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ELECTRONUCLEAR RESEARCH DIVISION

SEMIANNUAL PROGRESS REPORT

FOR PERIOD ENDING SEPTEMBER 20, 1955

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ELECTRONUCLEAR RESEARCH DIVISION

SEMIANNUAL PROGRESS REPORT

For Period Ending September 20, 1955

Robert S. Livingston, Director

Edited by F. T. Howard

DATE ISSUED

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Y-495	September 30, 1949
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Part I

UNCLASSIFIED WORK

ELECTRONUCLEAR RESEARCH DIVISION SEMIANNUAL PROGRESS REPORT

ABSTRACT

The installation of the beam deflector in the ORNL 86-Inch Cyclotron is sufficiently complete to allow initial testing; the system permits the optional use of high-current internal targets. A survey of (n,α) cross sections made with 14-Mev neutrons indicates qualitative agreement with statistical theory. An internal-conversion spectrograph and a fission-fragment spectrograph were built and put in operation. The excitation functions for several proton-induced reactions of possible use in isotope production were measured. A capsule-type target is being used for the irradiation of chemical compounds.

Nuclear physics research with 26-Mev nitrogen ions from the ORNL 63-Inch Cyclotron concerned the following: a theoretical interpretation of elastic nitrogen-nitrogen scattering; a detailed investigation of some nitrogen-nitrogen nuclear reactions; the measurement of reaction cross sections in boron and aluminum; and the identification and the energy spectra of protons and alpha particles resulting from nitrogen-induced reactions with light elements.

A study is being made of the practicability of a fixed-frequency cyclotron to accelerate protons to about 1 bev for application in meson research. Phase compensation would be obtained with an unusual magnetic-field configuration which has eight azimuthal cycles with about 72 deg of spiral. Also, a proposal was made to convert the 44-in. proton cyclotron; a new 48-in. magnet would permit the acceleration of heavy ions to energies up to 81 Mev.

THE 86-INCH CYCLOTRON

The installation of the beam-deflector system in the 86-in. cyclotron was essentially completed, and the initial testing is under way. In the meantime, previously collected experimental data were analyzed and prepared for publication, and new research instruments to be used in connection with the deflected beam were designed and fabricated.

INSTALLATION OF BEAM-DEFLECTOR SYSTEM

The modification of the vacuum system and resonant dee system and the installation of the essential components of the deflector system were completed, and preliminary tests are being made. The main vacuum tank was extended to house the magnetic channel, to which is attached the vacuum-lock type of intermediate target chamber. Also, since the oil diffusion pumps were badly contaminated with radioactive products, they were replaced; a silicone-base oil, D-C 703, is now being used in the pumps.

A new dee system, with deflector and septum, and a new tank liner are in place, and radio-frequency tests are being made. Two motor-generator sets are now available for use with the cyclotron, one to supply the cyclotron magnet and the other to energize the magnetic channel for the deflected beam. This magnetic channel was fitted in position for a series of magnetic-field measurements.

All these modifications were made in such a way that there will be no interference with the utilization of the unusually large internal proton currents obtained in the 86-in. cyclotron. The large grazing-incidence targets can be used to intercept the internal circulating beam, the beam can be deflected into the intermediate target chamber, and ultimately the deflected beam can be "piped" through focusing and analyzing magnets into a remote target room.

For the initial tests of the deflector system the magnetic channel was removed so that the beam can first be studied as it leaves the electrostatic deflector and enters the magnetic channel region. Voltage has been applied to the radio-frequency system and is being increased to the operating range as rapidly as normal startup conditions permit.

MAGNETIC-FIELD MEASUREMENTS

Extensive magnetic-field measurements in the circulating and deflected-beam regions were made, with a nuclear fluxmeter and with a current-carrying wire, in tension, used to simulate a proton beam in the magnetic field.

In the original design of the deflected-beam system the magnetic channel was placed so that the beam center had to be moved 4 in. closer to the edge of the poles to aid in deflection. An attempt to shim the magnetic field to compensate for the disturbances introduced by the channel and to provide the desired radial falloff near the channel was unsuccessful because of space limitations. To achieve the desired radial field fall-off and to reduce the first harmonic to a lower value, the channel was moved 2 in. toward the magnetic center. This required a 20% reduction in channel-coil current and thus resulted in an 80% increase in radial width of the proton beam at the intermediate target chamber, as measured by the current-carrying wire.

The usual system of measurements with a current-carrying wire was modified so that the balance, weight, and current regulator are eliminated. This is accomplished by calibration with a 180-deg arc of wire in the uniform magnetic field. The length of wire is adjusted until the 180-deg arc has the proper diameter to simulate the desired proton energy. The wire extends from the calibrating arc through the magnetic channel to the field-free region outside the cyclotron. When both ends of the wire are fixed, a change in current changes the tension but not the position of the wire in the magnetic field. The error due to the weight of the wire was reduced by maintaining the tension in the wire near the yield point.

These measurements indicate that, by the proper adjustment of the positions of the electrostatic deflector and the magnetic channel and of the currents to the channel and the beam-center-positioning coils, a beam will be satisfactorily deflected from the cyclotron.

NUCLEAR PHYSICS RESEARCH

An experimental survey of (n,α) cross sections was made with 14-Mev neutrons produced in the Biology Division's Cockcroft-Walton accelerator by the well-known (d,t) reaction. Cross sections were measured by activation methods and radiochemical separations. Initial results indicate qualitative agreement with the statistical theory of nuclear reactions, in sharp contrast to the results of a previous survey of (n,α) reactions.[1] These measurements are being continued.

Inasmuch as the cyclotron was shut down for the period covered by this report, there is no new cyclotron-connected research to report. Efforts of the group were devoted primarily to planning and constructing apparatus for experiments to be performed with the deflected beam.

Internal-Conversion Spectrograph

A spectrograph was built for use in studying the spectra of internal-conversion electrons produced by nuclear reaction products from the 86-in. cyclotron. It is a permanent-magnet, 180-deg spectrograph similar to one built at Brookhaven National Laboratory. The pole gap of the 127-gauss magnet is 2 in. over a 12×20 in. area. The energies of conversion electrons between 20 and 350 kev can be measured with an absolute accuracy of 0.3%. The relative intensities of the lines produced on photographic plates by the electrons are measured with a Leeds & Northrup recording densitometer. Calibration of the magnet and of the electron-line intensities was made with conversion lines of Ta^{182}, Hf^{181}, Ce^{141}, and Sb^{125}.

Fission-Fragment Spectrograph

An apparatus for measuring the energy distribution of fission fragments of a given mass, constructed for use with the ORNL Graphite Reactor, is shown in Fig. 1. The fragments originate in a thin uranium foil in the reactor core, come out through a hole, are magnetically analyzed by a 40-deg wedge-shaped magnet, and are collected in an aluminum foil at the focal plane. To determine the mass, the foil is then cut up and radiochemically processed for fission products. Since the momentum distribution is known from the magnetic analysis, the energy distribution can then be determined. The magnet weighs 4 tons and has a 2-in. gap and a pole-face area of approximately 400 in.^{2}. The field is uniform to better than 0.1% up to 2 in. from the ends. The completed apparatus was tested with alpha particles and is ready for installation in the reactor.

[1] E. B. Paul and R. L. Clarke, *Can. J. Phys.* **31**, 267 (1953).

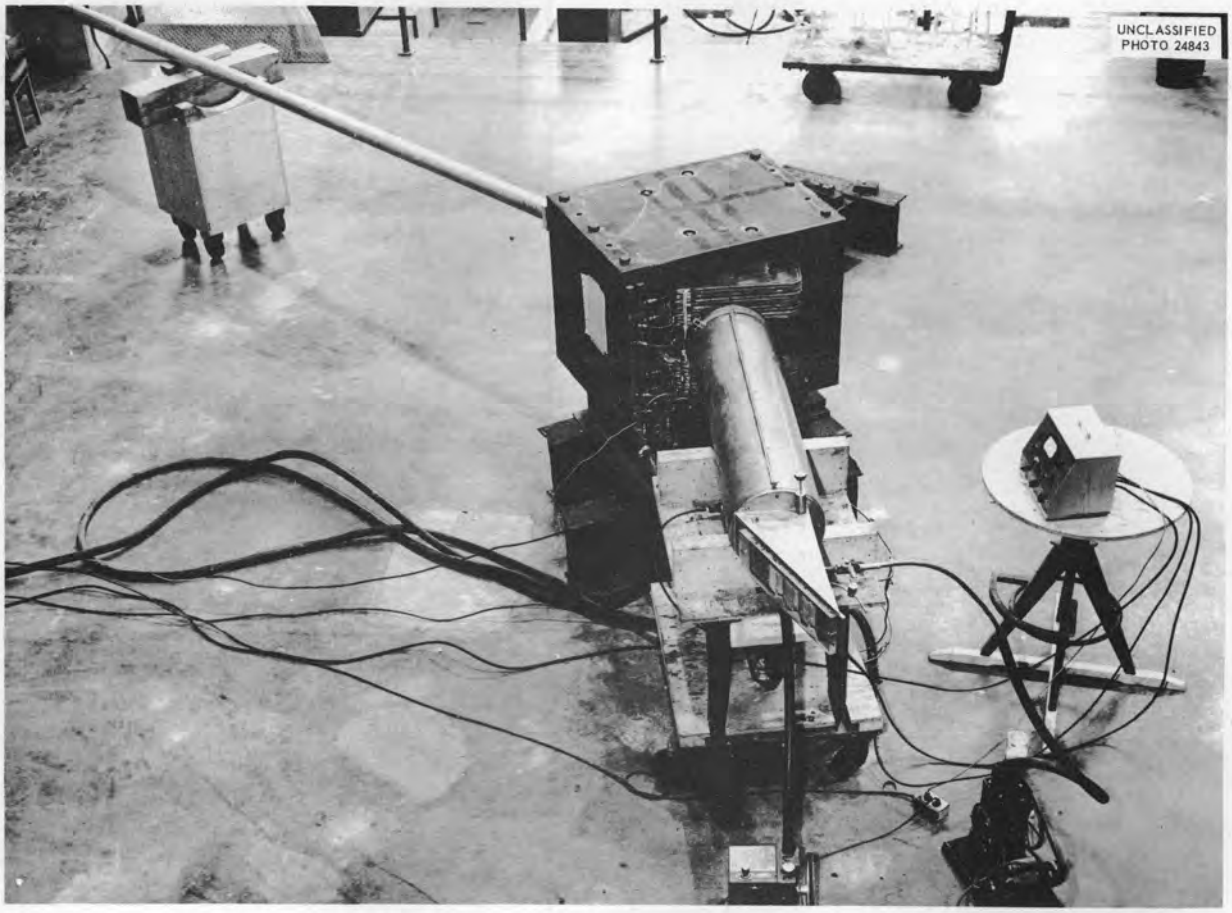

Fig. 1. Fission-Fragment Spectrograph. Tube at the upper left will extend into the ORNL Graphite Reactor.

APPLIED PHYSICS

Excitation functions were measured for the reactions $Cu^{65}(p,n)Zn^{65}$ and $Ag^{109}(p,n)Cd^{109}$ with 22-Mev protons. Foil stacks bombarded last year in the 86-in. cyclotron were used in making the measurements. The long-lived activities were counted several times during a one-year period after bombardment.

The excitation function for $Cu^{65}(p,n)Zn^{65}$ was determined by bombarding a stack of 52 high-purity copper foils of 16.46 mg/cm^2 thickness. Each foil was then counted, without chemical separation, for 9.3-hr Zn^{62}, 250-day Zn^{65}, and 12.8-hr Cu^{64} activities. From the activity of the foils and the range-energy relations for protons in copper, the relative cross sections (Fig. 2) were calculated for $Cu^{63}(p,2n)Zn^{62}$, $Cu^{65}(p,n)Zn^{65}$, and $Cu^{65}(p,pn)Cu^{64}$. Cohen's value[2] for the cross section of $Cu^{63}(p,2n)Zn^{62}$, $\sigma = 100$ mb for 21.5-Mev protons, was used in assigning magnitudes to cross sections for the three reactions.

The excitation function for $Ag^{109}(p,n)Cd^{109}$ was determined by bombarding a stack of 25 silver (27.47 mg/cm^2) and 25 copper (16.46 mg/cm^2) foils, alternately placed. The silver and copper foils were then counted for 470-day Cd^{109} and 250-day Zn^{65} activities, respectively. The relative cross sections obtained from two separate bombardments are in good agreement. The cross section for $Ag^{109}(p,n)Cd^{109}$ was assigned relative to the cross section for $Cu^{65}(p,n)Zn^{65}$.

Thick-target production rates for Zn^{65} and Cd^{109} were computed from the excitation functions of Cu^{65} and Ag^{109} and compared with yields from

[2] B. L. Cohen and E. Newman, *Phys. Rev.* **99**, 718 (1955).

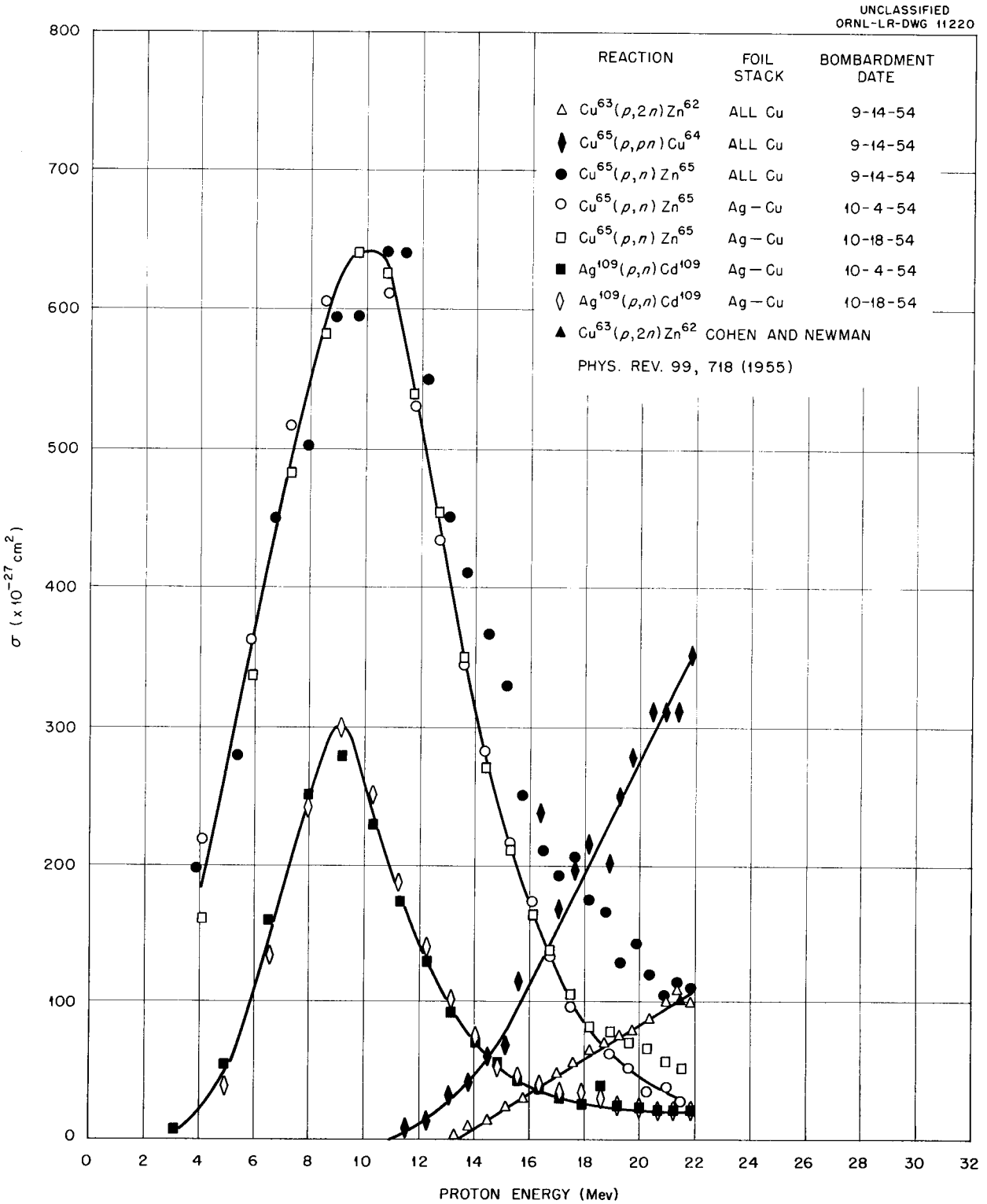

Fig. 2. Excitation Functions for Proton-Induced Reactions in Copper and Silver.

high-current bombardments of large copper and silver targets, and are shown in Table 1. The use of the deflected beam of the cyclotron for more precise determination of these excitation functions should give better agreement with yield data from radioisotope production runs made with the internal beam.

The distribution of activity within the target and the production efficiency relative to a bare target were calculated for the capsule-type target described in a previous report.[3] A cross section of the target assembly is shown in Fig. 3*b*. Useful residual range contours for typical (p,n) and (p,pn) reactions are shown for an aluminum capsule with a 10-mil wall thickness. From the radial distribution of beam intensity (Fig. 3*a*), the distribution of useful proton energies, and the relative thick target yields, the relative productivity for each position in the capsule was determined (Fig. 3*c*). The estimated yield efficiencies for typical (p,n) and (p,pn) reactions are 60 and 15%, respectively. For maximum utilization of expensive target material or for maximum specific activity in (p,pn) yields, unproductive target material is eliminated by using a plug of appropriate cross section to fill that portion of the capsule cavity which is beyond the proton range.

[3] *Electronuclear Research Semiann. Prog. Rep. Sept. 20, 1954*, ORNL-1795, p 5.

TABLE 1. PRODUCTION RATES OF Zn^{65} AND Cd^{109}

Isotope	Production Rate (mc/mah)			
	From Excitation Function		From Thick Target	
	At 22 Mev	At 18 Mev	At 22 Mev	At 18 Mev
Zn^{65} (250-day)	12.1	11.5	9.3	7.7
Cd^{109} (470-day)	2.4	2.2		2.6

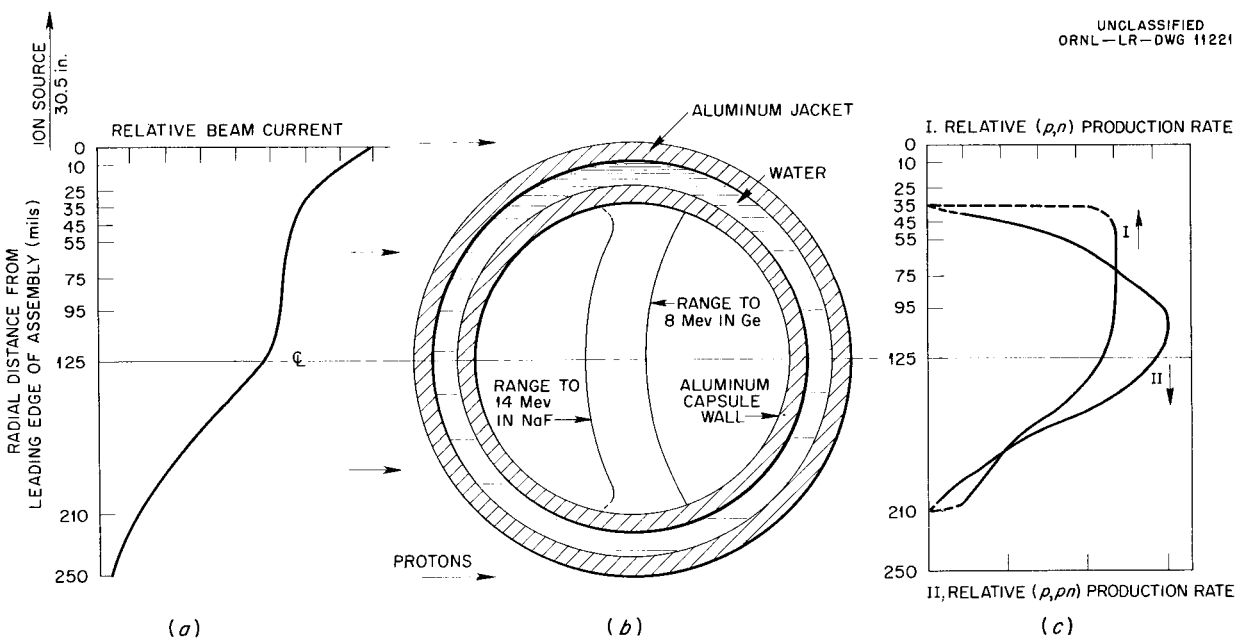

Fig. 3. Irradiation of Target Compounds in Capsule Target.

THE 63-INCH CYCLOTRON

Nuclear physics research with 26-Mev nitrogen ions from the ORNL 63-Inch Cyclotron dealt with the following topics in the last six months: a theoretical interpretation of elastic nitrogen-nitrogen scattering; a detailed investigation of some nitrogen-nitrogen nuclear reactions; the measurement of reaction cross sections in boron and aluminum; and the identification and the energy spectra of protons and alpha particles resulting from nitrogen-induced reactions with light elements.

NUCLEAR PHYSICS RESEARCH

Elastic Scattering

Some results of the elastic-scattering experiments were given in the last progress report.[1] An attempt has since been made to fit the data by a semiclassical strong-absorption model devised by Blair[2] for the scattering of alpha particles by heavy nuclei. The assumption is that if the potential barrier of the lth partial wave is low enough to allow the nuclei to touch or to overlap, then the wave is completely absorbed; the partial waves with l values high enough to keep the nuclei from touching remain undisturbed. This model is successful in the region where the ratio of the observed cross section to the Rutherford cross section is larger than 0.1. For nitrogen-nitrogen elastic scattering, $\sigma_{obs}/\sigma_{Ruth.}$ is greater than 0.2. The differential cross section for elastic scattering of nitrogen by nitrogen is then given by

$$\frac{d\sigma}{d\Omega} = \left(\frac{Z^2e^2}{MV^2}\right)^2 \left| \frac{1}{\sin^2\theta/2} e^{2i\eta_0} e^{-i\alpha \ln \sin^2\theta/2} \pm \frac{1}{\cos^2\theta/2} e^{2i\eta_0} e^{-i\alpha \ln \cos^2\theta/2} + \frac{1}{i\alpha} \sum_0^{l_{max}} (2l+1)\, e^{2i\eta_l} P_l(\cos\theta) \pm \frac{1}{i\alpha} \sum_0^{l_{max}} (2l+1)\, e^{2i\eta_l} P_l(-\cos\theta) \right|^2 4\cos\frac{\theta}{2},$$

where

$$\alpha = \frac{Z^2e^2}{\hbar V},$$

$$e^{2i\eta_l} = \frac{\Gamma(l+1+i\alpha)}{\Gamma(l+1-i\alpha)},$$

θ = center-of-mass angle.

The first two terms are due to the scattering of the coulomb potential, and the last two terms represent the nuclear absorption. The positive sign is taken for the symmetric-space wave function and the negative for the antisymmetric one. For nitrogen, which has a spin of 1, the symmetric total wave function is required, and the differential cross section is

$$\frac{d\sigma}{d\Omega} = \frac{1}{3}\left(2\,\frac{d\sigma_{sym}}{d\Omega} + \frac{d\sigma_{antisym}}{d\Omega}\right).$$

If the radius of the nitrogen nucleus is taken to be 4.0×10^{-13} cm, from fast-neutron-scattering results (corresponding to $R_0 = 1.66 \times 10^{-13}$ cm), the cutoff l value is 6.2, from the relation

$$l(l+1) = 2MR^2\hbar^{-2}\left(E - \frac{Z^2e^2}{R}\right).$$

The cross sections for nitrogen-nitrogen scattering are shown in Fig. 4. The solid curve is the calculated elastic-scattering cross section at 21.7-Mev laboratory energy, with l values up to 6 absorbed completely. The dots are the experimental points normalized at small angles. The classical as well as the Mott cross section for identical particles are shown as dashed curves. The fit between the theoretical and experimental curves is remarkably good for such a simple model.

Nitrogen-Nitrogen Reactions

The following nitrogen-nitrogen reactions were examined in detail: (1) $N^{14}(N^{14},N^{13})N^{15}$ and (2) $N^{14}(N^{14},O^{15})C^{13}$. Cross sections for both reactions were measured for energies from 10 to 26 Mev (see Fig. 5). The range distribution of the radioactive residual nuclide N^{13} showed that at least 90% of reaction 1 goes directly to the ground states of N^{13} and N^{15}. This is to be expected in a stripping type of reaction where a neutron passes from one nitrogen nucleus to the other. The ground

[1] *Electronuclear Research Semiann. Prog. Rep. March 20, 1955*, ORNL-1884, p 9.

[2] J. S. Blair, *Phys. Rev.* 95, 1218 (1954).

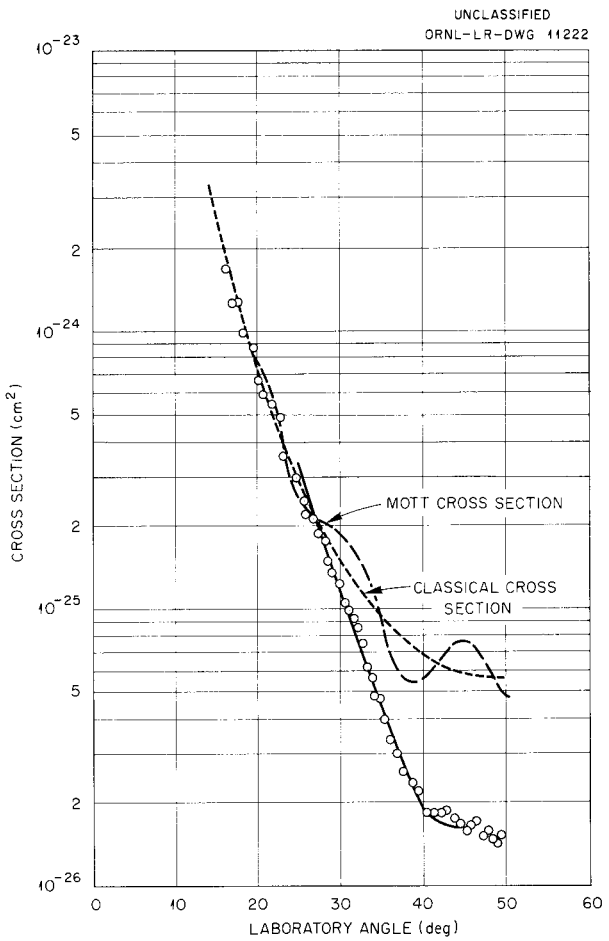

Fig. 4. Cross Sections for Nitrogen-Nitrogen Scattering.

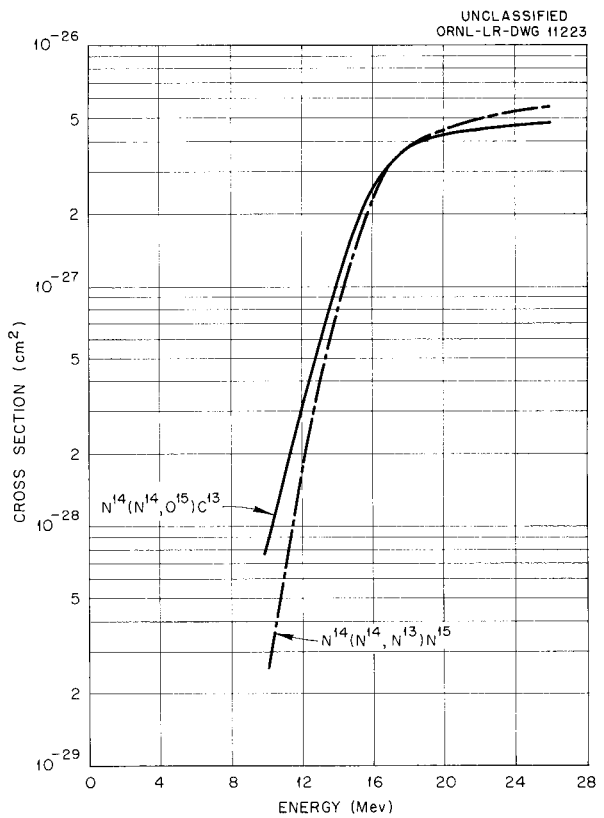

Fig. 5. Cross Sections for Nitrogen-Nitrogen Reaction.

state of N^{14} is $(1S)^4\ (1p_{3/2})^8\ (1p_{1/2})^2$, spin 1, and even parity. A neutron removed from N^{14} would most likely come from the $p_{1/2}$ shell, leaving N^{13} with odd parity and spin ½, which is its ground-state configuration. To obtain the first excited state of N^{13}, which has even parity and spin ½, a neutron must be removed from the $p_{1/2}$ shell and a nucleon placed in $2S_{1/2}$ from a $p_{3/2}$ level, an unlikely circumstance in a stripping reaction. Similar arguments may be used to show that N^{13} and N^{15} would not be left in other excited states in a stripping reaction.

Angular distributions of N^{13} from reaction 1 were measured at four different energies. While these measurements are not accurate enough for a detailed analysis to be made of the distribution, they do show two main features: the angular distribution is not isotropic, and the peak of the distribution moves forward with increasing energy. Since large l values are important for nitrogen-nitrogen reactions, it would be expected that any reaction involving a compound nucleus would result in an isotropic distribution. The observed distributions do not support the compound-nucleus mechanism for these reactions. In fact, if it is assumed that very little momentum transfer accompanies the neutron exchange, the angle at which N^{13} is emitted can be correlated with the distance of closest approach between the nuclei. Then the angular distribution for a stripping reaction should be similar to the angular distribution for Rutherford scattering, except for a minimum cutoff angle below which the two nuclei are too far apart for the neutron to be exchanged. Some particles can be emitted, however, at angles less than the cutoff, as a result of collisions with small impact parameters. At 23 Mev the angular distribution has a peak at 50 deg in the center-of-mass system. This corresponds to an approach distance

of about 1×10^{-12} cm. From the elastic-scattering results, the nitrogen nuclear radius is 4.0×10^{-13} cm.

Bombardment of Al^{27} with 30-Mev protons leads to an Si^{28} compound nucleus of the same excitation as is produced by 26-Mev nitrogen ions on nitrogen. Proton bombardments of Al^{27} made at Berkeley with the linear accelerator failed to produce either N^{13} or O^{15}. In fact, the cross sections for these reactions were no more than one-hundredth the corresponding nitrogen-nitrogen cross sections. This evidence further supports the hypothesis that a nucleon crossover mechanism plays the dominant role in the nitrogen-nitrogen reactions studied here.

Cross Sections in Boron

Excitation functions in boron were measured for the following reactions: (1) $B^{10}(N^{14},O^{15})Be^{9}$, (2) $B^{10}(N^{14},F^{18})Li^{6}$, (3) $B^{10}(N^{14},C^{11})C^{13}$, (4) $B^{10}(N^{14},N^{13})B^{11}$, and (5) $B^{11}(N^{14},Na^{24})p$. The results of the measurements are shown in Fig. 6. Reactions 1 and 2 are compound-nucleus reactions; they were observed in the 30-Mev proton bombardment of Na^{23}, which leads to the same state of excitation in the compound nucleus Mg^{24} as is obtained with 26-Mev nitrogen on B^{10}. It is probable that the stable reaction products here are $2\alpha p$ and αpn instead of Be^{9} and Li^{6}. The formation of these fragments is energetically possible.

Reactions 3 and 4 are most likely of the stripping type, as is evidenced by the flat cross sections. Probably some of the O^{15} results from a proton crossing over from B^{10} to N^{14}. This may account for the unusually high cross section of reaction 1 at low energies.

Reaction 5 is obviously of the compound-nucleus type; it displays the characteristic maximum in the cross section. At higher energies the cross sections for this reaction decrease as competing reactions become energetically possible.

Reactions in Aluminum

Aluminum foils were bombarded with nitrogen ions, and the following radioactive residual nuclei were identified by standard chemical methods: C^{11}, N^{13}, F^{18}, Na^{24}, Cl^{38}, K^{38}, and P^{32}. The F^{18} and the Na^{24} may be due to carbon contamination; a few micrograms of pump oil per square centimeter condensed on the foils could account

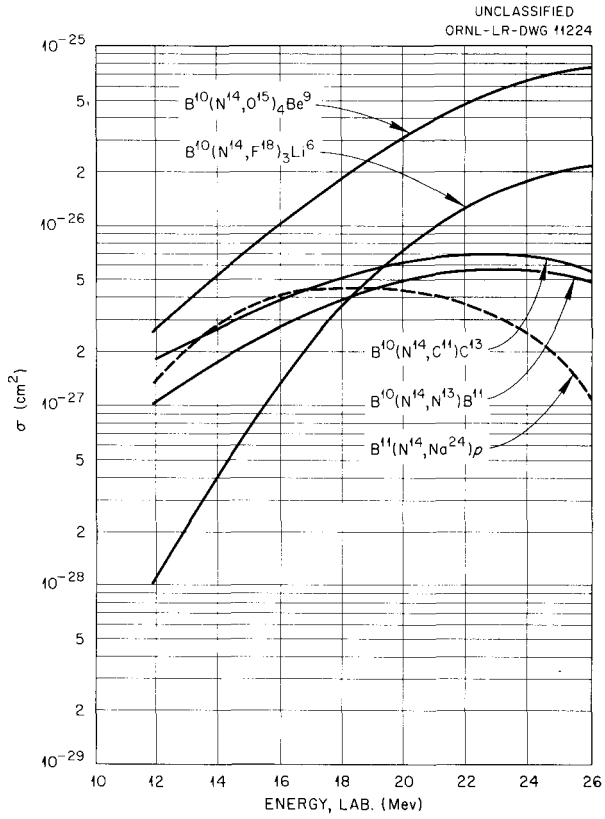

Fig. 6. Excitation Functions for Nitrogen Reactions on Boron.

for the yields. Cross sections for the three reactions tabulated below were measured at several energies by differentiating the thick-target-yield curves.

Reaction	Energy (Mev)	σ (cm^2)
$Al^{27}(N^{14},N^{13})Al^{28}$	24.4	4×10^{-29}
	22.5	2×10^{-29}
$Al^{27}(N^{14},3p)Cl^{38}$	24.5	1.4×10^{-29}
	22.5	4×10^{-30}
$Al^{27}(N^{14},p2n)K^{38}$	24.5	7×10^{-28}
	22.5	4.2×10^{-28}
	20.5	3.9×10^{-29}

The first reaction is most likely of the stripping type, and its low cross section is probably due to a negative Q value of -2.89 Mev. It is interesting to compare the last two reactions, in which nucleons are evaporated from a compound nucleus. After an initial proton has been emitted, the evapo-

ration of two neutrons is 50 times more probable than the evaporation of two protons. An approximate theoretical treatment[3] for the difference in the $3p$ and $p2n$ cross sections predicts that the $p2n$ cross section should be greater than the $3p$ cross section by 2 orders of magnitude. The agreement is certainly as good as the assumptions warrant. The unsuccessful search for Si^{31} in aluminum irradiated by nitrogen showed that the cross section for the reaction $Al^{27}(N^{14},Si^{31})C^{10}$ is no greater than 10^{-30} cm^2.

From the evidence thus far collected in heavy-particle experiments it appears that two types of reactions occur: a conventional compound-nucleus reaction and a stripping reaction. No instance was found where a compound nucleus can be shown to fission into two nuclides of about equal mass and charge. Of course the energy of the accelerated ions limits the experiments to regions close to the coulomb barrier and close to the energetic threshold. Also, the methods used thus far in the identification of heavy reaction products give results for only radioactive residual nuclides, which are generally less tightly bound than stable nuclides. Therefore, the information available concerns the processes less favored energetically, and it may be that more exoergic reactions will reveal true fissions in compound nuclei.

Protons and Alpha Particles from Nitrogen Bombardment of Light Elements

A spectrometer was constructed for use in identifying and measuring the energy of protons, deuterons, alpha particles, and other light fragments produced by nitrogen on light elements. The spectrometer consists of two counters in coincidence, a proportional counter which measures dE/dx and an NaI scintillation counter which measures the energy of the particle. A single-channel pulse-height analyzer is used to set the acceptable dE/dx range, and the energy spectrum is obtained on a 20-channel pulse-height analyzer. Preliminary measurements obtained for the alpha-particle spectrum from a thin Li^6 target are illustrated in Fig. 7. The peaks observed at high energy are due to transitions to the ground state and to the two lowest excited states of O^{16}. The alpha-particle yield increases at lower energies as the levels in O^{16} become denser. A systematic survey of protons and alpha particles from light elements bombarded with nitrogen is planned.

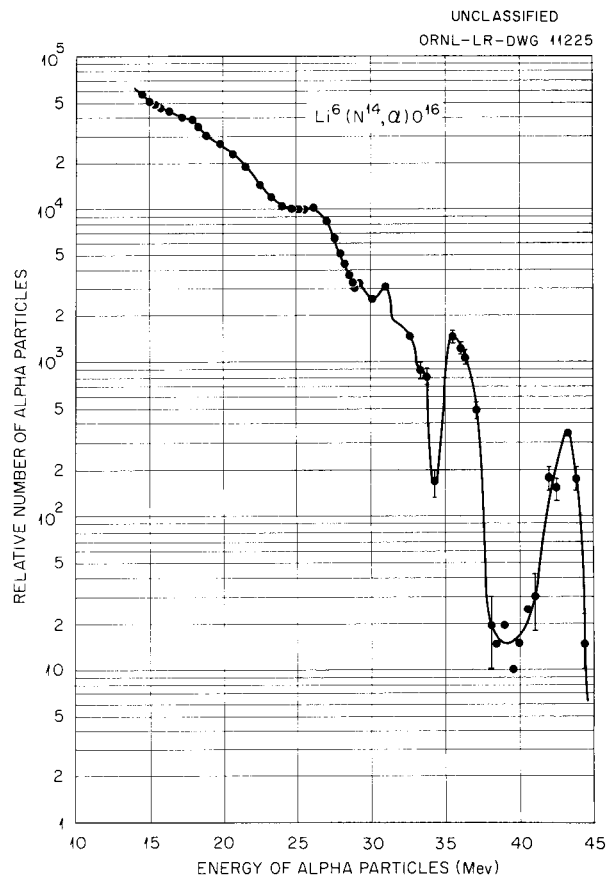

Fig. 7. Preliminary Measurement for Alpha-Particle Spectrum from Nitrogen Reaction on Li^6.

ANALYZING MAGNET

The fabrication of the double-focusing, 90-deg magnet to be used in analyzing the reaction products of nitrogen-induced reactions proceeded essentially on schedule. The assembled yoke and poles were received from Permanent Magnet Co. Careful inspection showed that the critical tolerances were maintained. However, the thickness of the two arms of the yoke which receive the poles was found to be ⅛ in. less than that specified. Since the principal function of these pieces is to carry the return flux and since the cross section is reduced only 2.7%, the change was considered insignificant.

The motor-generator power supply was installed on its footing, and installation of the conduit and

[3] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics*, p 373, Wiley, New York, 1952.

wiring is in progress. The design for the vacuum tank was completed, and the material for fabrication (Everdur) was ordered. The design of the current regulator for the analyzing magnet is complete, and a number of the components have been received; the only other major items on order should arrive within the next three weeks. A nuclear-magnetic-resonance fluxmeter for magnetic-field monitoring is being repaired and should be in operating order within the next month. Copper for the coils is being procured from The American Brass Company; since their plant was affected by the recent flood, delivery of the copper was delayed four to six weeks. Insulation for the windings has already been received.

CYCLOTRON OPERATION

The 63-in. cyclotron was operated routinely during the last six months. It is usually scheduled to operate four days each week; during the fifth day the magnetic field is used for other projects. The deflected beam of 25-Mev N^{3+} ions varied from a microampere to a tenth of a microampere, as required by the experiment. The life of the hot-filament cathode, in the ion source, averages 6.5 hr and is still the chief factor interrupting cyclotron operation.

ELECTRONUCLEAR MACHINES

STUDY OF A 1-bev PROTON CYCLOTRON

A study is being made of the practicability of a fixed-frequency cyclotron designed to accelerate protons to about one billion electron volts. At this energy range the large currents of protons usually associated with a fixed-frequency machine would be extremely useful in meson research.

As reported earlier, calculations performed with the Oracle indicate that it is feasible to accelerate protons well into the 1-bev energy range in a fixed-frequency, fixed-magnetic-field machine. The relativistic mass effect which has previously limited the energy obtainable on fixed-frequency cyclotrons is overcome by the use of an unusual magnetic-field configuration. The average magnetic field increases radially, and thus the ions remain in phase, even though their mass may increase over 100%. The defocusing forces produced by this increasing average field are compensated for by periodic azimuthal field variations which tend to restore the ions to the median plane.

The azimuthally varying field can be produced by radial "hill and valley" contours in the pole faces, by special pole-face windings, or by both. Calculations show that the required field variations are substantially reduced if the axes of the hills and valleys are spiraled in the direction of the orbital path. The optimum number of azimuthal cycles and the optimum amount of spiral were investigated. Interest is presently centered on a magnetic-field configuration which has eight azimuthal cycles with about 72 deg of spiral, Fig. 8.

This study is being made in collaboration with the Physics Division. The theoretical problems in optimizing the design are chiefly the concern of the Physics Division, while the Electronuclear Research Division is more directly concerned with the conceptual design of the equipment in relation to costs and with the design of preliminary experiments required for solving certain theoretical and design problems. The work in this Division has involved the equivalent of one full-time staff member and, during the summer months, the cooperative efforts of four research participants from southern universities.

The Theoretical Data

The data which served as the basis for an evaluation of conceptual designs were calculated with the Oracle. Calculations were made for configurations having 4, 6, 8, 12, and 16 azimuthal cycles and for several different degrees of spiral.

The orbits are of the form

$$q = \text{normalized radius} = q_0 \left[1 + q_1 \cos (p\theta + \phi)\right] ,$$

where

p = number of azimuthal cycles in the magnetic field,

ϕ = spiral parameter $= \alpha_1 q + \alpha_2 q^2 + \dots$.

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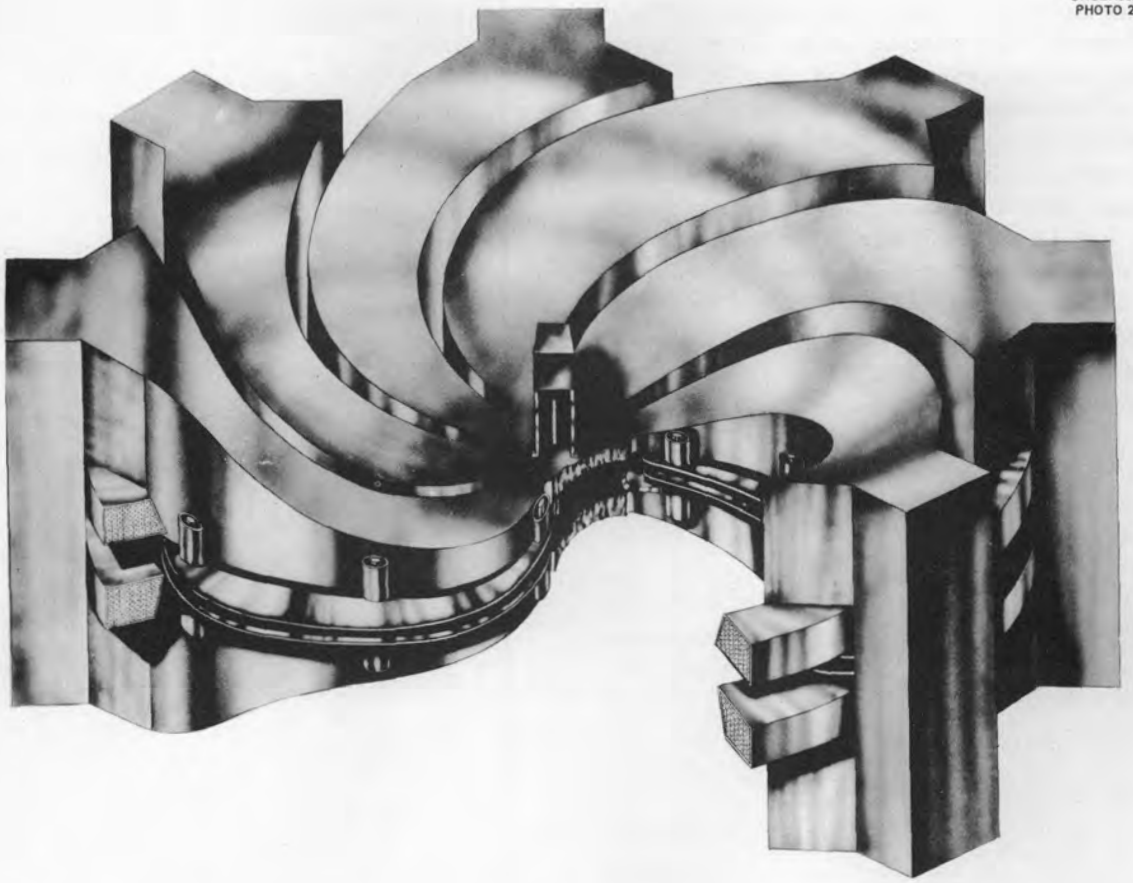

Fig. 8. Artist's Sketch of Conceptual Design of a Fixed-Frequency Cyclotron with an Eight-Cycle Azimuthally Varying Magnetic Field (cut away to show some internal details).

The quantities q_0 and q_1 are calculated to produce constant-frequency orbits of a selected vertical-focusing frequency. Since the orbits have a sinusoidal variation about a circle, the magnetic-field variation is only approximately sinusoidal azimuthally.

The information about each magnet configuration consists in the vertical- and horizontal-focusing frequencies for some 60 orbits, with energies taken in steps from zero to at least the third resonance energy. Along approximately 12 of these orbits, the Oracle is made to calculate and print out normalized values for the radius and for the magnetic field.

Design Specifications

The feasibility of accelerating particles to high energies in a fixed-frequency cyclotron equipped with an azimuthally varying magnetic field was demonstrated at Berkeley[1] with a test cyclotron which accelerated electrons to $v/c = 0.51$. Theoretical studies at ORNL indicate that it should be possible to accelerate protons into the 1-bev energy range with such a machine. The many factors affecting the cost of the large magnet that will be required are being examined carefully in order to arrive at a design that is both economical and practicable.

Design Energy. – In the selection of the design energy, resonance between the frequency of the radial oscillations about the equilibrium orbit and the frequency of ion revolution in the orbits must be considered. The resonances occur at the frequency ratios of 1/1, 3/2, 2/1, etc. The first

[1] R. Pile, *The Second Electron Model Phase-Compensated C-W Cyclotron*, UCRL-2435 rev (March 1955).

resonance, which occurs in the initial accelerations in all cyclotrons, causes no great loss of ions if the magnetic field is adequately shimmed. The second, 3/2, resonance may cause some loss of ions, but it is expected that an appreciable number of ions can be transmitted through this zone. The third resonance, 2/1, which can be made to occur at about 900 Mev, may be a serious barrier to further acceleration. The increase in beam width at this resonance should prove helpful, however, in deflecting the ions. Consequently, the design energy was set at the 2/1 resonance level.

Number of Azimuthal Cycles. – The number of azimuthal cycles of variation to be introduced in the magnetic field is, of course, limited by practical considerations. More important, however, is the effect of the number of cycles on the energy levels at which resonance occurs. The energy for the 2/1 resonance for an eight-cycle field is 300 Mev greater than that for a four-cycle field, but rather little is gained in going to a more expensive sixteen-cycle field. Therefore, an eight-cycle machine was specified for further study.

Effect of Spiral. – The energy levels for the resonances are also found to increase rapidly as the hill and valleys are made to spiral but a few degrees from the straight, radial configuration; further tightening of the spiral increases the energy only slightly. As the spiral is made tighter, the field variation from hill to valley along an orbit decreases, the width across a hill decreases, and the length of the hill from the center of the magnet to the periphery increases. If the hill-and-valley field configuration is produced by pole-face windings, this lengthening and narrowing causes the power requirement to be a function of the degree of spiral. Cost estimates show an optimum spiral to exist.

Magnet Design and Cost Estimates

The magnet design problem was that of determining the details of the iron pole tips, or the proper combination of iron and pole-face windings, which would give the required field shape at the lowest cost. For the cost estimate the field was converted to an approximately two-dimensional one. The simplification was considered to be accurate enough for the preliminary cost study, and the time and effort were considerably less than would have been required by the more exhaustive three-dimensional analysis. A path in the median plane of the machine to be studied was plotted so as to always be perpendicular to the spirals of the hills and valleys (see Fig. 9). The required field along this path was plotted vs the length of path.

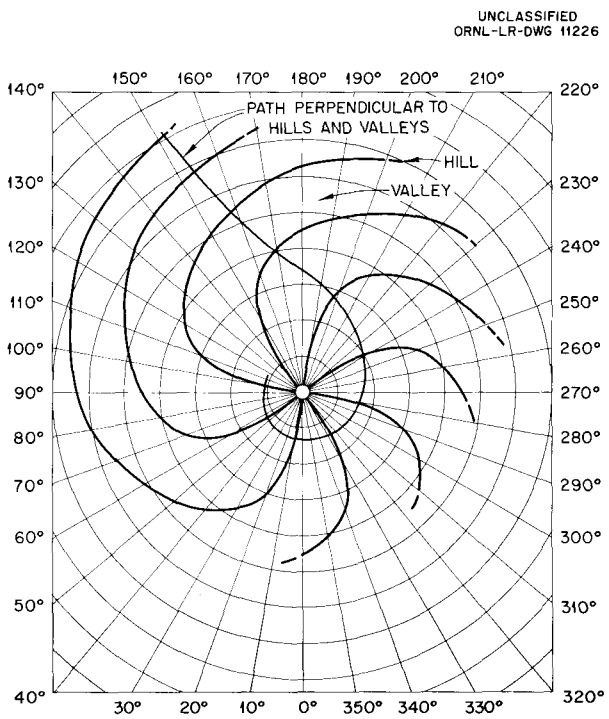

Fig. 9. Configuration of Eight-Cycle Azimuthally Varying Magnetic Field.

The problem was approached in three steps:

1. Magnetic equipotential surfaces needed to produce a given sinusoidal distribution of flux in the median plane were calculated. From these data the required contours of the pole faces, used without pole-face windings, could be calculated.
2. The magnitude of the current required in flat coils, placed above and below the median plane, used without iron to produce the desired field, was calculated as a function of the flux magnitude, width of a flux cycle, and the gap between coils.
3. Flat, iron pole faces were combined with the flat coils for a more economical design.

Pole Tips Without Pole-Face Windings. – The location of the iron for pole tips with contoured pole faces was determined from the data for magnetic equipotential surfaces. The result was that for the eight-cycle machine the minimum gap, which occurs at the outside edge of the field,

could be no more than about 4 in. Since this gap does not permit the insertion of any accelerating structures, the distribution of the iron and the pole-face windings required for machines having larger gaps were investigated.

Pole Tips with Pole-Face Windings. – For a given field variation and geometry and with the gap as a variable, the current required in coils backed by iron pole pieces was found to vary as $\sinh kh/2$, where π/k is the width of a hill and h is the magnetic gap. This rapid variation of current with h and k was found to be the controlling factor in the magnet design. In preparing the cost estimate, the iron pole tips are assumed to supply the average field and the pole-face windings to superimpose the azimuthally varying field.

In the first calculation the pole tips were designed to provide the average field, with a large gap at the center and a narrow gap at the periphery; the pole-face windings were to be attached directly to the pole faces. The current in the pole-face windings reached extremely large values near the center of the magnet, and therefore the design was considered impractical.

As a second attempt, flat pole faces were assumed, with the gap held constant at all radii to reduce the current and power in the pole-face windings; these windings are attached directly to the flat faces of the pole tips (see Fig. 10). To obtain the correct average field in this case, the reluctance of the iron in the pole faces must be controlled. This adjustment may be made by pruning the iron on the top of the upper pole and, symmetrically, on the bottom of the lower pole. This scheme, whose

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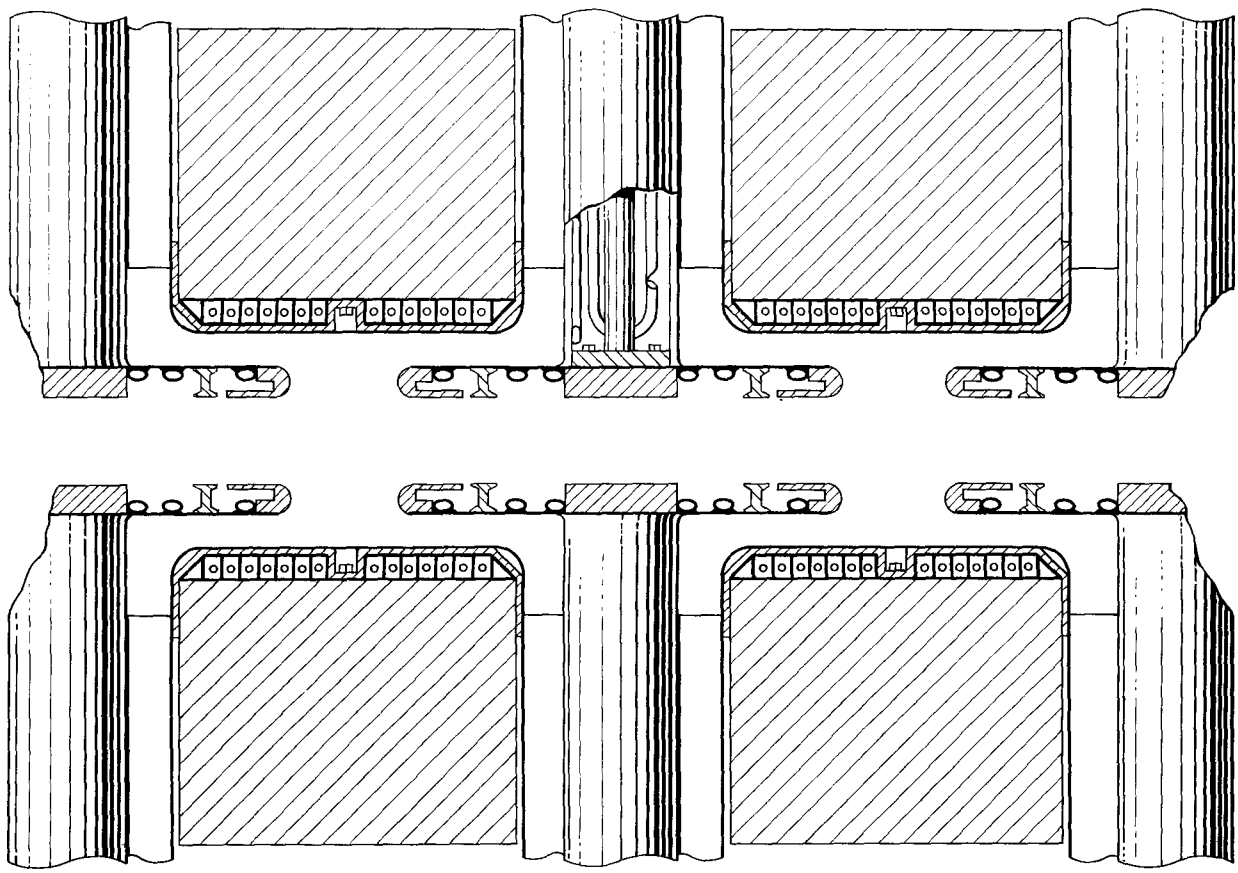

Fig. 10. A 90-deg-Arc Section Through the Cyclotron, Suggesting an Arrangement of Pole Tips, Pole-Face Windings, and an Eight-Electrode Accelerating System.

practicality has not been thoroughly investigated, would certainly result in a minimum amount of iron in the magnet. In addition, it would reduce the current required in the pole-face windings, since the iron gap is everywhere the minimum value and the current in the hill-and-valley coils decreases as the coils spiral in from the outside toward the center of the magnet.

The pole-face windings would consist of 32 identical coils, 2 for each hill and 2, with reversed current, for each valley. Because of the rapid variation of the current with gap, a thickness of winding exists for which the power requirement is least. The power needed in the windings for various central flux densities was calculated (see Fig. 11).

Iron and Copper Required. – The most important items in the cost estimate are the iron in the pole pieces and return yoke, the copper for the pole-face windings and for the large coil which produces the average field, the total power for both the windings and the large coil, and the motor-generator capacity. A flux density of 18,000 gauss in the iron was used in all calculations. Because the flux density at the center of this magnet was lower than that at the outside, the iron required for the pole pieces is much less than that needed in a comparable frequency-modulated cyclotron. The thickness of the iron should vary somewhat as a parabola from the center to the outside edge of the magnet, instead of being constant. To provide a basis of cost comparisons for the several magnet designs, which use varying amounts of iron and copper, the cost of the power required for 50,000 hr of operation is included in the total estimate.

Cost Estimates. – The following unit costs were assumed in the calculation of total magnet costs:

	Cost
Iron, erected (per ton)	$500
Copper, erected (per ton)	$3000
Power (mills/kwhr)	6
Motor-generator capacity, installed (per kw)	$100

Because of the large power requirements for the pole-face windings of high-flux magnets with even quite small gaps, the cost of the magnets was examined as a function of orbit diameter, with the assumption that the beam space in the gap should be directly proportional to the orbit diameter. This analysis was prompted by the fact that, for a given

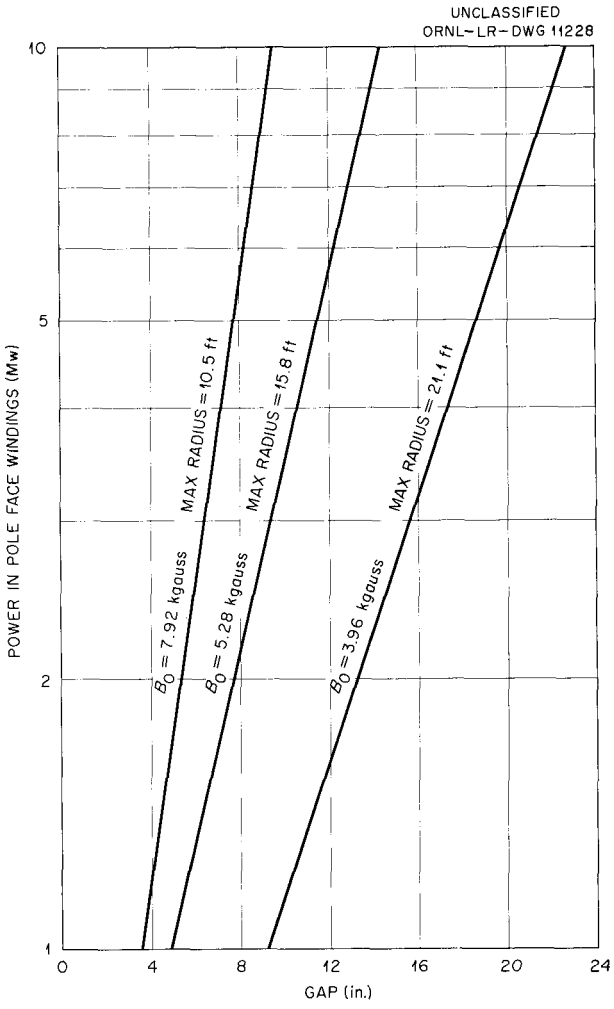

Fig. 11. Power Required in Pole-Face Windings to Produce Magnetic Field for Accelerating Protons to 850 Mev.

amount of power in the pole-face windings, the magnet gap increases more than linearly as a function of diameter. The magnet gap must provide space both for the beam and for the placing of accelerating electrodes. The effects of the magnet gap and of the diameter on the total magnet cost are illustrated in Fig. 12.

The Accelerating System

The large size and the unusual shape of the cyclotron being considered introduce some difficult problems in the design of a suitable accelerating system. Three possible systems have been considered briefly: conventional dees, an eight-electrode system, and a cavity system.

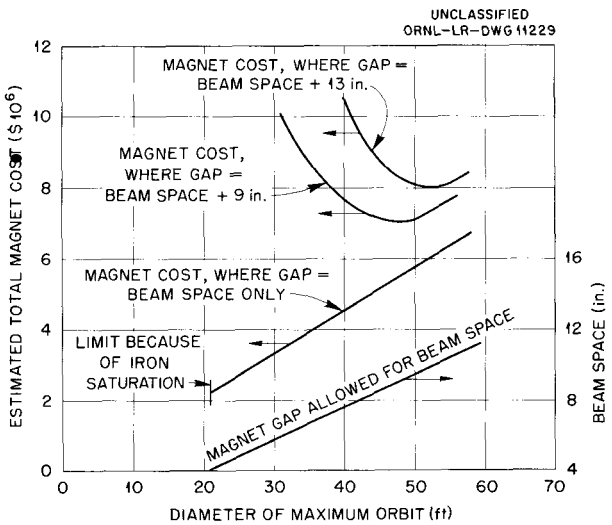

Fig. 12. Magnet Cost Estimates. Specifications: Proton energy, 850 Mev; azimuthal cycles in magnetic field, eight; spiral constants, $a_1 = 0$ and $a_2 = 32$. Total cost includes cost of power for 50,000 hr of operation.

Conventional-Dee System. – There are rather serious disadvantages in the use of a conventional-dee system. The space it would occupy in the magnet gap would greatly increase the cost, and because of the size of the dee its mechanical design would be very difficult. Also, because of the space required for inserting and removing the dee, it would be necessary to replace the several small magnet yokes with a large yoke; this conventional design would require more magnet iron than would be required with the other systems.

Eight-Electrode Accelerating System. – Since this type of magnet may be designed with large gaps in the valleys, it would appear reasonable to concentrate the accelerating structures in these spaces. The valleys are 22½ deg wide, azimuthally, and the eight electrodes could be from 20 to 40 deg wide. To make full use of the voltage on the electrode, the particles should pass through the field-free region inside the electrode in the time required for the voltage to reverse. Therefore, an electrode which is 22½ deg wide should be driven at a frequency eight times the ion frequency. Such an electrode could not be driven through a stem at the edge of the machine, as in a conventional cyclotron, because the voltage standing wave along the electrode would pass through zero inside the radius of maximum orbit. The electrodes could, however, be driven and supported from above and below by stems through the valleys (see Fig. 8). The applied frequency would then be four or eight times the ion frequency, depending upon the width of the electrodes. This system is believed to be worthy of further consideration.

Cavity System. – A square cavity operating in the TE_{011} mode seems to offer the simplest accelerating system. This cavity could be made very thin, be curved to fit the spiral, and be placed through the center of the machine in two opposite valleys, separating the machine into two identical halves. A slit in the cavity would permit the beam to pass through an electric field much like that between two dees. The size of this cavity is such that operation at a frequency twice the ion frequency would best fit the dimensions of the magnet.

Two cavities positioned at right angles to each other should probably be used. The cavities would be driven with a 180-deg phase difference to provide the properly phased voltages. The radio-frequency equipment for such a system of cavities would be much simpler than that for a multielectrode structure. Suitable cavities would be quite efficient; most important, they would require no space in the magnetic gap, and savings in magnet cost would be quite large (see Table 2). A possible disadvantage is that the magnet would have to be constructed in four identical sectors for a two-cavity accelerating system.

Test-Model Electron Cyclotron

No adequate experimental evidence exists on which to base an estimate of the difficulties to be expected in accelerating large currents of protons through the 3/2 resonance. The electron cyclotron used at UCRL to demonstrate the effectiveness of the Thomas-type magnetic field was not designed to accelerate electrons through their 3/2 resonance energy level. Consequently, an electron cyclotron was designed to be operated as a test model.[2] It is to be the simplest machine which will yield the required information about the 3/2 resonance. Knowledge is needed concerning the effects of small variations in the magnetic field on beam

[2]Research participants working with the Division on this problem during the summer were B. P. Foster, North Texas State College; A. W. Hanson, The Citadel; D. L. Lafferty, Vanderbilt University; and H. M. Moseley, Texas Christian University.

TABLE 2. COMPARISON OF THE TWO-CAVITY AND THE EIGHT-ELECTRODE ACCELERATING SYSTEMS

	Accelerating System	
	Two-Cavity	Eight-Electrode
Design Features		
Magnet gap (in.)	4	23
Orbit diameter, maximum (ft)	21	52.5
Flux density, central (kilogauss)	7.9	3.2
Flux density, maximum (kilogauss)	20	9.8
Applied radiofrequency (megacycles/sec)	24.4	19.5
Requirements		
Iron, total (tons)	1850	8500
Copper, main field coil (tons)	82	400
Copper, pole-face windings (tons)	16	143
Power, main field coil (Mw)	0.75	1.5
Power, pole-face windings (Mw)	1.8	2.1
Magnet Cost, from Fig. 12	$2,200,000	$8,000,000

attenuation and on threshold voltage, especially in the region of this resonance.

Several cyclotron and magnet designs were considered before a design was selected. A four-cycle magnetic field was found to be sufficient to accelerate electrons through their 3/2 resonance, which occurs at about 150 kev. For simplicity, in this test machine the hills and valleys of the four-leaf-clover magnet were not spiraled. To accelerate electrons to 220 kev, which is the 2/1 resonance, the central field was fixed at 40 gauss; this makes the maximum orbit radius 12.2 in. and the ion frequency 112.2 megacycles/sec.

Dish-shaped iron pole faces are used to establish the average field in the magnetic plane. The azimuthal field variations are produced by 16 coils spaced at a fixed distance above and below the median plane. The hill coils and valley coils are identical and will carry equal currents, but, since the currents will be in opposite directions, the coils will have very little effect on the average field. Also, there are circular coils which can produce small changes in the average field without affecting the hill-and-valley flux. Because of the iron pole faces, the calculation of the field produced by the hill-and-valley coils is somewhat complex; the problem is being studied with the Oracle.

The resonant system will consist of two dees driven by a self-excited oscillator. To prevent any unbalance in the r-f voltage, which would have the effect of introducing undesirable components in the accelerating field, the two dees are to be driven symmetrically.

THE 44-INCH CYCLOTRON

The over-all modification of the 44-in. cyclotron to provide for high-current operation at proton energies of either 1.5 or 5 Mev is nearly complete; the machine should be ready for test operation in November. Major modifications[3] include the new 44-in. dee assembly with the dee stems completely enclosed in the vacuum chamber, a larger oscillator, and a 450-kw power supply. The machine is to be used in continuation of the study of problems associated with the acceleration of large ion currents.

The resonant circuit, composed of the grounded-grid radio-frequency oscillator, the dees and dee stems, and the networks which connect the oscillator to the dee system, was tested. Oscillations at 9.3 megacycles/sec were readily obtained with the application of 1-kv plate voltage. An oscilloscope showed that the dee-to-ground voltages were 180 deg out of phase, which indicates the desired push-pull mode of operation. The test was made with the dees in air; tests under vacuum are to be made soon.

The system of water connections between the cyclotron proper and the building supply is nearly

[3] *Electronuclear Research Semiann. Prog. Rep. March 20, 1955,* ORNL-1884, p 10.

complete. The protective interlock system, using pressure differential across an orifice, was designed and fabricated and is being installed. Revision of the existing calutron power cubicles to provide a d-c power supply for the oscillator is 85% complete. The ion source is ready for operation. The experimental probe and the handling equipment for the source and probe are nearing completion.

PROPOSED 48-INCH HEAVY-PARTICLE CYCLOTRON

It has been proposed that preparations be made to convert the 44-in. proton cyclotron to a machine for the acceleration of carbon and nitrogen ions to energies up to 81 Mev. A well-shielded cyclotron room would be built adjacent to Building 9204-3, and a 48-in., 20,000-oersted magnet would be constructed. The existing dees, dee stems and housing, coupling circuits, vacuum-pumping system, and oscillator with its 45-kw power supply and control system could all be adapted for use in the new magnet. The new 48-in. heavy-particle cyclotron would provide a versatile and reliable instrument for continuing and greatly extending the basic nuclear work now being done with the 63-in. cyclotron.

The preliminary conceptual design of the 48-in. magnet is being re-examined in preparation for the final design. The original choice of copper for the magnet winding is being re-evaluated; aluminum may prove to be a better choice. Price quotations from the Aluminum Company of Canada indicate that the cost per ton is essentially the same as that for copper. Since aluminum can be extruded in long continuous lengths, whereas copper cannot, it is expected that winding costs of the coils would be lower. A model magnet to be used in determining the pole profile required to obtain the desired radial field variation was designed. The iron for the yoke and poles of the model is already available locally, and the copper is to be shipped on about October 1.

Part II

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ABSTRACT

Further successful calutron operation has increased the quantities of enriched isotopes of plutonium available for research studies. New techniques were developed to prevent the holdup of plutonium in processing equipment.

Work on the Army Package Power Reactor 1 is progressing on schedule, and arrangements were made to advance the completion date from December 1957 to July 1957. The contractor's design for the APPR-1 plant was approved by the Advisory Committee on Reactor Safeguards, and the contractor has started the initial phases of construction at Fort Belvoir, Virginia. Critical experiments and other supporting development work at the Laboratory are proceeding on schedule.

SPECIAL SEPARATIONS

PLUTONIUM PROGRAM

The heavier isotopes of plutonium are being separated from highly irradiated feed for distribution to AEC installations. This makes available purified isotopes for accurate measurement of their nuclear properties; also, the experience gained in handling plutonium in the electromagnetic facilities allows a continuing appraisal of the suitability of the process for possible large-scale plutonium separations which are of interest for processing plutonium from high-burnup, plutonium-producing reactors.

Separations of enriched Pu^{240} and Pu^{241} are being made from a feed bank originally containing 140 g of 3000 Mwd/t plutonium. This feed material, which originally assayed 12.7% Pu^{240}, now contains only 10.8% Pu^{240}; the dilution in Pu^{240} content resulted from small residues of 1200 Mwd/t (5.6% Pu^{240}) plutonium processed earlier in the same equipment.

The plutonium contained in the central one-third of four highly irradiated NRX uranium fuel elements is being obtained for isotope separations. Nearly 200 g of plutonium irradiated to 3900 Mwd/t will be available. The uranium rods will be processed at ORNL in the Metal Recovery Facility.

Calutron Performance

A sixth separation of the plutonium isotopes was made from plutonium assaying 10.8% Pu^{240}, 1.13% Pu^{241}, and 0.10% Pu^{242}. The feed material was obtained by a recovery of the unresolved plutonium chloride vaporized in the fourth and fifth separations reported previously. The efficiency of conversion of $PuCl_3$ vapor to well-focused Pu^+ ions was 5.7%. Production and product assay data for the run are given in Table 3. Two batches are reported for each product isotope. The batches are a result of selective recovery from the graphite collector pockets.

TABLE 3. RESULTS FOR ISOTOPE SEPARATION FROM SIXTH CALUTRON RUN

	Isotopic Content (at. %)				Total Weight of Plutonium (g)
	Pu^{242}	Pu^{241}	Pu^{240}	Pu^{239}	
Feed vaporized	0.10	1.13	10.8	97.96	76.0
Pu^{240} product					
Batch P6-50-1		0.88	83.10*	16.02	0.449
Batch P6-40-2		1.41	74.46	25.13	0.0904
Pu^{241} product					
Batch P6-41-1	0.68	52.37	15.35	31.6	0.0488
Batch P6-41-3	0.61	46.74	20.22	32.43	0.0255

*Isotope desired.

[redacted]

Plutonium Recovery and Chemical Processing

A large fraction of the unresolved plutonium recovered from the calutron units is in a nearly insoluble form. The original flowsheet for the plutonium recycle was based on the assumption that a large fraction of the plutonium could be recovered in nitric acid wash solution. It was assumed that the rapid purification of this wash solution by extraction would provide adequate feed material for the subsequent separation runs. The product resulting from a much slower, constant holdup, solid-salvage purification cycle was to be introduced into subsequent solution cycles.

The high holdup per cycle, together with a crossover of plutonium between two assay levels during the past five runs, indicated the following deviations from the design assumptions:

1. Plutonium metal or oxide can be held on equipment in relatively large quantities, since the plutonium is not being removed by simple solution.
2. Solids filtered from the wash solutions contain most of the plutonium recovered from the calutron equipment.
3. The high solids content of the wash solution shows that there is a possibility of holdup in equipment piping.

Modifications of the process equipment were made necessary by the large amounts of solids in the wash solutions.

The efficiency of calutron wash operations must be very high if over-all recovery efficiency is to approach 100%. The calutron ion-source unit and the collector components can be visually inspected; however, the 90-deg baffle arrangement prevents complete inspection of the vacuum-tank liner. The use of carbon baffle plates permits holdup of solution. Metal or oxide deposits are removed only slowly by nitric acid washing. Various wash solutions that are compatible with the structural materials of existing equipment are being evaluated, along with the effectiveness of repeated washing. In each test the liner was washed for 2 hr with 14 gal of solution at a temperature of 23°C; the results of nine successive washings are given in Table 4. The filter solids have not yet been analyzed, but as indicated by the amount of plutonium remaining in the wash solutions the HNO_3 wash is inadequate.

The use of hydrogen iodide as a reducing agent in the preparation of solutions for oxalate precipitation was discontinued. The hydroxylamine sulfate or sulfur dioxide reductions now used eliminate a sodium hydroxide precipitation step previously necessary for iodine elimination. The plutonium extraction efficiency of TBP in Varsol was erratic for solutions derived from oxalate precipations. Boiling these solutions with HNO_3 effectively removed all oxalate and eliminated the difficulty.

TABLE 4. RESULTS OF NINE SUCCESSIVE WASHINGS OF A CALUTRON LINER

Wash Solution	Plutonium Remaining in Solution (g)	Filter Solids (g)
8% HNO_3	1.1	3
8% HNO_3	1.2	3
8% HNO_3	0.5	3
8% HNO_3	0.7	3
H_2O	0.4	None
0.07% HF 8% HNO_3 1% $Al(NO_3)_3$	6.1	50
8% HNO_3	0.8	10
8% HNO_3	0.4	5
0.07% HF 8% HNO_3 1% $Al(NO_3)_3$	1.4	25

Since Am^{241}, the daughter product of Pu^{241}, is not completely removed in the usual plutonium purification process, a purge step was added to prevent its buildup. By changing the pH of the extraction raffinate after the bulk removal of plutonium, an americium-rich extract is obtained with an americium-to-plutonium ratio of 1:2.

To simulate the high-temperature conditions required to vaporize and ionize plutonium, anhydrous chlorides of the rare-earth elements are used in ion-source development runs. In preparing these chlorides, alternate chlorination methods employing, for example, phosgene, CCl_4, and high-temperature reactions, are being investigated. Halogen-plutonium reactions may prove useful in refractory salvage processing. Thorium chloride, $ThCl_3$, was successfully prepared by refluxing the oxychloride with hexachloropropene. Cerium

[redacted]

was found to be a poor substitute for plutonium in halogen reaction experiments. Plutonium appears to be more reactive than cerium with chlorine-to-carbon linked compounds, while cerium appears to be more reactive toward elemental halogens. The $PuCl_3$ charge for all isotope separations has been prepared by refluxing plutonium oxalate or oxychloride with hexachloropropene.

Product Processing

Product processing now includes a purification step not previously used. Iron, the major impurity found in separated plutonium isotope products, is removed by an oxalate precipitation. Calutron efficiencies are now based on the purified-product weights, and accountability accuracy is greatly improved.

ISOTOPE SHIPMENTS

The distribution of electromagnetically enriched isotopes of uranium, thorium, and plutonium since January 20, 1955, is shown in Table 5.

LOW-INTENSITY ISOTOPE SEPARATOR

A low-current isotope separator to be used for processing millicurie amounts of cyclotron and reactor products and transuranic elements was designed and assembled. The standard 24-in. Beta calutron was modified as follows:

1. The calutron ion source was scaled down to operate at about one-tenth charge consumption rate and one-tenth output.
2. A vacuum lock was provided in the ion-source assembly for inserting and removing charge material.
3. A small-sized collector was constructed which can be adapted to separating all the different elements, can be used to collect simultaneously all the isotopes of one element, and can be readily disassembled.

It is expected that the low-intensity separator will retain the standards of enhancement and efficiency of the present calutron. This would mean enhancements of 20 to 200 and process efficiencies of 5 to 20%.

The ion source is now being tested for the vaporization and ionization of elements of low, intermediate, and high atomic weights.

TABLE 5. DISTRIBUTION OF ISOTOPES

Isotope	Shipped To	Amount (mg)	Purity (%)
U^{235}	Argonne National Laboratory	1,001	99.994
	DuPont – Savannah River	100	99.994
	Argonne National Laboratory	21	99.91
	Los Alamos Scientific Laboratory	1,547	99.90
	Los Alamos Scientific Laboratory	4,178	99.90
	Los Alamos Scientific Laboratory	9,247	99.90
	Carnegie Institution of Washington	100	99.76
	General Electric – Hanford	1,016	99.76
U^{236}	General Electric	20	96.65
U^{238}	DuPont – Savannah River	100	99.9999
	DuPont – Savannah River	100	99.9997
	Oak Ridge National Laboratory, Y-12	10,067	99.9997
	DuPont – Savannah River	100	99.9988
	General Electric – Hanford	3,038	99.9988
	Oak Ridge National Laboratory, Y-12	793,090	99.983
Pu^{239}	Oak Ridge National Laboratory, Y-12	238	99.80
Pu^{241}	Oak Ridge National Laboratory, X-10	3	49.20
Th^{230}	DuPont – Savannah River	60	90.02

ARMY PACKAGE POWER REACTOR PROGRAMS

Work on the final design of the Army Package Power Reactor (APPR-1) by the Alco Products, Inc. (formerly the American Locomotive Co.) is progressing on schedule. A recent AEC request to shorten the construction and testing period by five months met with a favorable reply from Alco. The projected completion date is now July 1957, instead of December 1957.

On August 30, 1955, the design for the APPR-1 plant was presented to the Advisory Committee on Reactor Safeguards at Schenectady, New York. The Committee approved the plant for operation, without qualification. As a result of the approval, ground will be broken at the Fort Belvoir reactor site in October 1955.

The Alco Products, Inc., notified the AEC that ORNL has been selected for the construction of the APPR-1 fuel assemblies.

DESIGN STUDIES

Seven conceptual design studies, described in the previous progress report,[1] on advanced package-type reactors power plants proposed for supplying Distant Early Warning (DEW) Stations were received and evaluated by ORNL during June.

The evaluations by the groups at the Laboratory and the Army Reactors Branch (ARB) indicated that the pressurized water type of reactor is still favored over other types of reactors; the boiling heterogeneous reactor (ANL type) should be the next type constructed; and the gas-cooled reactor should be selected for potential long-range study.

Negotiations were completed between the Army Reactors Branch and the Argonne National Laboratory for the design and construction of a prototype boiling reactor.

APPR DEVELOPMENT PROGRAM

The Laboratory is continuing to furnish technical advice and evaluations to the ARB in addition to the scheduled development programs in support of the APPR-1 contract.

Fuel Irradiation Experiment

The irradiation of a stainless-steel-clad APPR-type fuel assembly[1] in the STR Mark I was terminated on June 21, 1955, after 190 hr, at full power, of reactor time because of higher priority experiments. No apparent damage could be detected by visual observation. Discussions are now in progress with Westinghouse and NRB to determine the feasibility of placing the fuel assembly in the STR after the new core is installed in this reactor. It is most desirable to obtain additional burnup on the fuel assembly to obtain a more realistic evaluation of the fuel element design.

A three-plate dummy assembly was placed in the Westinghouse Bettis Field loop D facility to obtain a long-term corrosion test. The assembly has now been operated at rated temperature, pressure, and flow for over 1400 hr with very satisfactory results.

The program for irradiating fuel elements in the MTR is now well under way. In phase I of the program a series of small APPR-type fuel plates with varying UO_2 particle sizes are to be irradiated to 20 and 40% burnup. This irradiation was started on June 24 and is tentatively scheduled to be completed by December. Phase II of the program is the irradiation of a full-size fuel assembly in the lattice of the MTR. The assembly was inserted in the lattice on June 24 and was removed on August 22; the estimated average burnup was 25% and the maximum was 40%. The individual fuel plates of this assembly will be separated in the MTR hot cell after a sufficient cooling period and shipped to Oak Ridge for metallurgical examination. A preliminary examination of the fuel assembly was made in the MTR canal by means of an underwater periscope; no damage could be observed.

Critical Experiments

The design and construction of apparatus for a series of critical experiments on a mockup of the APPR core were completed. The experiments will begin about September 20, and it is expected that the cold, clean critical mass of the mockup will be obtained by October 1. Measurements of control-rod worth, of effects of burnable poison and external structure, of temperature coefficient, and of flux and power distribution will follow sequentially. It is expected that the complete results from this series of measurements will be available within the next four to six months.

The critical mockup, Figs. 13 and 14, was constructed as a reasonably exact copy of the proposed

[1] *Electronuclear Research Semiann. Prog. Rep. March 20, 1955*, ORNL-1884, p 22–25.

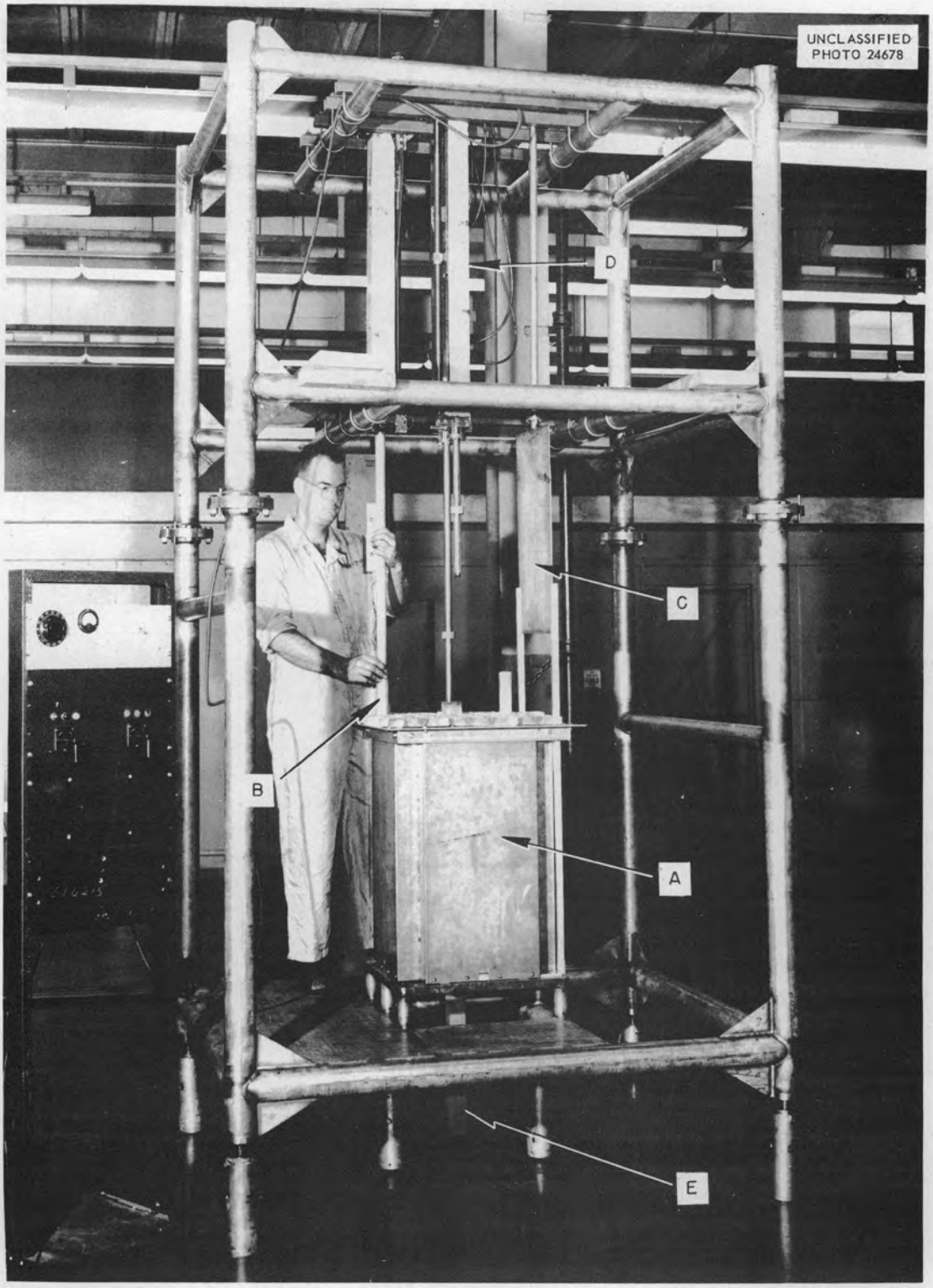

Fig. 13. Over-all View of APPR-1 Mockup Before Insertion in Water Tank. (*a*) Reactor core. (*b*) External rod for reactor control during critical experiment. (*c*) Safety blade for use in critical experiment. (*d*) Rod drive mechanisms. (*e*) Fuel section of design control rod (control rod in down position).

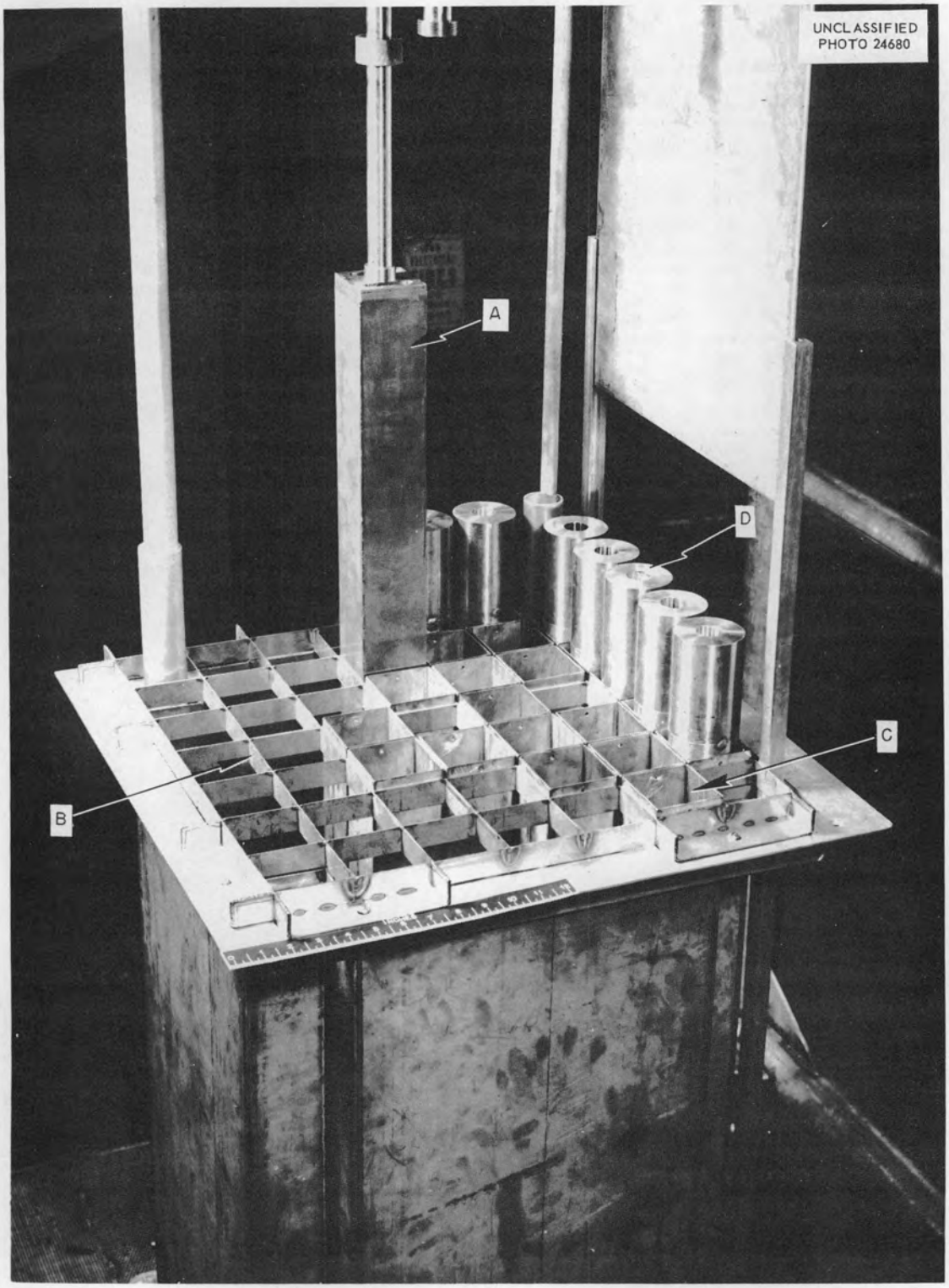

Fig. 14. Closeup of Core for APPR-1 Critical Experiment. (*a*) Absorber section of design control rod (control rod in up position). (*b*) Grid for holding fuel element boxes in position. (*c*) Fuel element box. (*d*) End structure mockup.

APPR.[2] Sensitive features, such as fuel loading, poison loading, stainless steel content, moderator and reflector composition, and control-rod design, duplicate the proposal very closely. Variation in the loading is made possible by having slotted boxes, as shown in Fig. 15, for the fuel elements; plates of stainless-steel-clad uranium, stainless-steel-clad boron, and plain stainless steel fit into the slots. The core of the mockup will accommodate 850 plates; any desired loading can be obtained by selecting the type, number, and arrangement of plates. Additional inhomogeneity over and above that in the design reactor is introduced, of course, by having the three types of plates. Preliminary calculations indicate that the effect of these inhomogeneities will be small; more precise calculations are under way.

Reactor Simulator Tests

The thermal kinetic equations for the APPR-1 were derived,[3] and then the six equations were solved[4] with the ORNL Reactor Controls Computer for a number of different perturbing factors. The thermal kinetic equations are:

Time delays of 3 and 7 sec in Eqs. 3 and 4, respectively, account for the time that the coolant takes in flowing through the upper plenum chamber of the reactor pressure vessel, through the piping to the steam generator, and returning to the core through a longer route. The type of flow postulated is slug flow in the piping with some, but not complete, mixing in the plenum chambers.

The equations were solved for a number of different perturbing factors such as step increases in reactivity and power demand. The curves obtained show that the reactor is quite stable and self-regulating. The temperature coefficient of reactivity is approximately -2×10^{-4} (°F)$^{-1}$, but

[2] A. L. Boch *et al.*, *A Conceptual Design of a Pressurized-Water Package Power Reactor*, ORNL-1613 rev (Nov. 2, 1955).

[3] J. G. Gallagher and M. L. Winton, *Derivation of the Thermal Kinetic Equations for the Package Reactor*, ORNL CF-55-4-53 (April 13, 1955).

[4] F. P. Green and M. L. Winton, *Analog Simulation of the Thermal Kinetic Equations of the APPR*, ORNL CF-55-5-109 (May 18, 1955). (Rough-draft copies of this report were issued and a final report is being prepared.)

$$\frac{d\theta_F(t)}{dt} = 0.0216P(t) - 10.01\theta_F(t) + 10.01\theta_C(t) \quad (1)$$

$$\frac{d\theta_C(t)}{dt} = 0.000270P(t) + 1.99\theta_F(t) - 6.684\theta_C(t) + 4.694\theta_{C_1}(t) \quad (2)$$

$$\frac{d\theta_{B_1}(t + 3.00)}{dt} = 0.995\theta_C(t) - 0.4975\theta_{C_1}(t) - 0.4975\theta_{B_1}(t + 3.00) \quad (3)$$

$$\frac{d\theta_{C_1}(t + 7.00)}{dt} = 0.5952\theta_B(t) - 0.2976\theta_{B_1}(t) - 0.2976\theta_{C_1}(t + 7.00) \quad (4)$$

$$\frac{d\theta_B(t)}{dt} = 1.587\theta_{B_1}(t) - 1.8345\theta_B(t) + 0.2475\theta_S(t) \quad (5)$$

$$\frac{d\theta_S(t)}{dt} = 0.0543\theta_B(t) - 0.0543\theta_S(t) - 3.20A \quad (6)$$

where

θ_F = mean fuel temperature, °F,

P = reactor power, Mw,

θ_C = mean coolant temperature, °F,

θ_{C_1} = coolant temperature at core inlet, °F,

θ_{B_1} = coolant temperature at steam generator inlet, °F,

θ_B = mean coolant temperature in steam generator, °F,

θ_S = steam temperature, °F,

A = throttle opening (wide open corresponds to $A = 1$).

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Fig. 15. Typical Fuel Element Box. (*a*) Slots for positioning of steel, uranium, and boron plates. (*b*) Steel plates showing typical insertion into box (partial loading, partially inserted).

for coefficients as small as -5×10^{-5} $(°F)^{-1}$, the power oscillations for step reactivity changes of 0.30% are small (see Figs. 16 and 17).

The way that the reactor power responds to step changes in power demand is shown in Fig. 18. In this test the power demand was changed step-wise to 50% of initial power and also to 25% of initial power. The deficit between the power demanded and the power generated is supplied by the energy stored in the system, which is about 12,000 Btu/°F. It appears that the energy stored in the system is able to take care of any short-time power deficit. There are no power oscillations for a temperature coefficient of -2×10^{-4} $(°F)^{-1}$, even for large changes in reactivity. It seems, therefore, that a servo system for controlling a regulating rod is unnecessary.

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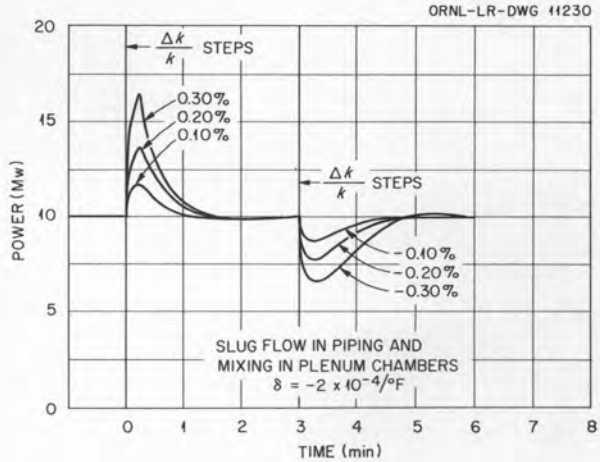


Fig. 16. Power Fluctuations for Step Changes in Reactivity Where Temperature Coefficient of Reactivity Is -2×10^{-4} $(°F)^{-1}$.

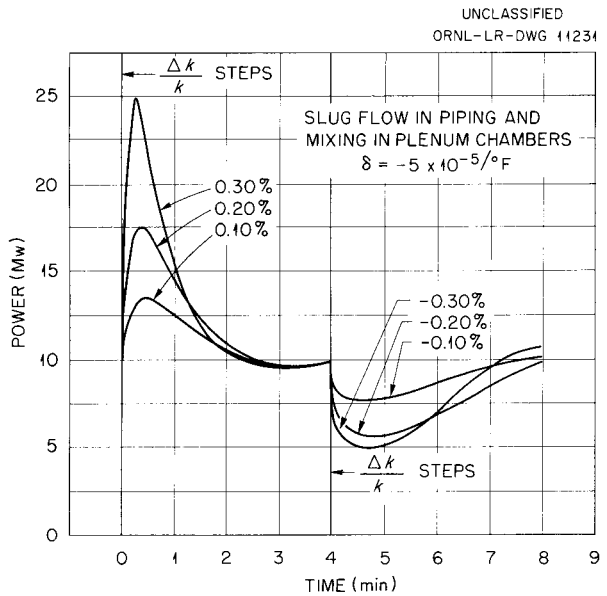


Fig. 17. Power Fluctuations for Step Changes in Reactivity Where Temperature Coefficient of Reactivity Is -5×10^{-5} (°F)$^{-1}$.

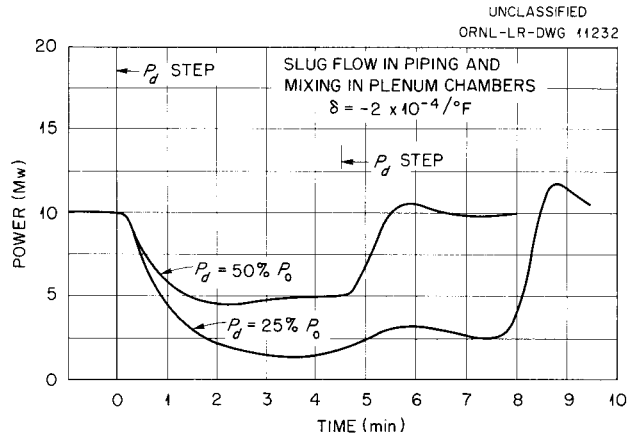


Fig. 18. Reactor Power Response to Step Changes in Power Demand.

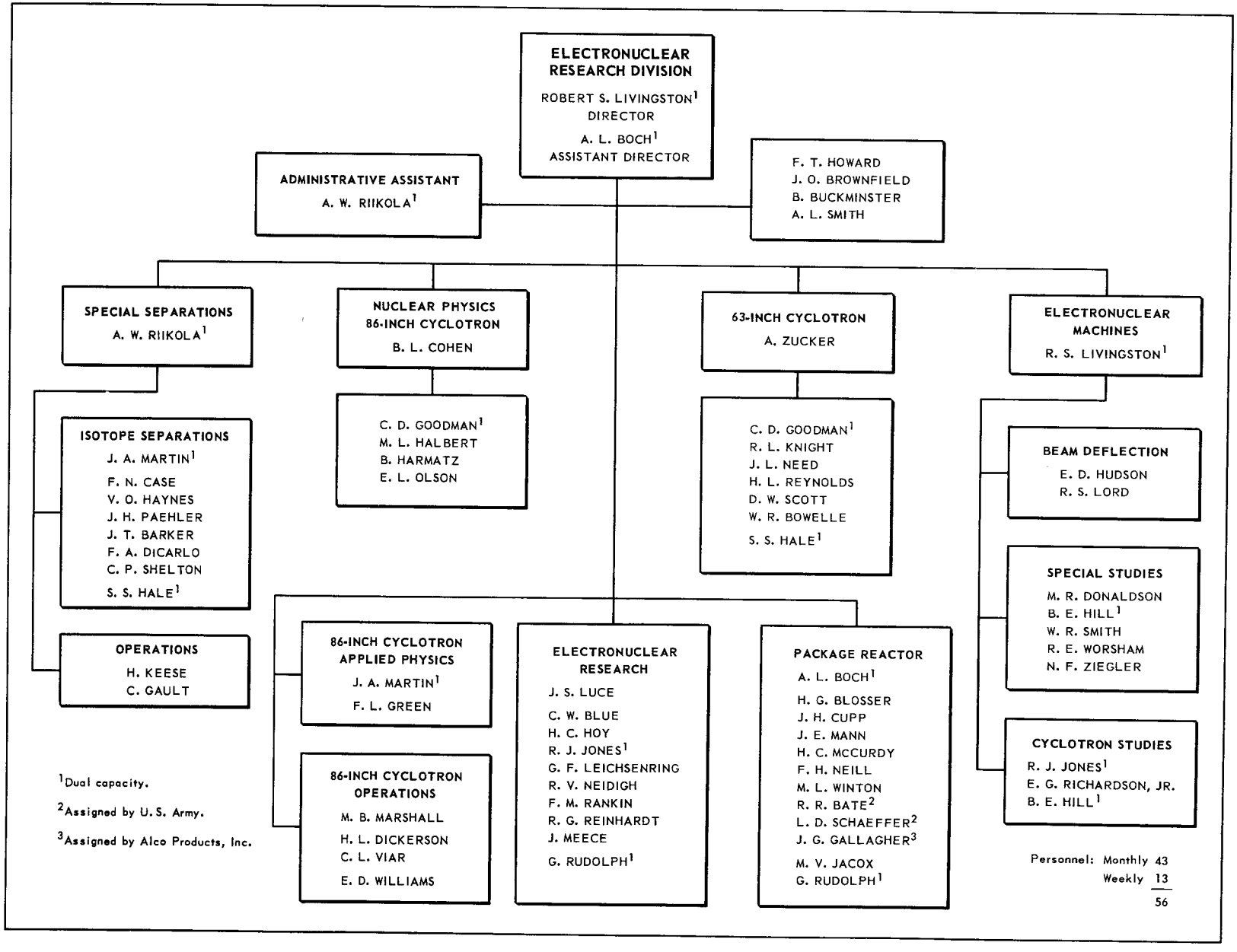
OPERATIONS SUMMARY

The experimental and production runs in Buildings 9204-3 and 9201-2 from March 20 to September 20, 1955, are summarized below; the distribution of shop time charged to each of the various projects is given in Table 6. The assignment of personnel to the several projects is indicated in the organization chart.

Project	Number of Runs
Special separations	13
86-in. cyclotron	2
63-in. cyclotron	112
Electronuclear research	150
Total	277

TABLE 6. TIME DISTRIBUTION – MECHANICAL SERVICE AND MACHINE SHOPS

Account Number and Project	Mechanical Service		Machine Shops			
			Carbon		Metal	
	Hours	Per Cent of Total Time	Hours	Per Cent of Total Time	Hours	Per Cent of Total Time
33 Special separations	2,324.0	17.09	469.8	27.10	486.0	12.41
34 86-in. cyclotron applied physics	509.0	3.74				
35 86-in. cyclotron operations	3,540.0	26.03			616.0	15.72
37 Electronuclear machines	548.0	4.02	44.0	2.54	199.2	5.09
39 86-in. cyclotron nuclear physics	457.0	3.36			224.0	5.72
40 63-in. cyclotron physics	74.5	0.55	62.0	3.58	18.0	0.46
41 63-in. cyclotron operations	1,054.0	7.75	154.0	8.88	135.8	3.47
43 Army Package Power Reactor	522.0	3.84	48.0	2.77	6.0	0.15
46 Fundamental electronuclear research	4,451.0	32.7	955.6	55.13	2224.4	56.78
1 Building maintenance	122.0	0.90			8.0	0.20
Total	13,601.5	100.00	1733.4	100.00	3917.4	100.00


ELECTRONUCLEAR RESEARCH DIVISION
ROBERT S. LIVINGSTON[1]
DIRECTOR
A. L. BOCH[1]
ASSISTANT DIRECTOR
ADMINISTRATIVE ASSISTANT
A. W. RIIKOLA[1]
F. T. HOWARD
J. O. BROWNFIELD
B. BUCKMINSTER
A. L. SMITH
SPECIAL SEPARATIONS
A. W. RIIKOLA[1]
NUCLEAR PHYSICS 86-INCH CYCLOTRON
B. L. COHEN
63-INCH CYCLOTRON
A. ZUCKER
ELECTRONUCLEAR MACHINES
R. S. LIVINGSTON[1]
ISOTOPE SEPARATIONS
J. A. MARTIN[1]
F. N. CASE
V. O. HAYNES
J. H. PAEHLER
J. T. BARKER
F. A. DICARLO
C. P. SHELTON
S. S. HALE[1]
C. D. GOODMAN[1]
M. L. HALBERT
B. HARMATZ
E. L. OLSON
C. D. GOODMAN[1]
R. L. KNIGHT
J. L. NEED
H. L. REYNOLDS
D. W. SCOTT
W. R. BOWELLE
S. S. HALE[1]
BEAM DEFLECTION
E. D. HUDSON
R. S. LORD
SPECIAL STUDIES
M. R. DONALDSON
B. E. HILL[1]
W. R. SMITH
R. E. WORSHAM
N. F. ZIEGLER
OPERATIONS
H. KEESE
C. GAULT
86-INCH CYCLOTRON APPLIED PHYSICS
J. A. MARTIN[1]
F. L. GREEN
86-INCH CYCLOTRON OPERATIONS
M. B. MARSHALL
H. L. DICKERSON
C. L. VIAR
E. D. WILLIAMS
ELECTRONUCLEAR RESEARCH
J. S. LUCE
C. W. BLUE
H. C. HOY
R. J. JONES[1]
G. F. LEICHSENRING
R. V. NEIDIGH
F. M. RANKIN
R. G. REINHARDT
J. MEECE
G. RUDOLPH[1]
PACKAGE REACTOR
A. L. BOCH[1]
H. G. BLOSSER
J. H. CUPP
J. E. MANN
H. C. MCCURDY
F. H. NEILL
M. L. WINTON
R. R. BATE[2]
L. D. SCHAEFFER[2]
J. G. GALLAGHER[3]
M. V. JACOX
G. RUDOLPH[1]
CYCLOTRON STUDIES
R. J. JONES[1]
E. G. RICHARDSON, JR.
B. E. HILL[1]
Personnel: Monthly 43
Weekly 13
56
[1]Dual capacity.
[2]Assigned by U. S. Army.
[3]Assigned by Alco Products, Inc.