cost includes one spare pump and motor, piping, fire protection, switchgear, and motor control center.

Cyclotron Building

The cyclotron building is a four-level structure attached to and extending over the cyclotron vault. The costs for the vault are estimated as part of the larger shielded area. The estimates for the cyclotron building also include the shop machinery, the gantry crane, and all equipment which has the prime purpose of serving the building requirements. A summary of the principal items of this building cost estimate are given in Table 13. 3.

The building contains most of the cyclotron support equipment including power supplies, ion injector, water system, forevacuum pumps, and some air handling equipment. These costs are treated as part of the cyclotron cost figures.

Table 13.2. Costs: Outside Construction

Item	Cost	Contingency	Total
1. Cooling tower	\$ 442,550	\$ 87,050	\$ 529,600
2. Roads and parking	31,000	6,200	37,200
3. Walks	2,300	460	2,760
4. Landscaping	13,050	1,100	14,150
5. Storm drains	48,700	9,700	58,400
6. Potable and process water, and fire line	83,375	16,675	100,050
7. Steam	98,100	19,600	117,700
8. Electrical service	657,400	131,500	788,900
9. Land preparation	9,200	2,000	11,200
	<u>\$1,385,675</u>	<u>\$274,285</u>	<u>\$1,659,960</u>

Table 13. 3. Costs: Cyclotron Building

Item		Costs	Contingency	Total
1.	Excavation	\$ 38,980	\$ 8,700	\$ 47,680
2.	Footers, tunnel, stairwell, elevator shaft	29,740	5,950	35,690
3.	Steel framing	74,550	14,910	89,460
4.	Columns, floor beams, floors	117,150	23,430	140,580
5.	Siding	76,170	15,230	91,400
6.	Roof	27,390	5,480	32,870
7.	Gantry crane	263,400	52,600	316,000
8.	South wall door	75,420	15,080	90,500
9.	Elevator	72,500	14,500	87,000
10.	Power and high voltage supplies	115,600	23,200	138,800
11.	Electrical and lighting	385,955	77,655	463,610
12.	Sanitary facilities and sump	14,500	2,900	17,400
13.	Shop	106,845	5,355	112,200
14.	Fire protection, including alarms	24,700	4,900	29,600
15.	Compressed air system	119,970	23,980	143,950
16.	Doors	5,795	1,160	6,955
17.	Miscellaneous structural	36,245	7,250	43,495
18.	Fallout shelter	14,750	2,950	17,700
19.	Earth fill	23,880	4,775	28,655
20.	Potable and process water	1,900	380	2,280
21.	Roof drains	5,625	1,125	6,750
22.	Shield door	5,000	1,000	6,000
Totals		\$1,636,065	\$312,510	\$1,948,575

The cost of the gantry crane, south wall canopy door, elevator, and air compressor were based on price quotations. Shop equipment prices are based on cost experience from recent purchases of similar equipment at the Laboratory. The shop is sized to provide research and cyclotron maintenance support. Heavy machine work will be done at the main shops, or by outside fabricators.

The design of the cyclotron building follows standard structural practice. The cost estimate for the structure is based on prevailing material and labor costs for the Oak Ridge area.

Laboratory and Office Building

This building consists of two stories and a basement. In layout it follows the same modular design used extensively at the Laboratory. This minimizes costs and still provides the flexibility required of a research building. A suspended floor in the 7000 ft² control and counting room provides space for the thousands of control and data cables that enter the area and also maintains flexibility for the placement of control and monitoring equipment for experiments. In the basement a 48-ft wide aisle gives access for trucks and equipment to go directly into the beam rooms. Three heavy-load bearing floor sections are provided for the rolling shield doors.

The prices of most of the building equipment are based on quotations obtained by telephone, but the costs of the larger items, such as the elevator, distilled water equipment, and air conditioning compressors are based on written quotations. It should be noted that most of the equipment in the basement serves the ion optics system, to which its costs is assigned. The cost estimate for the structure is based on past experience at the Laboratory, and takes into account prevailing labor and materials costs.

In the summary of the building costs, Table 13.4, contingencies are about 20% of base cost.

Table 13.4. Costs: Laboratory and Office Building

Item		Costs	Contingency	Total
1.	Excavation	\$ 104,110	\$ 22,450	\$ 126,560
2.	Backfill	14,700	2,900	17,600
3.	Footers, stairwells, ext walls, elevator shaft	127,000	25,400	152,400
4.	Columns, floor beams, floors	165,984	33,176	199,160
5.	Exterior walls	43,085	8,615	51,700
6.	Roof system	62,490	12,490	74,980
7.	Interior masonry and partitions	42,600	8,500	51,100
8.	Floor covering	92,080	18,410	110,490
9.	Power and high voltage supplies	485,000	97,000	582,000
10.	Lighting and miscellaneous equipment	235,000	47,000	282,000
11.	Elevator	30,000	6,000	36,000
12.	Laboratory equipment	101,335	20,265	121,600
13.	Sanitary facilities	56,600	11,300	67,900
14.	Fire protection	85,150	17,050	102,200
15.	Distilled water	9,750	1,950	11,700
16.	Process water system	63,600	12,700	76,300
17.	Earth fill	119,500	23,900	143,400
18.	Retaining wall and tunnel	15,750	3,150	18,900
19.	Potable and process water	2,320	460	2,780
20.	Process sewer	2,375	475	2,850
21.	Suspended ceiling	41,725	8,365	50,090
22.	Doors and windows	50,555	10,115	60,670
23.	Painting and finishing	30,725	6,105	36,830
24.	Portico	7,190	1,410	8,600
25.	Steam	56,300	11,200	67,500
Totals		\$2,044,924	\$410,386	\$2,455,310

Shielded Experiment Area

The shield area, which includes the cyclotron vault, was cost estimated on the basis of layouts and engineering analyses made by the civil engineering group after considerable study to determine the most economical construction methods. These studies, reviewed in Chapt. 12, showed that solid concrete walls can be placed for about 2/3 the cost of walls cored with compacted rock fill. The arched roof design with earth as the shielding material was also determined to provide minimum cost.

The tabulated costs for the shielded area, Table 13.5, include concrete footings. The size of the footings is based on the assumption of a maximum bearing load of 10,000 pounds/ft². This is believed to be a moderate point of view for general construction practice in this area. If future core drilling shows that higher bearing loads can be used, significant savings will result.

The cost of vault beams, cranes, beam port blocks, and beam dump blocks are from price quotations of vendors in the respective fields. The cost of 2000-lb concrete at \$12 per yd³ and 3000-lb concrete at \$13 per yd³ are the delivered prices from local suppliers. The 3000-lb concrete is used in the footings, structural walls, lintels, and arches. Unless otherwise noted, costs were derived from past experience using prevailing material and labor costs for the Oak Ridge area.

Cyclotron

The cyclotron represents about 35% of the basic cost of the project, as was shown in Table 13.1. Items for which preliminary quotations were submitted include the vacuum tank, the forevacuum system (not including piping), rf power supply, motor-generator sets, battery room, and much of the equipment in the water system. The cost of most of the components of the high vacuum system, high vacuum header, and compressors for the diffusion pump baffles were estimated from standard catalog prices. Quantity prices and competitive bidding will probably result in savings. Details of cyclotron costs are given in Table 13.6.

Table 13.5. Costs: Shielded Experiment Area, including Cyclotron Vault

Item	Cost	Contingency	Total
1. Excavation	\$ 787,200	\$ 184,415	\$ 971,615
2. Footers	1,297,800	259,600	1,557,400
3. 2,000 # Concrete	1,088,610	216,250	1,304,860
4. 3,000 # Concrete	1,006,060	201,115	1,207,175
5. Forms	440,735	93,690	534,425
6. Arches	344,200	68,300	412,500
7. Vault beams	654,200	130,800	785,000
8. Beam corridor extension	11,000	1,800	12,800
9. Floors	25,400	5,000	30,400
10. Retaining walls	59,400	11,900	71,300
11. Shield door	264,250	50,850	315,100
12. Pion iron plug	276,900	55,100	332,000
13. Beam port blocks	207,650	12,350	220,000
14. Power and high voltage supplies	249,100	50,000	299,100
15. Electrical and lighting	355,950	70,050	426,000
16. Cranes	378,625	75,725	454,350
17. Penetrations	111,050	22,200	133,250
18. Compacted rockfill	19,010	3,805	22,815
19. Earth shielding	592,400	118,500	710,900
20. Hot storage	15,776	3,140	18,916
21. Fire protection (see lab and office bldg.)			
22. Power supply rooms	63,500	10,400	73,900
23. Beam dump blocks	39,300	7,900	47,200
Totals	\$8,288,116	\$1,652,890	\$9,941,006

Table 13.6. Costs: The Cyclotron

Item	Cost	Contingency	Total
1. Vacuum tank	\$ 398,000	\$ 100,000	\$ 498,000
2. High vacuum system	296,310	44,515	340,825
3. High vacuum header	9,828	2,220	12,048
4. Forevacuum system	222,400	47,600	270,000
5. DP baffle compressors	10,925	2,185	13,110
6. Magnet iron	3,360,000	890,000	4,250,000
7. Magnet support	287,500	57,500	345,000
8. Main coils	800,000	280,000	1,080,000
9. Radial coils	1,120,000	390,000	1,510,000
10. Magnetic channel	175,930	43,990	219,920
11. Injector	411,960	102,990	514,950
12. RF cavity	611,960	189,570	801,530
13. RF amplifier	218,920	85,200	304,120
14. RF power supply	197,040	30,400	227,440
15. Water system	154,600	30,900	185,500
16. Motor-generator sets	1,075,980	161,350	1,237,330
17. DC bus lines	82,000	41,000	123,000
18. Battery room	8,700	1,700	10,400
19. Control system	599,270	119,855	719,125
20. Radiation protection	55,500	11,100	66,600
Totals	\$10,096,823	\$2,632,075	\$12,728,898

The items most difficult to estimate are the magnet iron, the main and radial coils, and the rf cavity. As mentioned earlier in this chapter and covered otherwise in Chapter 8, the cost estimates for the magnet iron were made after several consultations with large steel producers. Consideration was given to ingot and forging size, the amount of removed metal (which would be repurchased by the producer at scrap prices), and the machining required. The estimate of \$0.35 per pound for the finished magnet appears reasonable when compared with the unit price of \$0.26 per pound paid for another large magnet at the Laboratory. The increase is mainly attributable to the more complex machining requirements and to more waste metal.

The cost of the coils was based primarily on the costs experienced in the construction of other similar coils at ORNL; a somewhat larger unit cost was used, however, because of the complexity of the coil shapes. The base figure of \$5.00 per pound of conductor includes the cost of canning the coils in stainless steel. In addition, a contingency of 35% was added. In the event that the alternate magnet design is used, it is possible that the main coils would cost somewhat less because the coils are of much simpler design.

The rf cavity costs are based on \$60/ft² of copper surface. The one-side surface area of the cavities is about 10,000 ft². The figure is based on ORNL cyclotron construction experience but has a large factor added because of the greater size, complexity of assembly, and detailed design problems. Because of the uncertainty in this item a 30% contingency is added.

Other items of the cyclotron cost are obtained by extrapolating costs for similar, but smaller, systems in use at the Laboratory. These include the power amplifier, dc bus lines, control system, and radiation protection components.

It is unavoidable that the cost estimate for the cyclotron is relatively less precise; large contingency factors are used, however, to guard against underestimates. Better estimates can only be provided when detailed designs (Title I and Title II) are completed.

Ion Optics

Provision for multiple use of dc power supplies was a basic consideration in the design of the ion optics system. In addition, power supplies are located at minimum distances from loads; for example, the inclusion of power supply rooms in the arches of the pion and muon rooms greatly reduces bus lengths.

The costs of the components of the ion optics system, summarized in Table 13.7, were obtained through discussions with prospective fabricators. From these discussions, unit prices of \$0.35/lb for finished iron and \$3.00/lb for finished copper were derived. Costs for the magnet supports were derived from cost experience at the Laboratory for similar units. As an example of the detail of the specifications used in these discussions, the code designations of the magnets, their size, weight, and power requirements are listed in Appendix F.

Costs of several components of the water system, such as heat exchangers and water pumps, are based on quotations from vendors. Beam pipe valves and vacuum station costs are from listed catalog prices. The cost of beam pipe plugs was extrapolated from the cost of similar units at ORNL. Likewise, the remote handling equipment is estimated from similar equipment recently installed in the Laboratory.

Power supply costs were obtained through discussions with prospective suppliers and by comparison with the cost of units of like size built recently for other research laboratories. Costs for other items such as magnets, vacuum tanks, beam dumps, and target shields were obtained from discussions with personnel of the Laboratory's fabrication shop.

Table 13.7. Costs: Ion Optics

Item	Cost	Contingency	Total
1. DC lines	\$ 448,180	\$ 89,620	\$ 537,800
2. Water system	186,575	36,975	223,550
3. Beam pipe	31,875	6,375	38,250
4. Magnet vacuum tanks	21,330	4,265	25,595
5. Beam pipe valves	17,770	2,670	20,440
6. Vacuum stations	106,920	21,300	128,220
7. Beam dumps	64,855	12,960	77,815
8. Beam pipe plugs	93,450	23,350	116,800
9. Magnets	2,378,070	211,305	2,589,375
10. Quadrupoles	618,265	63,090	681,355
11. Power supplies	939,710	95,640	1,035,350
12. Target shields	84,665	16,935	101,600
13. Remote target handling and observation	160,000	32,000	192,000
14. Radioactive water system	15,000	3,000	18,000
Totals	\$5,166,665	\$619,485	\$5,986,150

Medical and Neutron Time-of-Flight Facilities

As indicated in Chapt. 12, the medical and neutron time-of-flight facilities are considered as important possible future additions to the Mc² Cyclotron Facility; their costs were not included, however, in the cost summaries presented above. Cost estimates for these proposed additional facilities have also been prepared; they are summarized in Table 13.8. The escalation is again based on 4% per annum, and commitment is assumed to be FY-1968. More detailed estimates are given in Tables 13.9 and 13.10. It should be noted that the analyzing and focusing magnets required by the Medical Facility are included in the tabulations of Appendix F, but these costs were not included in the basic costs for the Mc² Cyclotron Facility.

Table 13. 8. Cost Summary: Medical and Neutron Time-of-Flight Facilities

<u>Medical Facility Summary</u>	
Building	\$ 883,760
Ion optics	609,585
	<hr/>
Basic Cost	\$1,493,345
Engineering	224,000
Contingencies	243,055
Escalation	235,250
	<hr/>
	\$2,195,650
.	
<u>Neutron Time-of-Flight Facility Summary</u>	
Laboratory and office bldg	\$ 765,900
Experiment area	763,850
	<hr/>
	\$1,529,750
Engineering	229,500
Contingencies	311,650
Escalation	331,300
	<hr/>
	\$2,402,200
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Table 13.9. Cost Estimate: Medical Facility

Item	Cost	Contingency	Total
1. Excavation	\$ 22,080	\$ 4,800	\$ 26,880
2. Laboratory area	36,600	7,300	43,900
3. Experiment area, footers	4,845	1,615	6,460
4. Experiment area, walls and roof	73,225	14,645	87,870
5. Barytes concrete	153,000	30,600	183,600
6. Iron plug (two-story)	449,130	89,820	538,950
7. Floor covering	1,745	350	2,095
8. Painting	4,120	820	4,940
9. Equipment	62,430	12,470	74,900
10. Electrical	12,080	2,420	14,500
11. Fire Protection	3,000	600	3,600
12. Power and high voltage supplies	23,575	4,675	28,250
13. Sanitary	2,080	420	2,500
14. Process and sanitary sewers	3,945	790	4,735
15. Earth fill	30,750	6,150	36,900
16. Potable and process water	1,155	230	1,385
17. Analyzing magnets	359,315	35,270	394,583
18. Quadrupoles	120,650	12,240	132,890
19. Medical power supplies	81,820	8,280	90,100
20. DC lines	47,800	9,560	57,360
Totals	\$1,493,345	\$243,055	\$1,736,400

Table 13.10. Cost Estimate: Neutron Time-of-Flight Facility

Item	Cost	Contingency	Total
Laboratory and office building	\$ 720,000	\$144,000	\$ 864,000
Parking lot	6,600	1,400	8,000
Outside utilities	39,300	7,800	47,100
Flight stations, above ground	22,300	4,400	26,700
Flight stations, below ground	14,650	2,950	17,600
Above-ground stations, services	26,500	5,300	31,800
Below-ground stations, services	8,350	1,650	10,000
Flight station, power	29,900	6,000	35,900
Flight station, control conduit	11,400	2,300	13,700
Flight station, comm conduit	6,100	1,200	7,300
Flight station, vacuum	18,900	3,800	22,700
Flight station, water services	2,100	400	2,500
Flight station, evac system	2,500	500	3,000
Flight station, beam tubes	211,600	42,400	257,000
Alterations to Mc^2	75,300	15,100	90,400
Neutron source, shield	158,550	31,850	190,400
Neutron shield, target device	20,500	4,100	24,600
Neutron shield, cranc	9,100	1,800	10,900
Neutron shield, services	10,800	2,200	13,000
Neutron shield, tunnel	12,300	2,500	14,800
Beam transport equipment	<u>120,000</u>	<u>30,000</u>	<u>150,000</u>
	\$1,529,750	\$311,650	\$1,841,400

14. REVIEW OF SCHEDULE

In the past five or six years planning and scheduling techniques based on logical network diagrams implemented by data processing with digital computers have become recognized as efficient, perhaps indispensable, aids to scheduling and cost control of large projects. Such a system is known as the CPM, Critical Path Method, by Mauchly Associates⁽¹⁾ and as PERT, Program Evaluation Review Technique, by the U. S. Navy⁽²⁾.

In the preparation of this Mc² Cyclotron proposal a rather general schedule based on the CPM system was prepared. We feel the degree of detail in this initial schedule reflects a level consistent with the pre-Title-I studies which are described in this document. Because the major novelties and complexities of the project lie in the area of the machine and the beam handling, these areas were programmed. The building and shielding portions of the project were not programmed; it is felt that they can be handled readily by the project Architect Engineer at the appropriate time.

Schedule Summary

The bar graph of Fig. 14.1 was prepared for a more ready interpretation of the proposed time scale for the Mc² project. The distribution of activities and operations is based partially on several CPM runs by the computer, which used a very coarse manpower leveling, and partially on estimates of sequential requirements.

The complete schedule, from preliminary design to completion of pre-operational checkout, extends over six and three-fourths years. The bulk of the actual construction work will require about four and one-half years; the remainder of the scheduled time is assigned to the preliminary design in the early phase of the project and to the final test operation as the project nears completion.

The largest part of the design work, as shown on the chart, will be finished during the first three and one-half years. Subsequently, supervision of fabrication, testing, and modifications in the field will require the attention of a large engineering group throughout the duration of the project.

Fig. 14.1. Schedule for the Mc² Cyclotron Project.

The Critical Path Method

The first step in the CPM system is the preparation of a network or arrow diagram. The project is divided into a large number of activities and events. The activities are the specific tasks; the events denote the completion of one activity or the start of another. The activities that comprise a phase of the project are arranged in logical series from initial effort to completion. Similarly, other phases consist of sequences of activities which may run parallel in time. Each activity is assigned a duration and a quota of manpower "resources" required for completion in the time given.

To prepare the arrow diagram for the Mc² project each phase of design, fabrication, installation, testing, and start-up was reviewed by appropriate technical personnel to identify the required activities and to determine the time and resources necessary for each. This information was then transferred to the arrow diagram in the proper format. The CPM arrow diagram, Fig. 14.2, shows the twenty-odd general phases that comprise the Mc² project.

A typical activity line is shown below:

The numbers 1260 and 1265 are the initial and completion events, I and J, which uniquely define the activity indicated by the brief word description above the line. The number 63 shows the estimated work days required to perform the activity. 4 EN, 8D indicate resources of 4 engineers and 8 draftsmen are required. The further identification number 101-099 is composed of two parts; 101 classifies the activity, in this case as a design activity; 099 is a number which distinguishes this design activity from all other design activities. The identification number can be used for cost accounting and work assignments.

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To indicate on the network diagram the required sequence of activities (some activities must be complete before others start), so-called dummy activities are inserted between events concerned.

Dummy activities are also used to comply with the logic restriction that no two activities can have identical I and J numbers. Dummy activities are zero-time, zero-resource, activities represented on the arrow diagram by dashed lines.

The information contained in the arrow diagram is transferred to data sheets and then to punched cards. From this input data the computer selects the path requiring the longest elapsed time from start to finish. Such a path is known as the Critical Path. All other paths will have some reserve or "slack" time. The listing of resources for each activity provides a means for balancing and shifting of manpower throughout the overall job so that manpower or resource limits can be most efficiently utilized, without ever being exceeded.

The output data from the computer has the following form.

<u>Ident.</u>	<u>I</u>	<u>J</u>	<u>Duration</u>	<u>Start</u>		<u>Finish</u>		<u>Total Float</u>
				<u>Early</u>	<u>Late</u>	<u>Early</u>	<u>Late</u>	
101-099	1260	1265	63.0	459	814	522	877	355

The first four columns have been described previously. The start times are: early, which is the earliest time the activity could start, and late, which is the latest time it can start without extending the total project. The early and late finish times are analogous. The float time is that time available for possible delay of the activity and is the difference between early and late start times. Any use of the total float may affect other activities in line but will not extend the overall project.

Preliminary Runs

A preliminary machine run was made for the Mc² arrow diagram with the appropriate CPM 7090 program⁽³⁾. The output indicated the critical path, the float time for all activities off the critical path, and the total work days required. The initial total of 2,234 work days, or equivalent elapsed time of approximately 8 years, 10 months, was indicated. Quite naturally, this was felt to be excessive.

All activities on the critical path were then re-evaluated. Consideration was given to additional resources and to additional work shifts (per day) in critical phases. Also, the building construction work was divided into two activity periods. It was decided that the cyclotron vault and cyclotron building could be completed first, to allow the magnet assembly to begin at an earlier date. Appropriate adjustments were made and a new computer run was processed. The new output indicated a different critical path and the total time was reduced to 1697 work days. This critical path can be identified in Fig. 14.2 by the double hash mark on each activity arrow. These activities on the critical path are detailed in the machine printout, Table 14.1. On the basis of 252 work days per year the project now requires 6 years and 9 months of calendar time.

Limitations and Need for Future Work

Preparation of the detailed increments of breakdown required for comprehensive analysis and control have not been possible within the scope of our study. Upon authorization of actual Title-I studies for the project, the major phases of work, as represented here by single lines originating at the starting date, will be further divided into smaller units with suitably precise detail. The manpower assignments will need to be more detailed to give both the exact type and the number of personnel necessary. In effect, the next CPM scheduling step will be the preparation of a detailed diagram for each major project phase; each diagram will be approximately as comprehensive as the present single generalized diagram.

Table 14.1. Computer printout of activities on the critical path.
(Descriptions have been typed in at the left.)

	IDENTIFICATION	I	J	DURATION	DELAY	START TIME	FINISH TIME
Calculate phase II magnet iron des	101-021	10	1085	42.00	0.	0.	42.00
Design $\frac{1}{2}$ scale magnet iron	101-022	1085	1090	42.00	0.	42.00	84.00
Prepare $\frac{1}{2}$ scale magnet iron specs	100-037	1090	1095	60.00	0.	84.00	144.00
Procure $\frac{1}{2}$ scale magnet iron	100-038	1095	1100	126.00	0.	144.00	270.00
Deliver $\frac{1}{2}$ scale magnet iron	100-039	1100	1120	10.00	0.	270.00	280.00
Plot $\frac{1}{2}$ scale magnet fields	111-001	1120	1125	42.00	0.	280.00	322.00
Perform analy. $\frac{1}{2}$ scale field plots	111-002	1125	1130	63.00	0.	322.00	385.00
Prelim. des full scale mag. iron	101-023	1130	1140	30.00	0.	385.00	415.00
Final des full scale mag. iron	101-024	1140	1145	30.00	0.	415.00	445.00
Prep. mag. iron detail dwgs.	101-025	1145	1150	42.00	0.	445.00	487.00
Rev. and check mag iron dwgs.	101-026	1150	1155	10.00	0.	487.00	497.00
Prep. magnet iron bid specs	100-027	1155	1200	21.00	0.	497.00	518.00
Send out mag. iron bids	100-028	1200	1205	40.00	0.	518.00	558.00
Evaluate mag. iron bids	100-029	1205	1210	5.00	0.	558.00	563.00
Inspect mag. iron vendor	100-030	1210	1215	3.00	0.	563.00	566.00
Award bid on mag. iron	100-031	1215	1220	5.00	0.	566.00	571.00
Fabr. mag. iron by vendor	100-057	1220	2495	300.00	0.	571.00	871.00
Inspect mag. iron at vendor	102-008	2495	2500	5.00	0.	871.00	876.00
Deliver mag. iron	100-058	2500	2505	10.00	0.	876.00	886.00
Inspect mag. iron at Mc ²	112-019	2505	2630	2.00	0.	886.00	888.00
Begin install lower mag yoke & cav.	124-003	2630	2685	15.00	0.	888.00	903.00
Comp. install lower mag yoke & cav.	124-004	2685	2690	25.00	0.	903.00	928.00
Align yoke	112-002	2685	2695	25.00	0.	903.00	928.00
	DUMMY	2690	2695	0.	0.	928.00	928.00
Install lower tips	124-005	2695	2700	3.00	0.	928.00	931.00
Align tips	112-003	2700	2705	20.00	0.	931.00	951.00
Install lower magnet coils	113-001	2705	2710	10.00	0.	951.00	961.00
Assemb. rad coils to upper tips	113-002	2705	2715	10.00	0.	951.00	961.00
	DUMMY	2710	2715	0.	0.	961.00	961.00
Position upper tips in mag	124-006	2715	2720	5.00	0.	961.00	966.00
Begin install upper yoke members	124-007	2720	2725	5.00	0.	966.00	971.00
Comp. install upper yoke members	124-001	2725	2730	15.00	0.	971.00	986.00
	DUMMY	2730	2745	0.	0.	986.00	986.00
Comp. align upper mag parts to lwr.	112-022	2745	2755	5.00	0.	986.00	991.00
Energize coils low power	113-020	2755	2760	3.00	0.	991.00	994.00

Table 14.1, cont.

	IDENTIFICATION	I	J	DURATION	DELAY	START TIME	FINISH TIME
Full power check	113-021	2760	2765	5.00	0.	994.00	999.00
Test regulators	113-004	2765	2770	10.00	0.	999.00	1009.00
Realign magnet iron	112-006	2770	2775	20.00	0.	1009.00	1029.00
Install field plot equipment	112-007	2775	2780	10.00	0.	1029.00	1039.00
Hook-up electronics	113-005	2775	2785	10.00	0.	1029.00	1039.00
	DUMMY	2780	2785	0.	0.	1039.00	1039.00
Check out field plot equipment	113-006	2785	2790	10.00	0.	1039.00	1049.00
Begin magnet field plots	113-007	2790	2795	50.00	0.	1049.00	1099.00
Complete magnet field plots	113-041	2795	2800	50.00	0.	1099.00	1149.00
	DUMMY	2800	2805	0.	0.	1149.00	1149.00
Complete computer analy. of data	111-005	2805	2810	15.00	0.	1149.00	1164.00
Shim if necessary	112-008	2810	2815	15.00	0.	1164.00	1179.00
Begin to re-plot fields	113-008	2815	2820	15.00	0.	1179.00	1194.00
Complete field re-plot	113-042	2820	2825	11.00	0.	1194.00	1205.00
Begin analysis of re-plot data	111-004	2820	2830	11.00	0.	1194.00	1205.00
	DUMMY	2825	2830	0.	0.	1205.00	1205.00
Complete analy. of re-plot data	111-006	2830	2835	10.00	0.	1205.00	1215.00
Remove field plotting equipment	112-009	2835	2840	5.00	0.	1215.00	1220.00
Recheck iron alignment	112-010	2840	2845	5.00	0.	1220.00	1225.00
Complete vacuum tank assembly	100-045	2845	2850	50.00	0.	1225.00	1275.00
Install upper tank lids	100-046	2850	2855	25.00	0.	1275.00	1300.00
	DUMMY	2855	2860	0.	0.	1300.00	1300.00
Pump down tank	107-018	2860	2875	10.00	0.	1300.00	1310.00
Leak test vacuum tank	107-019	2875	2880	15.00	0.	1310.00	1325.00
Eliminate leaks	107-020	2880	2885	10.00	0.	1325.00	1335.00
Recheck vacuum	107-021	2885	2890	5.00	0.	1335.00	1340.00
Perform cavity power tests	114-006	2890	2895	42.00	0.	1340.00	1382.00
Make final RF adjustments	114-007	2895	2900	45.00	0.	1382.00	1445.00
Perform ion acceleration start-up	119-016	2900	2905	126.00	0.	1445.00	1571.00
Perform mag channel beam deflec	119-017	2905	3060	84.00	0.	1571.00	1655.00
Complete Mc ² operational check-out	119-001	3060	3065	42.00	0.	1655.00	1697.00

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APPENDIX A: Cyclotron Analogue II

The eight-sector electron cyclotron, Cyclotron Analogue II, was conceived as an experimental device to examine the practicability of isochronous acceleration of particles to kinetic energies approaching the rest mass energy; to reveal any unexpected phenomena which might prevent the use of an isochronous machine as a high-current, high-energy accelerator; and finally, to demonstrate the feasibility of a high efficiency beam extraction system.

The performance of the Analogue has been very satisfactory. It has been shown that the imperfection resonances are traversed without attenuation or beam distortion. The axial and radial focusing frequencies correspond closely to the predicted values, thus demonstrating the validity and accuracy of the design method. Electrons can be accelerated to maximum energy with as little as 170 eV/turn energy gain; this corresponds to 310 keV/turn in the Mc^2 Cyclotron, for which an energy gain of 1 MeV/turn is planned. The improved performance of the Analogue obtained with high energy electron injection has demonstrated the value of the 1-MeV injector planned for the Mc^2 Cyclotron.

The very encouraging work on beam extraction was described earlier in Chapter 5. This appendix includes a review of the theory of the AVF cyclotron, briefly describes the Analogue, and gives an account of the observations of its performance as related to the internal beam. Much of the material included here was given in an earlier status report ⁽¹⁾ but some new information is presented concerning the interpretation of internal beam attenuation curves.

Theory

In the classical cyclotron, the magnetic field must decrease with radius to provide focusing of the ions toward the median plane; otherwise, the ions are lost to the dees or the walls of the vacuum chamber after only a few revolutions. The classical cyclotron is not isochronous; the radially decreasing magnetic field necessary for axial focusing produces an undesirable decrease of orbit frequency with radius. Ions initially in phase with the radio frequency gradually get out of step and cease to be accelerated when the phase shift reaches 90° . The increase of mass with velocity produces an additional departure from isochronism which cannot be compensated because of the axial focusing requirements. The rapid departure from isochronism limits the ordinary cyclotron to low energies, typically 20 MeV for protons. The impracticability of the classical cyclotron as a high energy accelerator stimulated the development of the frequency-modulated cyclotron, or synchrocyclotron. These modulated machines are limited, however, to low beam intensities.

In recent years there has been much interest in a new class of cyclotrons which are truly isochronous. They achieve axial focusing by new methods which circumvent the limitations of the classical cyclotron.

In 1938, L. H. Thomas⁽²⁾ showed that the inclusion of azimuthal variation in the magnetic field of a cyclotron would provide axial focusing forces of sufficient magnitude to permit the use of the positive radial gradient of the average field which is required to compensate the relativistic mass increase. Briefly, the focusing arises from the non-circular orbit shape introduced by the magnetic field variation with azimuth; the radial velocity component and the azimuthal component of magnetic field at the edges of the azimuthal "hills" produce a force toward the median plane.

In 1956, it was shown⁽³⁾ that large additional axial focusing forces are produced if the azimuthal variation in the magnetic field is made to spiral. This is an alternating gradient force which derives from the interaction of the angular velocity of the ion with the alternating

radial gradient of the spiral magnetic field. It is the spiral focusing that has made cyclotrons in the energy region 400-900 MeV practical. The required magnitude of the azimuthal variation in magnetic field is impractically large for a machine with pure Thomas focusing (straight radial sectors).

In an AVF cyclotron, the magnetic field on the median plane, specialized to a sinusoidal variation with N periods (sectors), may be expressed as

$$B_z(r, \theta) = \langle B(r) \rangle \left\{ 1 + f(r) \cos N [\theta - \zeta(r)] \right\} \quad (1)$$

The term $\langle B(r) \rangle$ is the average of the magnetic field at radius r , $f(r)$ is the amplitude of the azimuthal variation, and $\zeta(r)$ describes the spiral of the magnetic field with radius.

The focusing of the particles is ordinarily expressed in terms of the frequency, ν_z and ν_r . These frequencies are given approximately by equations based on the work of Smith and Garren:⁽⁴⁾

$$\nu_z^2 = - \frac{R}{\langle B \rangle} \frac{d \langle B \rangle}{dR} + \frac{N^2 + 1}{N^2} F^2 \left\{ 1 + \frac{2N^2 + 1}{N^2 + 1} \tan^2 \gamma + \right. \quad (2)$$

$$\left. \frac{1}{N^2} \left[\frac{R^2}{F^2} \frac{dF^2}{dR} - \frac{N^2}{N^2 + 1} \left(\frac{R}{F} \frac{dF}{dR} + \frac{R^2}{F} \frac{d^2 F}{dR^2} \right) \right] \right\}$$

$$\nu_r^2 = 1 + \frac{R}{\langle B \rangle} \frac{d \langle B \rangle}{dR} + \frac{N^2}{(N^2 - 1)(N^2 - 4)} F^2 \left\{ 3(1 + \tan^2 \gamma) + \right. \quad (3)$$

$$\left. \frac{5N^2 - 8}{N^2} \frac{R}{F} \frac{dF}{dR} + \frac{N^2 - 1}{N^2} \frac{R^2}{F^2} \left(\frac{dF}{dR} \right)^2 + \frac{N^2 - 4}{N^2} \frac{R^2}{F} \frac{d^2 F}{dR^2} \right\},$$

where: $F^2 = \frac{1}{2} f^2$ and $\tan \gamma = R \frac{d\zeta}{dR}$.

For many purposes, particularly for machines with a large number of sectors, the following equations are adequate:

$$\nu_z^2 = -\frac{R}{\langle B \rangle} \frac{d\langle B \rangle}{dR} + F^2 (1 + 2 \tan^2 \gamma), \quad (4)$$

$$\text{and } \nu_r^2 = 1 + \frac{R}{\langle B \rangle} \frac{d\langle B \rangle}{dR}. \quad (5)$$

It can be shown that ν_r (in the approximation of Eq. (5), which is independent of sector number) is given by $(1 - \beta^2)^{-1/2}$ and, hence, is numerically equal to the total energy of the particle, expressed in units of rest energy. This means, of course, that $\nu_r = 1$ at the center of the cyclotron and increases monotonically with energy; $\nu_r = 2$ occurs at a kinetic energy equivalent to the rest energy, which is 938 MeV for protons or 511 keV for electrons. In a machine with a finite number of sectors, however, $\nu_r = 2$ occurs at a lower energy, for example, at about 810 MeV in an eight-sector cyclotron with moderate spiral.

During acceleration the radial focusing frequency will pass through 1/4 integral, 1/3 integral, 1/2 integral, and integral values. For a particular cyclotron, depending on the pole number, these may be regions of instability in the radial motion of the particles. The situation may be briefly summarized by consideration of an equation of the form

$$a \nu_r + b \nu_z = n \quad (6)$$

where a , b , and n are zero or integers. Where $n = N$ the number of sectors in the machine, the resonances are called "essential resonances." Otherwise, the resonances are called "imperfection resonances." A resonance with $b = 0$, $a \neq 0$ is a radial resonance; $a = 0$, $b \neq 0$ is an axial resonance. Where neither a nor b are zero, a coupling resonance is described. In a properly designed magnetic field the axial resonances cause no difficulty since ν_z is kept in the range 0.2 to 0.3, away from the imperfection resonance $\nu_z = 1/2$.

The reason for the choice of eight sectors for the Mc² Cyclotron can be stated briefly. In a three-sector cyclotron the essential half-integral radial resonance, $2 \nu_r = 3$, causes serious instability. Likewise, in a four-sector cyclotron the essential resonance $3 \nu_r = 4$ causes

substantial beam loss. Six- and eight-sector machines are free from strong essential resonances; $\nu_r = 3/2$ and $\nu_r = 4/3$ are imperfection resonances, but if the strength of the imperfection harmonics, the third and fourth, are low, no difficulty is anticipated if the ions are started at the center of the cyclotron with low radial amplitude. Eight sectors are preferred for the Mc^2 Cyclotron because the energy at $\nu_r = 2$ is somewhat higher than for six sectors; also, the symmetry easily permits four accelerating gaps per revolution, a situation well suited to rf cavities.

Description of the Electron Cyclotron

The Analogue, Fig. A.1, is an eight-sector spiral-pole cyclotron with the same basic field parameters, spiral law, flutter, etc. as the Mc^2 Cyclotron. Electrons are accelerated to, and beyond, the integral resonance, $\nu_r = 2$, which occurs at a kinetic energy of 443 keV ($v/c = 0.84$). Axial focusing and an isochronous mean field are provided to an energy of 530 keV. The main characteristics of the Analogue are listed in Table A.1.

The magnet, a completely iron-free system, shown in exploded view in Fig. A. 2, consists of three principal parts: 8 pairs of sector coils, which produce the proper azimuthal variation and spiral in the magnetic field for axial focusing; five pairs of large circular coils, which, together with the sector coils, produce the average magnetic field required for isochronous orbits; and, finally, 32 pairs of trimming coils, which are used for fine adjustment of the average magnetic field to within a few parts in 10^4 of the isochronous requirement. The coil system is mounted on a massive support casting, which serves to maintain precise alignment. A magnet pole assembly is shown without the trimming coils in Fig. A.3 and with the trimming coils in place in Fig. A.4.

For high precision the sector coils were machined rather than wound. Machining of the unusual shapes was by means of precision numeric-controlled equipment; high strength epoxy adhesives were used for bonding of the various components. The method of fabrication is illustrated in Fig. A.5. The insulation of the copper

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Fig. A. 1. Cyclotron Analogue II.

Table A.1. Characteristics of Analogue II.

Cyclotron unit (c/ω)	16.000 in.
Central field (B_0)	41.926 gauss
Orbit frequency	117.399 Mc/sec
Axial focusing frequency, ν_z	~ 0.2
Energy for $\nu_r = 8/4$	445 keV
Energy for $\nu_z = 0$	530 keV

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Fig. A. 2. Artist's drawing of the Analogue to reveal relationship of components.

Fig. A. 3. Eight sector coils mounted on the lower support casting.

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Fig. A. 4. The lower pole assembly with trimming coils installed.

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Fig. A. 5. A sector coil, showing configuration and fabrication method.

from the aluminum is provided by a 0.0003 in. thickness of aluminum oxide prepared by anodizing prior to installation of the copper conductor.

The magnetic field configuration produced by the magnet system is shown in Fig. A.6.

The accelerating system consists of a quarter-wave strip-line resonator driven by a modified commercial communications transmitter operating at a frequency of 117.4 Mc/s. A feedback loop around the transmitter, with the screen voltage of the final amplifier as the control parameter, stabilizes the output to a few tenths of a percent.

A two-region vacuum system eliminates atmospheric loading from the coil structure and organic materials from the high vacuum beam space. The beam space, separated from the coil system by two thin aluminum diaphragms, is maintained at a pressure of 10^{-6} torr by a 6-in. mercury diffusion pump, with a liquid nitrogen baffle. The region containing the coil system and its support structure is maintained at about 10 microns by a mechanical pump.

The periphery of the high vacuum space is provided with several large ports for the installation of either viewing windows or experimental apparatus. The rear of the vacuum tank has a single large port which permits removal of the dee system without disturbing the precise alignment of the magnet coils.

Power supplies for the Analogue field coils are of two types. Fifteen trimming coils which contribute less than 1% of the central magnetic field are energized from a single 100-volt regulated source, with individual adjustable resistance networks for precise adjustment of the currents. Transistor-regulated power supplies with 1 part in 10^4 stability are used to energize coils which contribute more than 1% to the magnetic field. Several sizes are used; each matches the particular requirements of the load. The largest unit provides 530 A at 10 V for the sector coils.

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Fig. A. 6. Magnetic field distribution in the median plane.

Performance of the Analogue

The characteristics of the external beam in the Analogue have been studied extensively. In the following paragraphs the important observations concerning resonances, beam attenuation, dee voltage threshold, and performance of the electron injector are described.

Resonances - During the initial operation of the Analogue, a major fraction of the beam was lost at a radius of 10.4 in.; also an axial oscillation of the beam envelope was noted at 12.6 in. The trouble at 10.4 in. was at first thought to be caused by either the $\nu_r = 4/3$ or $8/6$ resonance, but it was later shown to be the difference-coupling resonance $\nu_r - \nu_z = 1$. When the horizontal component of the geomagnetic field was canceled, this attenuation was eliminated. The disturbance at 12.6 in. was thought to be the sum-coupling resonance $\nu_r + \nu_z = 2$, and this was verified as described later.

To identify the resonances uniquely, advantage was made of the fact that large changes in the axial focusing frequency can be produced by small changes in the amplitude of the azimuthal variation in the magnetic field; the radial focusing frequency is practically unaffected. The azimuthal variation was modified by changing the sector-coil current. The cyclotron was operated at 97, 98.5, 100, 102.5, and 105% of the standard sector-coil current settings. Each setting required a different set of currents for the five main circular coils and the 32 trimming coils. These currents were derived by least-squares fitting to provide an isochronous mean magnetic field in each case. For the several conditions of operation, the locations of the resonances were recorded. These are indicated in Fig. A.7 by bars which extend from the point where the attenuation or axial motion began to the point where the effect ceased. The solid lines are the computed equilibrium orbit properties for the several currents. The results show clearly that the movement of the inner and outer resonances is in accordance with $\nu_r - \nu_z = 1$ and $\nu_r + \nu_z = 2$ respectively.

Fig. A. 7. Correlation of the location of the sum and difference resonances with ν_r and ν_z at several values of sector coil current.

Attenuation of Electron Beam

In the early operation of the Analogue, a large axial loss of beam was observed. This was subsequently found, as mentioned previously, to be the result of the difference coupling resonance $\nu_r - \nu_z = 1$. It was shown that the attenuation at this resonance is completely eliminated by cancellation of the horizontal component of the earth's magnetic field, see Fig. A.8. Beyond a radius of 10 in., however, a substantial decrease in observed beam persists. Additional studies, discussed below, show that this drop is primarily a result of electron scattering from the probe tip. It is now believed that the actual beam loss, if any, is very small.

The decrease in metered beam results from an increase in scattered current associated with the decreasing radial width of the beam relative to the effective range of the electron. At the 10-in. (150 keV) radius the range of the electrons in the aluminum probe is about 0.1 mm and the radial width of the beam is about 0.3 mm. At 450 keV the radial width decreases to 0.1 mm and the range increases to about 0.55 mm. At this much greater ratio of range to radial width, the probability of electrons leaving the probe tip after scattering through small angles is greatly increased.

Some tests of this hypothesis were made by using probe tips of different materials. Attenuation curves taken with aluminum and tantalum probes under identical cyclotron operating conditions are given in Fig. A.9. At low energies the tantalum shows much lower readings, in agreement with published back-scattering ratios, but at the highest energies the relative decrease is much lower. This is because the maximum range of electrons in tantalum is less than that in aluminum by a factor of 6. The ratio of beam width to range for tantalum is 1 rather than 5.5 for aluminum; hence the fractional loss by small-angle scattering is much reduced.

A recently completed theoretical analysis of the loss of electrons from the probe edge via multiple scattering is in general agreement with these observations. Fig. A.10 shows the fraction of incident 450-keV electrons collected as a function of beam width for

Fig. A. 8. Attenuation curve showing the effect of the difference coupling resonance.

Fig. A.9. Attenuation curves taken with aluminum and tantalum probes.

Fig. A.10. Effect of loss of electrons scattering from edge of probe.

aluminum and tantalum. Comparison of the two curves show clearly that the scattering loss is much lower for tantalum than aluminum.

The dips in beam current that occur at outer radii, Fig. A. 9, are located at points where the radial betatron frequency ν_r has the values $3/2$, $5/3$, $7/4$, and $9/5$. The decrease in current results from narrowing of a portion of the beam on the probe tip. At these values of ν_r , a node in the betatron oscillation about the equilibrium orbit recurs after an integral number of revolutions; for example, at $\nu_r = 3/2$, three complete oscillations occur in precisely two revolutions. The fact that the dips in the attenuation curve are much smaller with the tantalum probe is also explained by the previous arguments. To illustrate the narrowing at resonances of a beam with finite radial betatron amplitudes, the beam width was computed as a function of radius by assuming an amplitude of 0.001 cyclotron units. The radius of a single particle is given by the expression:

$$r(n) = (\gamma_0 + an)^{-1} [(T_0 + an)^2 + 2(T_0 + an)]^{1/2} + b \sin \left\{ 2\pi [\gamma_0 n + (an^2/2)] + \psi_0 \right\},$$

where:

- r = radius in cyclotron units
- γ_0 = initial total energy (rest mass units)
- a = energy gain per turn (rest mass units)
- n = turn number
- T_0 = initial kinetic energy (rest mass units)
- b = initial betatron oscillation amplitude
- ψ_0 = initial phase of oscillation

The above expression neglects all effects due to the azimuthal variation in the magnetic field, that is, $\nu_r = \gamma$, $r = \beta$, $\gamma = (1 - r^2)^{-1/2}$, and does not take into account adiabatic damping of oscillation amplitude with energy.

The width of the beam (the distance from the edge of the probe to the point where a particle strikes) is determined by finding the first $r(n)$ which exceeds the probe radius R_p and plotting the difference

$w = r(n) - R_p$ vs R_p . Fig. A.11 is such a plot for four particles started at the center of the cyclotron with $\psi_0 = 0, \pi/2, \pi$, and $3\pi/2$. It illustrates the marked narrowing which occurs at $\nu_r = 3/2$ and $\nu_r = 2$ and the more modest beam narrowing which occurs at the higher order resonances.

Threshold Voltage. - The minimum threshold dee voltage measured for acceleration of electrons to an energy of 443 keV ($\nu_r = 2$) is 60 volts rms, which indicates a maximum energy gain of 170 eV/turn. The threshold is practically independent of radius. At 70 keV the threshold is 50 volts rms, a decrease of less than 20%; thus the threshold seems to be limited by conditions at the center, phase-slip or otherwise, rather than by field errors throughout the machine. The 170-eV threshold for electrons is equivalent to 310 keV/turn for 810 MeV in the Mc^2 Cyclotron, for which a 1 MeV/turn energy gain is planned.

Injection of Electrons. - The observations and measurements previously reported were obtained with a fixed filament mounted at the center of the cyclotron. In a later version the filament could be moved radially between the excited dee and the dummy dee to optimize its location for a given dee voltage. An attempt to improve the performance of this later system by the addition of an accelerating slit mounted on the lip of the excited dee was only moderately successful, chiefly because the accelerating slit was fixed and the system was difficult to optimize. Finally, an electron source was evolved which injects a highly collimated beam at an energy of 3.3 keV.

The electron injector, shown schematically in Fig. A.12, is a two-stage device; the first stage defines the beam, and the second adjusts the energy. This arrangement has the advantage of minimizing the size of the device without unduly sacrificing performance. Electrons from a heated filament are accelerated by a potential of about 600 V through the first slit, which has an aperture of 4 mm axially by 1 mm radially. They then pass through a 180° spectrometer to an image slit of the same dimensions. At 90° a 1-mm slit defines the angular acceptance. As the electrons emerge from the image slit, they are

Fig. A. 11. Effect of resonances on beam width.

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Fig. A. 12. Schematic of electron injector.

accelerated through an additional 2700 V so that their final energy is 3300 eV, which corresponds to an orbit radius of 45 mm in the central field of the Analogue. The assembly pivots about the exit slit so that the angle of injection may be adjusted.

Certain features of the performance of the Analogue are much improved by the injection of the highly defined beam. It is now possible to accelerate the beam through the difference-coupling resonance $\nu_r - \nu_z = 1$ without attenuation, even without the horizontal magnetic field compensated. Also, the beam accelerates through $\nu_r = 2$ with only slight evidence of radial blowup. Finally, the results of the extraction studies, chapter 5, show that the radial amplitudes are so small as to be practically unaffected by the 8/4 resonance in the absence of the $\cos 2\theta$ bump field. With the $\cos 2\theta$ bump field the radial amplitude grows at two opposing hills only, which would not be the case if the beam entered the resonance region with large incoherent radial oscillations.

References

- (1) The Mc² Cyclotron, a Status Report, June 15, 1963, ORNL-3324.
- (2) L. H. Thomas, Phys. Rev., 54, 580 (1938).
- (3) K. R. Symon et al, Phys. Rev., 103, 1837 (1956).
- (4) L. Smith and A. A. Garren, "Orbit Dynamics in the Spiral-Ridged Cyclotron", UCRL-8598 (1959).

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APPENDIX B: Summary of Gatlinburg Conference

A Conference on "Advances in Meson Physics and Nuclear Research Below One BeV" was held in Gatlinburg, Tennessee on November 12 and 13, 1962. The Conference attracted 135 participants from forty institutions. The topics ranged widely, as can be seen from the program at the end of this appendix. Meson physics dominated one session, while nucleons and nuclear structure dominated a second, but other subjects also were examined, such as neutrino beams, radiation effects in manned space flight, and cancer therapy using negative pions.

The Conference was a lively one. It can best be epitomized by quoting from Professor Wolfenstein's summary:

"... It is very clear that one cannot predict very well what will be of interest five or ten years from now. It becomes immediately clear if one just thinks about some of the work that we have been discussing, which has been done in the last couple of years, and thinks how much of this work we could have predicted ten years ago. The fact of the matter is that the work that has been done is, I think, considerably more interesting; it is considerably richer in its content, than we would have predicted ten years ago when we did not know, of course, anything about parity non-conservation, about the various types of new mesons, as well as many new theoretical techniques.

"So I think we can look forward to many richer problems coming up which we cannot foresee, and also to a rather strong interaction between what goes on at higher energies and what we look for at more moderate energies.

"Let me just mention two examples of that kind of interaction which I think is bound to occur. One example comes in the theory of weak interactions. The weak interactions of strange particles have really hardly been explored, hardly been understood. I mean, they have been explored very much, but hardly understood. As we gain some understanding in strange

particle weak interactions, there undoubtedly are going to be new questions raised for the non-strange particle weak interactions, questions that are very hard to ask now, questions which it will be necessary to find answers to.

"The second example lies in the great interest that now obtains in interpreting total cross-section measurements at very high energies in terms of the exchanges of single ρ mesons, single ω mesons, or single η mesons, and in knowing something about the coupling, say the nucleon-nucleon coupling to the ρ meson. This is something which is being explored at high energies, but it is something which we hope would also come out from an analysis of such things as s-wave pion nucleon scattering, or a more detailed analysis of nucleon-nucleon scattering when we can see the contribution of, say, a one ρ meson exchange.

"It seems unlikely to me, then, that all the problems that we have raised here are likely to be solved in the next five years. However, for those who are interested in these machines, it is good to have learned that in case all these problems are solved, these machines will still prove very useful for the radiotherapy of tumors; and I think in this day when so many people feel that progress in nuclear science is associated with the great dangers of nuclear weapons, this life-saving feature of a high energy accelerator should not be belittled.

"In any case, let me conclude by saying that I believe that those who are now planning the building and the use of these high intensity accelerators in this energy range may state confidently that, if the politicians will provide them with the money and provide them with the years to come, both will be well spent. "

Advances in Meson and Nuclear ResearchBelow One BeV

Session I, Monday, November 12, 9:30 a. m.

Meson Physics

1. Low Energy Pion Physics	30 min
K. M. Crowe, University of California, Berkeley	
2. On Certain Rare Weak-Interaction Processes	30 min
H. Primakoff, University of Pennsylvania	
3. Properties of the Mu Meson and Muonium	30 min
V. W. Hughes, Yale University	
4. Mu Capture in Hydrogen	30 min
J. Rosen, Columbia University	
5. Mu Mesonic Atoms	30 min
H. L. Anderson, University of Chicago	

Session II, Monday, November 12, 2:00 p. m.

Nucleons, Nuclei, and Molecules

1. Nucleon-Nucleon Interactions	30 min
G. Breit, Yale University	
2. Nuclear Reactions in the BeV Range	30 min
A. E. Glassgold, University of California, Berkeley	
3. Nuclear Structure and the Inelastic Scattering of
High Energy Nucleons	20 min
G. R. Satchler, ORNL	
4. Secondary Beams	30 min
R. P. Haddock, UCLA	
5. General Radiobiological Aspects of Variation of LET	30 min
M. L. Randolph, ORNL	
6. Radiotherapy with Negative Pi Mesons	20 min
F. Comas, ORINS	

Session III, Tuesday, November 13, 9:00 a.m.

Diverse Topics

1. High Energy Nuclear Research Related to
Manned Space Flight
R. W. Peelle, ORNL	20 min
2. Pion-Nucleon Interactions
M. H. Hull, Yale University	20 min
3. Mu Mesonic X-Rays
C. S. Johnson, University of Chicago	10 min
4. Neutrino Beams
W. A. Blanpied, Yale University	10 min

Summary

L. Wolfenstein, Carnegie Institute of Technology

APPENDIX C: Site for Mc²

The principal criteria used for selecting a site were a suitable underground rock formation for supporting the building and proximity to the main ORNL area.

The site selected is about 1500 ft east of the main laboratory area and is directly south of the Oak Ridge Isochronous Cyclotron installations, see Fig. C.1. Since an existing road borders the site, only a short approach road need be constructed. This location provides for convenient use of the existing laboratory facilities, such as the library, shops, stores, cafeteria, etc.

At this site, a reasonably flat area about 2000 ft long and 1000 ft *wide* will provide ample room for constructing the facility, see Fig. C.2. An open area about 1000 ft long beyond the end of the beam corridor is available for future expansion, or for experiments.

Preliminary geological information on this area indicates that there are limestone formations about 20 ft below the surface. Core drillings should be made and evaluated to determine the underground rock structure before the final confirmation of the site can be made.

A new asphalt concrete access road with curbs, gutters, and storm drains will be required from the existing road to the building site. Asphalt access roads to the medical building, gantry crane staging area, and cooling tower will also be required. Asphalt parking areas will be needed at the laboratory and office building, cyclotron building, and medical building. Roof drains and a storm sewer system will provide drainage for all of the buildings. Service systems, including sanitary sewer, potable water, process sewer, and underground steam line will need to be extended to the site, Fig. C.3. A sanitary sewer lift station will be needed at the point of tie-in to the existing system.

Fire hydrants will be provided together with a water line encircling the Mc² complex. Miscellaneous retaining walls and truck ramps will be provided at building entrance points.

The earth fill over the experiment area and around the other buildings will be graded to facilitate site maintenance.

Fig. C. 1. Site of the Mc^2 Cyclotron with respect to other Laboratory installations.

Fig. C. 2. Topography of Mc² site.

Fig. C. 3. Service connection to existing ORNL systems.

APPENDIX D: Personnel Estimates and Associated
Development and Operating Costs

This review of personnel requirements for the Mc^2 project is divided into three sections. The first lists the manpower for operations and for high energy research which will pertain after the project is completed and the cyclotron is in operation.

The second section is an analysis of the team of research and design personnel who will take the responsibility for the whole project from the beginning, establishing criteria and detailed designs and supervising construction and operation of the cyclotron and its facility. This group will include both laboratory personnel and loanees from the Architect-Engineer contractor and other sources.

The third section combines the information from the previous two sections to provide an analysis of manpower by years for various phases of the program. As an aid to utilization of this information, associated cost and expenditure figures are tabulated in appropriate relationship to the manpower charts.

The personnel estimates presented in these three sections are for the personnel directly associated with the Mc^2 facility. These estimates assume normal support from the Laboratory organization in such matters as procurement, accounting, and other services ordinarily included as a part of operating overhead.

Research and Operations Personnel

The manpower estimates for the research and operations groups required after the construction of the Mc² Cyclotron is completed are described in this section, and summarized as follows:

Research and Operations Personnel Summary

Research	Professional	66
	Technical	22
	Administrative and Clerical	5
	Support	8
Operations	Professional	12
	Technical	13
	Administrative and Clerical	4
	Support	34
Total Staff	Professional	78
	Technical	35
	Administrative and Clerical	9
	Support	42

Research Groups. - The manpower estimate for research, Table D. 1, was developed by first estimating the size of an average research group (from experience at ORNL and information from other installations), and then determining the number of research groups a facility such as the Mc² Cyclotron could properly support.

The average group consists of 2 senior scientists, 5 scientists, 2 engineers, and 2 technicians. In practice, the size of the group would be determined by the research problem and by the characteristics of the people working on the problem.

Table D. 1. Research Personnel

	For each of six groups	Total
<u>Research in High Energy Physics</u>		
Senior Scientists	2	12
Scientists (Graduate Student, Postdoctoral, Junior Scientists)	5	30
Engineers	2	12
Technicians	2	12
Secretary	0.5	3
Total	11.5	69
<u>Medical Research</u>		
Scientists		4
Technicians		3
Clerical		1
Total		8
<u>Biology</u>		
Scientists		2
<u>Research Support</u>		
Engineers		
Electrical		3
Mechanical		3
Draftsmen		5
Technicians		2
Instrument Mechanics		8
Clerical		1
		22

The senior scientists would be the experienced physicists, or chemists, at the doctoral level who would provide the leadership for the various groups. The scientists are the postdoctoral fellows, junior scientists, or graduate students who would develop solutions of individual problems of the research and would assist generally in the work. The engineers would be experienced mechanical or electrical engineers of BS level; they would provide the planning for devices and instruments and would assist in preparing for the experiments. The technicians would provide normal assistance in support of experiments. Each secretary would serve two or more research groups.

The medical research group, as considered in this estimate, would comprise the resident personnel for the initial investigations and would not include personnel at other locations using Mc² research facilities, nor would it include the final complement of personnel for the future addition of the medical therapy facility.

Research Support. - A separate group for the support of the scientific research programs is shown in Table D. 1. This type of support group is considered most desirable and efficient for the following reasons: 1) The various research groups may differ widely in size, and the size of any one group may vary from time to time. This makes permanent assignment of adequate support personnel to the individual research groups difficult. 2) The support group can more readily provide assistance to temporary groups or to individuals from off-site locations. 3) This group can also give assistance to the operations group by providing maintenance of special apparatus. Their primary responsibility is, however, the development and design of new and novel components and systems and in various other ways to assisting the research groups to stay at the forefront of experimental technology.

Operations. - This manpower estimate, Table D. 2, is based on planned operations for 3 shifts per day, 7 days per week and is an extrapolation of experience on the 86-Inch Cyclotron, the 63-Inch Cyclotron, and the new Oak Ridge Isochronous Cyclotron. The shift personnel, indicated on the tabulation, is the portion of the personnel complement that would change with any modification of the operating schedule for the cyclotron.

The superintendent of operation would be responsible for the Mc² facility. His primary concern would be with operation of the cyclotron; responsibility for the building would be delegated to the building engineer. The three mechanical and three electrical engineers would be concerned with keeping the cyclotron operating properly to provide a high percentage of innage time, with improvements in the cyclotron, and preventive maintenance, and would assist experimentalists in their setups. During each shift, the crew chief would be immediately responsible for the operation of the cyclotron and for personnel safety. The cyclotron operating crew includes: assistant crew chief, health physicist, technician, instrument mechanic, millwright, pipefitter, and electrician. The day shift would have additional personnel, as follows: 1 technician, 3 machinists, 1 pipefitter, 2 electricians, and 2 utilities operators. Actual operation of the cyclotron would normally be performed by the assistant crew chief, aided by the technician.

Table D. 2. Operations Personnel*

	Day	Rotating Shifts	Total
Engineers			
Superintendent of Operations	1		1
Building Engineer	1		1
Mechanical Engineer	3		3
Electrical Engineer	3		3
Crew Chief		4	4
Asst Crew Chief		4	4
Health Physicist		4	4
Clerical	4		4
Technicians	1	4	5
Instrument Mechanics	1	8	9
Machinists	3		3
Millwrights	2	4	6
Pipefitters	1	4	5
Electricians	2	4	6
Utilities	2		2
Janitors	3		3
Total	27	36	63

* For operation 3 shifts per day, 7 days per week.

Development, Design, and Construction Personnel

The manpower estimate shown in Table D. 3 for the development and design of Mc^2 is based, to a large extent, on a comparison of manpower requirements with those experienced on the new Oak Ridge Isochronous Cyclotron. The size of the design and development group will remain essentially constant, after an initial buildup, throughout the Mc^2 design period. This approach eliminates undesirable fluctuations in manpower level.

The composition of a group that would function as a development and design team to supervise the project and to design and build the accelerator is characterized in this manpower table. It can be noted that the personnel whose cost would be charged as operating expense and the personnel charged as capital expense are both included. It is necessary to establish a uniform accounting practice to accumulate the appropriate total cost of the capital facility, which is being designed and built in intimate association with development and operating groups. The criteria established for distinguishing between capital and operation charges is whether a component or system being designed will or will not be a part of the final functioning machine. Development, testing, model work, and the direction of supporting research work would be denoted as operating expense. Design, drawing, fabrication, and installation of all components of the facility would be capital expense. The cost of manpower listed under capital, therefore, will be included in the capital cost of the cyclotron and not as a part of operation.

The architect engineer personnel who design the buildings and facilities are separately administered and therefore are not itemized in this report. Of course, allowance for the cost of these activities is included in the cost estimates.

The detailed manpower estimate is made by breaking the work into a number of logical categories. This breakdown is also influenced by the experience and capabilities of groups and individuals in the Laboratory. The general responsibilities of the various sections would be as follows.

Table D. 3. Personnel for Development and Design

	Development				Capital			Project
	S&T	Clk	Cfts	Total	S&T	Cfts	Total	Total
<u>Management</u>								
Project Director	1							
Assistant Project Director	1							
Budget and Purchasing		1						
Secretary		2						
Clerk		1						
				6				6
<u>Orbit Dynamics</u>								
Group Leader	1							
Co-Group Leader	1							
Junior Math Programmers	2							
	2							
				6				6
<u>Mechanical</u>								
Group Leader	1							
Co-Group Leader	1							
Engineers					7			
Design Draftsmen					10			
				2			17	19
<u>Magnetics</u>								
Group Leader	1							
Co-Group Leader	1							
Engineers	3							
Technicians	4							
Instrument Mechanic			1					
Millwright			1					
Machinist			5					
Electricians			4					
				20				20

Table D. 3. (Continued)

	Development				Capital			Project
	S&T	Clk	Cfts	Total	S&T	Cfts	Total	Total
<u>Electronics</u>								
Group Leader	1							
Co-Group Leader	1							
Engineers	4							
Technicians	2							
Instrument Mechanics			8					
Millwrights			2					
Machinists			4					
				22				22
<u>Instrumentation</u>								
Group Leader	1							
Co-Group Leader	1							
Design Draftsmen					4			
Instrument Mechanic			2					
				4			4	8
<u>Building and Installation</u>								
Group Leader	1							
Co-Group Leader	1							
Draftsmen	2							
Technicians	2							
Millwrights						4		
Electricians						3		
Pipefitters						2		
Welders						2		
Instrument Mechanics						4		
				6			15	21
Total	35	4	27	66	19 ²¹	15	36	102

Management. - The project director and assistant project director would be responsible for the direction of work. The budget and purchasing clerk, secretary, and clerk would assist all sections.

Orbit Dynamics. - This section would conduct all theoretical, computational, and particle-motion studies. This section, working very closely with the magnetic section, would compute the properties of model-magnet fields and help decide the direction of model work.

Mechanical. - This section would produce all mechanical designs and would supervise the work of the design engineers and draftsmen.

Magnetics. - This section would perform all model-magnet work, determine final magnet shape, make all magnet measurements, and design ion optics components.

Electronics. - This group would be responsible for electronic systems, such as rf cavity design, rf drive system for the cavities, ion-phase detectors, and special regulators.

Instrumentation. - This group would be responsible for all controls, positioners, and instrumentation.

Building and Installation. - This group would carry out the Laboratory's responsibility for building layout, checking of the architect engineer drawings, and inspection of building; representatives would be at the building site at all times to answer technical questions and to aid in the flow of information to the construction group. The installation of the cyclotron in the building will be the responsibility of this group. It should be pointed out here that the laboratory-office building, the shielded area, air conditioning, cyclotron water system, ac power supply systems, dc power supply system for the main magnet, and the mechanical (roughing) vacuum systems will be included in the lump-sum building contract.

Personnel Schedule and Operating Cost Summary

Table D. 4 presents a schedule of manpower required for the project. Personnel for supporting development during the design phase, and operations and research personnel during construction and after the project completion are listed.

For estimating the research and development costs the following basis was used:

<u>Type</u>	<u>Salary and Overhead/year</u>
Professional	\$25,000
Technical	16,000
Administrative	14,000
Support	14,000

Materials are estimated at 15% of salary and overhead; special materials are estimated separately. These numbers are escalated at 5% per year from FY 1964. Equipment for research is estimated at 10 to 20% of gross operating cost.

Table D. 5 shows the manpower schedule for the cyclotron project. Three categories of manpower are shown:

- (1) Design and engineering personnel to prepare construction drawings of all items not engineered by vendors.
- (2) ORNL support labor to install and adjust specialized equipment.
- (3) CPFF support labor. This is the bulk of the craft labor for installation of the cyclotron and beam optics.

Table D.4. Schedule of manpower and operating costs for the Mc² Cyclotron.

FY		Research and Development				Pre-Operations				Operations and Research				Total R & D Operations & Research
		Operating MY* Cost	Equipment Obl. Cost		Total R & D Cost	Operating MY Cost	Equipment Obl. Cost		Total Pre-Oper Cost	Operating MY** Cost	Equipment Obl. Cost		Total Oper Research Cost	
1st	Prof Tech Admin Support	23 10 4 23	\$1,280	\$115	\$115	\$1,395								\$1,395
2nd	Prof Tech Admin Support	23 12 4 27	1,450	195	195	1,645								1,645
3rd	Prof Tech Admin Support	23 12 4 27	1,520	195	195	1,715								1,715
4th	Prof Tech Admin Support	23 12 4 27	1,588	175	175	1,763								1,763
5th	Prof Tech Admin Support	13 3 1 2	573	125	125	698	14 9 1 45	1,570 300 200	1,770	7 4 1 0	350	1,000 500	850	3,318
6th	Prof Tech Admin Support	7 7 1	493	50	50	543	25 20 4 51	2,465 200 300	2,765	18 8 2 0	871	1,000 1,000	1,871	5,179
7th	Prof Tech Admin Support	0 0 0	0	0	0		7 7 0 0	130 50 50	480	57 28 9 55	4,140	1,000 1,000	5,140	5,620
8th	Prof Tech Admin Support									78 35 9 42	5,000	1,000 1,000	6,000	6,000

*ORNL Electronuclear staff, and support personnel.

**Staff of ORNL Research Divisions, and support personnel.

Table D. 5. Schedule of manpower and capital costs for Mc² Cyclotron.
(costs in thousands of dollars)

FY		Machine Design and Engr			Machine Fab and Inst			Building Design and Engineering		Building Const	
		MY*	Obl	Cost	MY	Obl	Cost	Obl	Cost	Obl	Cost
					ORNL** CPFF						
1st	Prof	6	\$ 415	\$ 415				\$2,147	\$ 810		
	Tech	13									
	Admin	0									
	Support				3						
2nd	Prof	7	2,005	485			\$19,565	\$1,165	1,337		
	Tech	14									
	Admin	0									
	Support				15						
3rd	Prof	7		505			9,072			\$18,554	\$ 6,806
	Tech	14									
	Admin	0									
	Support				15	4					
4th	Prof	7		530			7,900			9,184	
	Tech	14									
	Admin	0									
	Support				15	32					
5th	Prof	5		485			1,113			2,564	
	Tech	14									
	Admin	0			9	28					
6th	Prof	0		0			315				
	Tech	0									
	Admin	0									
	Support	3			9	12					
Totals				\$2,420			\$19,565	\$2,147		\$18,554	\$42,686

Note: Machine design, fabrication, and installation includes ion optics system.
All costs include a contingency.

*Loanees from Architect-Engineer, or other sources.

**ORNL crafts for fabrication and installation of specialized equipment.

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APPENDIX E: Building Structural Features

The structural drawings for the buildings of the Mc² facility, Fig. E. 1 through E. 8, were developed to provide a basis for estimating the quantities of materials required. Before these quantities could be estimated, however, several approximate stress analyses were made to establish major structural dimensions and geometric shapes, and to orient the building components properly with respect to each other. The importance of making stress analyses prior to estimating is demonstrated in the discussion of shielding construction in Chapt. 12.

The heavy foundations, the unusually high and thick walls, both structural and shielding, the arched roof systems, and the building orientation received special attention so that the quantities of rock excavation, reinforcing steel, form work, and concrete could be reasonably estimated. For each item under consideration alternate methods of construction were compared, as for example, the studies of roof and shielding wall structures reviewed in Chapt. 12. Even though these and other alternate systems were studied, the building concepts shown in these structural drawings should not be considered as the final design. The many unknown factors still awaiting detailed design can best be indicated by reviewing some of the building concepts and their limitations.

The high building over the cyclotron vault, the deep earth-fill shielding over the experimental rooms, and the thick concrete shielding walls, Fig. E. 5, could well have produced foundation loadings at several locations in excess of any design loadings previously used at the Oak Ridge National Laboratory. Therefore, every effort was made to select structural systems that would restrict overturning or foundation moment stresses. As a solution, the vertically loaded spread-type foundations shown in Fig. E. 5 and E. 6 were chosen. Limited data on subsurface rock, its bearing capacity, and its varying elevations dictated a conservative approach as to sizes, reinforcing steel (shown as a percentage of the concrete volume), and depth of foundations. A horizontal rock plane located just under the concrete floor of the beam corridor was selected as the basis for all rock excavation quantities.

Although the laboratory-office building and the cyclotron building presented foundation problems of a more conventional nature, loads and stresses were computed to back up the quantity take-offs for estimating purposes.

The high counter-fort walls for the cyclotron vault were chosen after a review of several other systems, such as gravity, box, horizontal bent, and cantilevered walls. The eccentric loading from the vault roof shielding beams (roughly 190 Kips per linear foot) aggravated the foundation loads on the toe so that conservatism again dictated larger and deeper foundations. The counter-fort walls shown in Fig. E. 2, E. 5, and E. 6 lack the final sizing that would follow from a knowledge of the allowable rock bearing pressures, rock elevations and strike planes, backfill friction coefficients, etc., that exist at the site.

The economic advantage of making one wall do the job of two was employed in the orientation of the laboratory-office building and the cyclotron building with respect to the experiment areas. It was found that a single wall with cheap earth-fill shielding between it and the wall of an adjoining building was more expensive than a single, solid concrete wall which serves as shield and as common wall for both buildings.

The concept of a vertically-loaded foundation system and a solid non-reinforced shield wall requires a structural method for resisting the horizontal forces from the roof arches (190 Kips per linear foot), a method which will not import overturning moments through the wall to the foundations. Numerous arch systems using horizontal tie beams, floors, prestressed cables, etc., were reviewed; the final selection is a reinforced springing beam tied at each end by reinforcing in the closed wall spandrels of each experiment room, Fig. E. 5. The thick shielding walls provide sufficient room for the calculated amounts of reinforcing steel required.

Other building systems, such as the removable shielding beams for the cyclotron vault, the gantry crane arrangements, the horizontal roll-out shielding doors, and the portals between the experiment rooms and the beam corridor were selected after the governing stresses were calculated, alternate approaches were reviewed, and economic comparisons were made.

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Fig. E. 2. First floor plan.

Fig. E. 3. Second floor plan.

Fig. E. 4. Third floor plan.

Fig. E.6. Building sections - 2.

Fig. E. 7. Building sections - 3.

Fig. E. 8. Neutron time-of-flight facility.

APPENDIX F: Some Examples of Cost Estimating Details

The broad range of information sources on which the cost estimates of Chapt. 13 are based is illustrated by a listing of the specific sources of preliminary bids and estimates for about 50 components totaling over \$11 million. As an example of the detailed work done in cost estimating, the specifications and requirements for some 50 magnet components of the ion optics system are also appended.

Broad Basis of Estimates

The sources of cost information for a wide range of components and materials are specified in Table F.1. Wherever possible, preliminary inquiries were submitted to potential vendors and bids were obtained; otherwise, discussions were held with prospective suppliers to determine representative prices. In general, preliminary bids were received from several vendors for each item submitted and a median price was chosen. Quotations were received on such fabricated items as heat exchangers, pumps, and the accelerator vacuum tank; the estimate of the cost of the iron for the cyclotron magnet was arrived at through consultations with potential suppliers. For the most part these estimated costs do not reflect the advantages of competitive bidding or quantity buying. These costs are suppliers' costs and do not, of course, include the costs of delivery and installation. The costs for structural materials and standard industrial items were provided by the Plant and Equipment Division of the Laboratory. Their costs were derived from preliminary bids, telephone quotations, catalogs, and current knowledge on existing projects here at the Laboratory. In all, about \$11.5 million is itemized; this represents a large portion of the total project cost.

Table F.1. Some sources of specific cost items

Item		Cost Source
Air compressor	\$ 51,500	Joy Manufacturing Company
Air dryer	18,900	Pittsburgh Lectrodryer
Blower vacuum pumps	112,800	Roots-Connersville Blower
Butterfly valves	11,400	Rockwell Valve Company
Canopy door	60,000	Fleming Steel Company
Chemistry hoods	9,600	Kewaunee
Chilled water coils	12,300	Trane Company
Chilled water compressors	84,400	Trane Company
Concrete	582,700	Concrete Supply Company
Concrete beams	561,700	Martin-Marietta
Concrete blocks	126,000	Southern Cast Stone
Conductivity metering	1,000	Independent Instrument Company
Cooling tower	225,000	The Marley Company
Cranes	453,200	Whiting Corporation
Demineralizers	12,700	Allis-Chalmers
Diffusion pumps	109,700	C. V. C. Catalog
Diffusion pump baffles	77,000	C. V. C. Catalog
DP baffle freon compressors	8,700	Hunley and Turner
Diverter valves	3,000	DeZurick Corporation
Ejectors	2,100	Deming
Electrostatic air filters	29,200	Electro-Air Company
Elevators	82,000	Doner Elevator Company
Fans	46,500	Buffalo-Forge
Fans	10,900	Trane Company
Fire alarms	2,500	Gamewell
Fire protection	3,400	Pyratronics
Heat exchangers	67,400	Struther-Wells
Heat exchangers	1,200	Bell-Gossett
Hoists	10,000	Yale Company
Hot water heater	2,450	Patterson-Kelly Company
Ion optics magnets	2,468,750	Pacific Electric Motor
Ion optics supplies	932,000	Pacific Electric Motor
Laboratory outlets	3,100	Chicago Faucet Company
Magnet iron, cyclotron	3,360,000	U. S. Steel Company
Mechanical vacuum pumps	21,400	N. R. C. Catalog
Motor generators	1,025,000	Allis-Chalmers
Power amplifier supply	175,000	General Electric Company
Sewage ejectors	1,900	Weil Pump Company
Suspended floor	39,900	Elaflor
Vacuum stations	106,100	C. V. C. Catalog
Vacuum tank	353,000	Chicago Bridge and Iron
Vacuum valves	112,400	C. V. C. Catalog
Water filters	9,700	Control Equipment Company
Water pumps	29,300	Peerless Pump Company
Water still	1,100	Barnstead
Water tanks	7,600	Nooter Corporation
Water valves	45,800	Crane Company
110 V dc battery supply	6,900	Exide Company
Total	\$11,478,200	

Details on the Ion Optics Components

The layout of the systems of magnets and quadrupoles shown in Fig. F.1 represents the present concept of the components needed to handle the extracted beam of 810-MeV protons and the secondary beams produced at the various target positions required by the research programs. Some specifications and characteristics of the magnets used to bend (B.), switch (S.), or analyze (A.) the proton and meson beams are listed in Table F.2. In the figure and the tables the magnets are labeled and numbered according to their function and position.

For transporting beams over rather large distances many quadrupoles (Q.) are required. The six types of elements (I-III) composing six types of lenses (A-F) are specified and described in Table F.3. Type E is actually one long assembly of 48 elements; it serves as a focusing channel for pions decaying, in flight, to the desired muons.

The cost estimates for all ion optics magnets and quadrupoles are summarized in Table F.4. These costs were arrived at by discussions with experienced fabricators. The costs for support structures are based on experience with similar systems at the Laboratory.

Fig. F.1. Key to ion optics compcnents. See also Tables F.2, F.3, and F.4.

Table F. 2. Specifications for magnets in ion optics system.

Magnet	Energy, max and Particle (MeV)	Field, max (kG)	Radius (in.)	Angle of Bend (deg)	Aperture (in.)	Iron (tons)	Copper (lbs)	Magnet Power (kW)
1 APE-1	810, p	8.1	240	164	5	1,236 ³⁷⁶	26,500 ^{31,200}	148 ¹⁷¹
2 APE-2	810, p	17.5	111	25	5	21	13,400	86
3 BPH-1	810, p	17.5	111	35	5	30	16,200	91
4 A π -1	810, p	19.4	100	92	8	276	85,000	495
5 A π -2	100, π	5	50	88	8	45	4,300	24
6 A μ -1	520, π	15	56.6	70	8	128	20,700	116
7 A μ -2	520, μ	15	56.6	70	8	128	20,700	116
8 SPT-1	810, p	17.5	111	60	5	169	26,750	171
9 SPT-2	810, p	17.5	111	8	5	6	9,000	57
10 SPH-1	810, p	17.5	111	30	5	57	15,400	99
11 S π -1	{ 520, π 810, p }	{ 15 17.1 }	{ 56.5 115 }	{ 30 15 }	5	29	19,450	109
12 AM-1	100, π	5	50	90	8	75	4,700	27
13 AM-2	100, π	10.7	24	90	8	51	8,700	48
14 AM-3	100, π	10.7	24	90	8	51	8,700	48
15 AM-4	100, π	10.7	24	90	8	51	8,700	48
16 AR-1	810, p	15	129	90	5	124	23,800	133
17 AR-2	810, p	15	129	90	5	124	23,800	133

Table F. 3. Specifications for quadrupole lenses in ion optics system.

Quadrupole Elements							
Element Type	Aperture (in.)	Field, max (kG)	Field Gradient, max (G/in.)	Length (in.)	Iron (lb)	Copper (lb)	Power (kW)
I	5	10	3800	15	1480	136	93
II	8	10	2400	8	1900	348	86
III	8	10	2400	15	3660	442	109

Quadrupole Lens								
Lens Type	Energy and Particle (MeV)	Aperture (in.)	No. and Type Element	Element Separation (in.)	Total Iron (lb)	Total Copper (lb)	Total Power (kW)	Number Req'd.
A	810, p	5	2-I	6	2,964	272	186	17
B	810, p	5	1-I	-	1,482	136	93	2
C	520, π	8	2-II	6	3,908	696	172	7
D	100, π	8	2-II, 1-III	6	7,571	1,138	281	4
E	520, π	8	48-III	6	75,824	21,216	5,232	1
F	100, π	8	1-II	-	1,954	348	86	4

Table F.4. Costs of magnets and quadrupoles for ion optics system.

Magnets						
Magnet	Iron		Coils	Support	Installation	Total
APE-1	\$256,900	\$	93,600	\$ 30,800	\$ 24,760	\$ 406,060
APE-2	14,700		40,200	2,180	2,220	59,300
BPH-1	20,650		54,000	3,080	2,875	80,605
A π -1	193,200		255,000	26,100	24,760	499,060
A π -2	31,500		12,900	3,860	5,860	54,120
A μ -1	90,000		62,100	11,400	18,660	182,160
A μ -2	90,000		62,100	11,400	18,660	182,160
SPT-1	118,100		80,300	14,950	24,760	238,110
SPT-2	4,500		27,000	900	1,150	33,550
SPH-1	39,900		46,200	5,300	6,150	97,550
S π -1	20,600		58,400	2,900	2,875	84,775
AM-1	52,500		14,100	6,300	8,110	81,010
AM-2	35,700		26,200	4,500	10,700	77,100
AM-3	35,700		26,200	4,500	10,700	77,100
AM-4	35,700		26,200	4,500	10,700	77,100
AR-1	87,100		71,400	11,150	21,875	191,525
AR-2	87,100		71,400	11,150	21,875	191,525
	\$1,213,850		\$1,027,300	\$154,970	\$216,690	\$2,612,810

Quadrupoles						
Type	Lens	Support	Installation	Cost Each	No. Req'd.	Total Cost
A	\$ 7,000	\$ 1,000	\$ 980	\$ 8,980	17	\$152,660
B	3,500	500	980	4,980	2	9,960
C	7,000	1,000	980	8,980	7	62,860
D	17,850	1,000	1,775	20,625	4	82,500
E	350,400	24,000	32,535	406,935	1	406,935
F	5,300	300	1,190	6,790	4	27,160
						\$742,075

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