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THE UNIVERSITY OF WASHINGTON
60 INCH CYCLOTRON

PROGRESS AND STATUS REPORT OF
DESIGN AND CONSTRUCTION

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DEPARTMENT OF PHYSICS
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1 INTRODUCTION

The University of Washington Cyclotron has been designed and constructed to produce a 20 MeV beam of deuterons, but with facilities available for the utilization of other particles. The basic element of this machine is a magnet having 60-inch pole pieces. A magnet of this size when used with deuterons, is about the optimum dimensions in which deuterons may be accelerated profitably without resorting to frequency modulation. The machine, therefore, will be initially used as a conventional or constant frequency cyclotron with the instrumentation designed to take advantage of the large currents that should be available.

This cyclotron is installed in a building specially built for the purpose and is on the University of Washington campus. It is designed so as to take maximum advantage of naturally occurring shielding of a small ravine. In addition, the building has been designed to provide excellent shielding in the vicinity of the beam to permit experiments requiring low background. Further instrumentation is planned which will permit analysis of the beam into well-defined particle energies for various experimental purposes.

Active work on the project began in June 1948. Initial support came from both the State of Washington and from the Office of Naval Research. In addition to State of Washington support, the project has been supported by the joint program of the Office of Naval Research and the Atomic Energy Commission. Since July 15, 1950, outside support has come from the Atomic Energy Commission. This report constitutes the first yearly report under this contract. As of the date of this report the cyclotron is an assembled machine ready for initial test.

Total expenditures to date from all sources, excluding University of Washington overhead and staff salaries, has been \$642,000. This

includes not only the construction of the cyclotron but the cyclotron building and its associated shop building.

1.1 Acknowledgments

The University of Washington Cyclotron which is described herein follows basically the Crocker Cyclotron at the University of California. We have had available for our use a complete set of the Berkeley plans which was kindly placed at our disposal by Professor E. O. Lawrence. These drawings have been followed closely on the magnet design, and have been invaluable to us in the major design work on the machine. In addition, we have enjoyed the competent advice and aid of many members of the staff of the Radiation Laboratory at Berkeley.

In the later phases of our work we have received excellent advice and counsel from other laboratories; notably, Massachusetts Institute of Technology, University of Pittsburgh, Brookhaven National Laboratory, Department of Terrestrial Magnetism Carnegie Institution of Washington, and Washington University at St. Louis. All of these we gratefully acknowledge.

We are particularly grateful to the Office of Naval Research, San Francisco Branch, and to the Atomic Energy Commission, Hanford Works, who have not only given us financial support but have aided us in many other ways over and above the normal expectations. The Bureau of Ordnance, U. S. Navy has made available to us most of the machine tools necessary for the construction of the cyclotron. Many suppliers, too numerous to mention specifically, have given us an unusual amount of technical assistance in the utilization and adaptation of their products. Without this kind of cooperation the machine could not have been built. We accordingly acknowledge this assistance.

2 BUILDINGS AND FACILITIES

The Nuclear Physics Laboratory buildings are located on the extreme northeast corner of the University of Washington campus, and are shown in photographs, figures 2.01 and 2.03.

Figure 2.01 shows the cyclotron building as it was completed in 1949. Half of the 5,000 square foot concrete building is buried in the hillside. A minimum of ten feet of earth has been provided for radiation protection in all directions except on the top of the 40 foot diameter cyclotron room, where there is a pool of water two feet deep. The circular fence encloses the water pool. The floor plan and equipment layout is shown in figure 2.02. The beam chamber is of water tight construction and can be filled with water for shielding or used for experiments along the beam. Preliminary plans have been completed for a 36 x 40 foot laboratory building addition to provide research area and facilities adjacent to the beam chamber.

Figure 2.03 shows the cyclotron shop building. This building is 40 feet by 100 feet, glass walled, radiant heated, and provides the machine tools and electronic facilities for construction of the cyclotron. It is equipped with adequate machine tools required for nuclear research work of this type. Almost all of the machine work is being performed in this shop except for the large vacuum, dee stem, and transition tanks. Before the shop building became available in February 1949, machine and fabrication work on the magnet coils was performed in the basement of Physics Hall.

FIGURE 2.01

The Cyclotron Building



FIGURE 2.02

Equipment Layout - Cyclotron Building

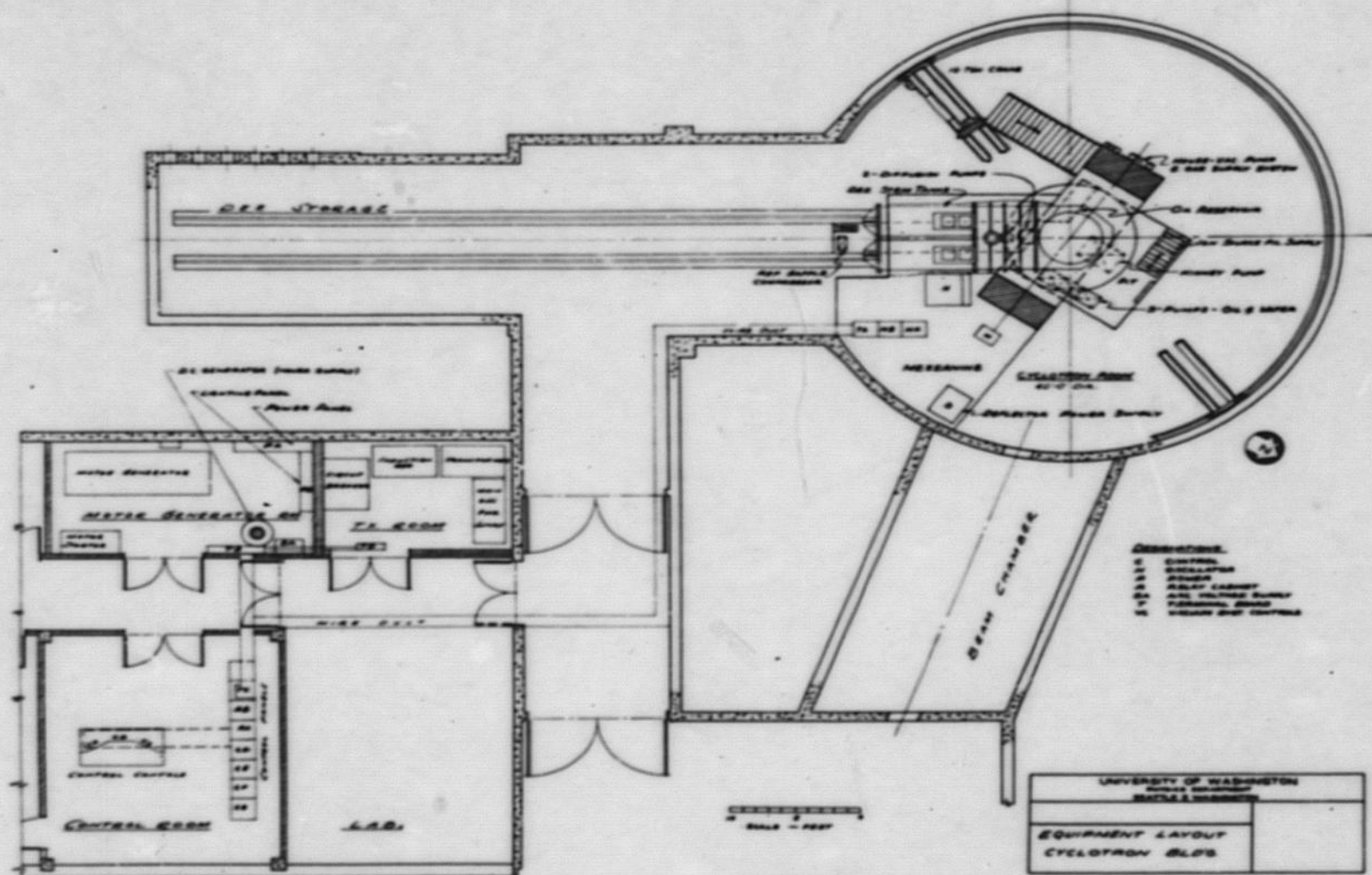
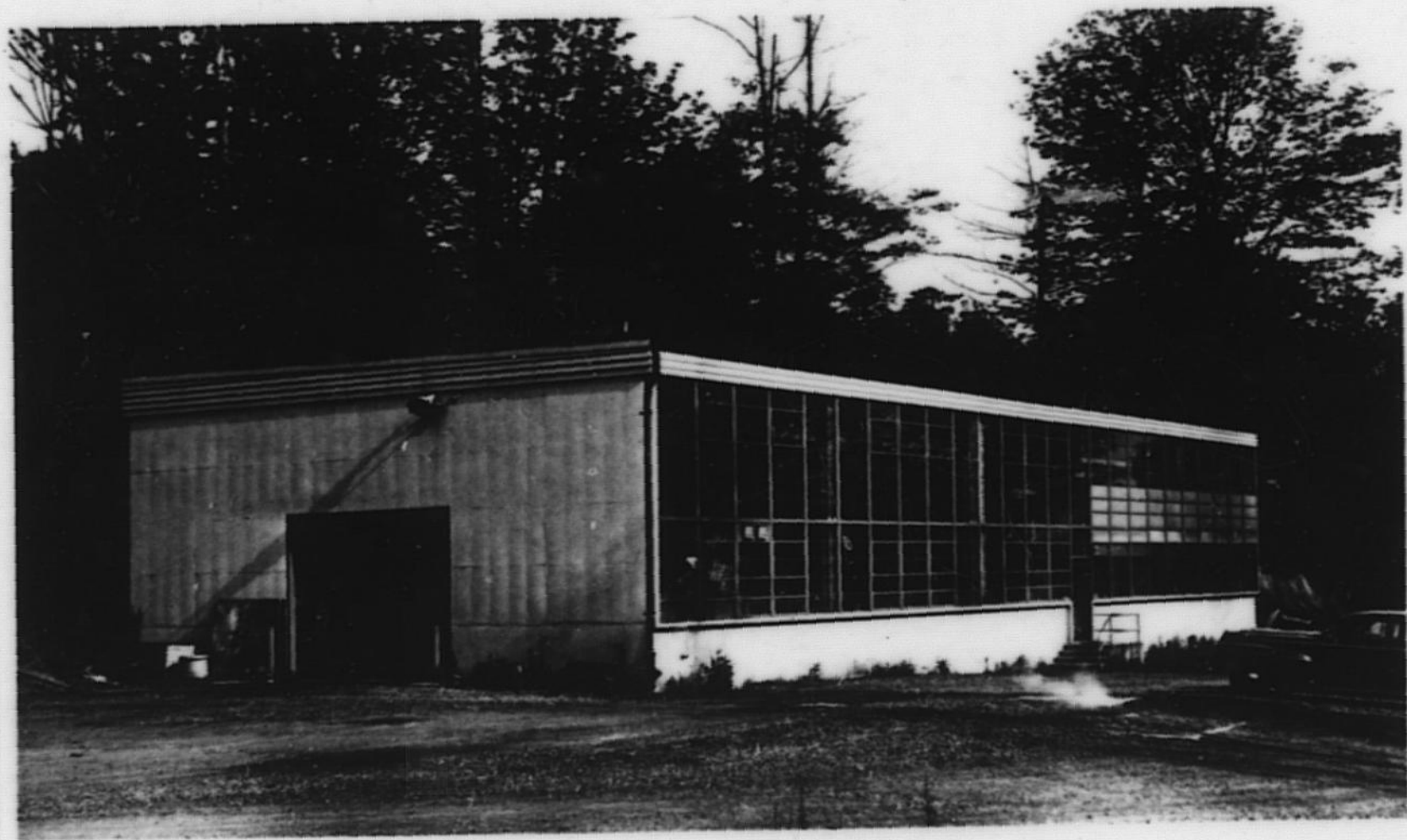


FIGURE 2.02

FIGURE 2.03

The Cyclotron Shop Building



3. MAGNET

3.1 Introduction

For efficient operation of the cyclotron the magnetic field must be of a rather large intensity and must be carefully shaped. The requirements on the shape are: (1) in the median plane the variation of the intensity with radial distance must conform closely to a fairly well defined relation, and (2) inside the exit radius and near the median plane the field must be accurately symmetrical with respect to the axis and with respect to the median plane.

3.2 Magnetization Properties of the Core

Apparently the control of the magnetic properties in the manufacture of steel is rather uncertain. In order to obtain high permeability the manufacturer advised the chemical composition as specified in Table A.

TABLE A

CHEMICAL COMPOSITION OF STEEL FOR CYCLOTRON MAGNET CORE (SPECIFIED)

C	0.15	per cent	maximum	
Mn	0.5	"	"	"
P	0.04	"	"	"
S	0.045	"	"	"
Si	0.2	"	"	"

A Howland ring was machined from a piece of forged steel from the same heat as the cyclotron magnet, and a magnetization curve was determined by the elementary method employing a ballistic galvanometer. The results shown in figure 3.01 were very satisfactory. Values of the magnetic induction at the center of the magnet gap for various exciting currents were calculated by means of elementary magnetic circuit theory and were greater than had been anticipated. These predicted values were later verified by direct measurement. The magnetic induction as a function of current is shown in figure 3.02.

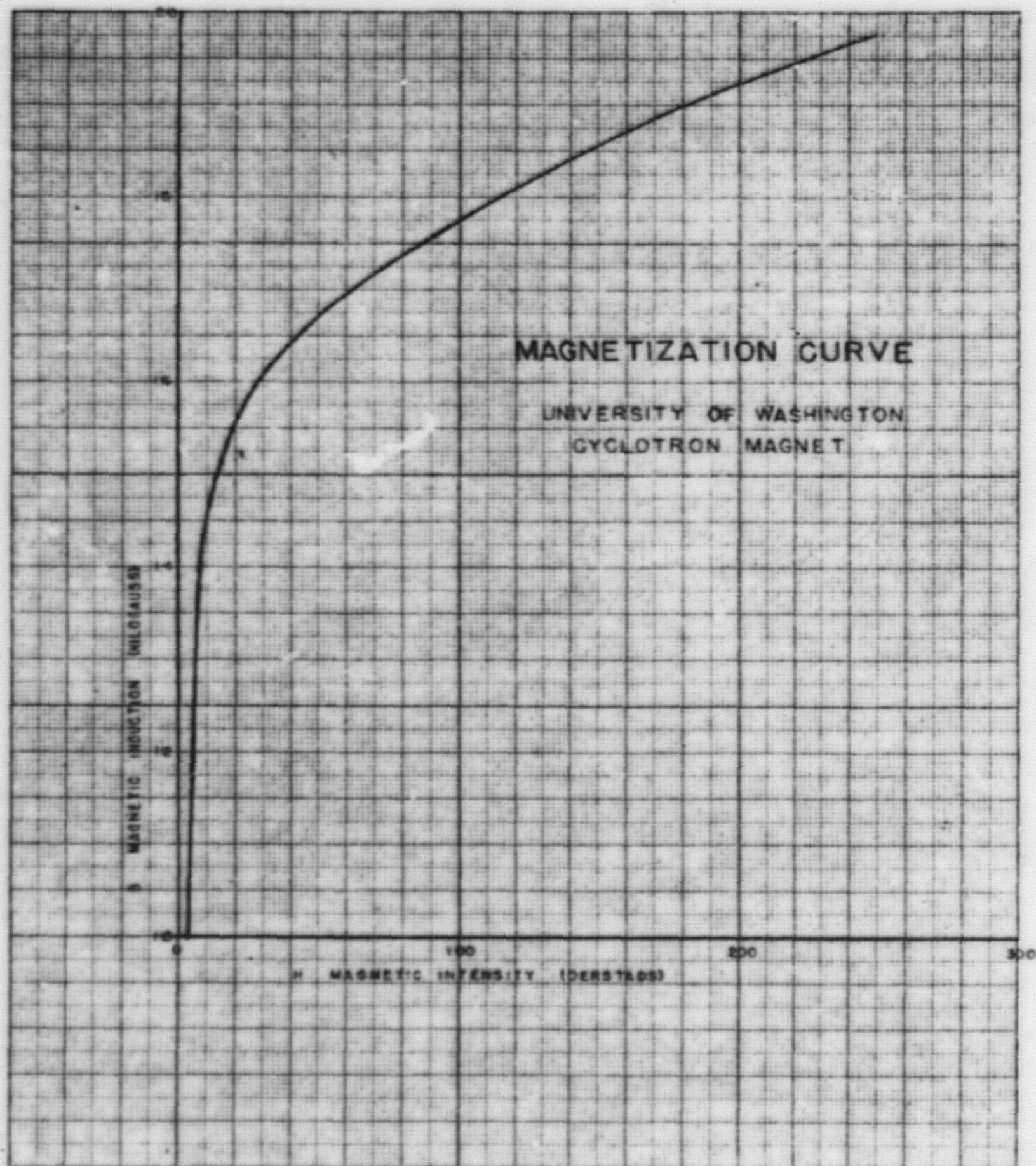


FIGURE 3.01

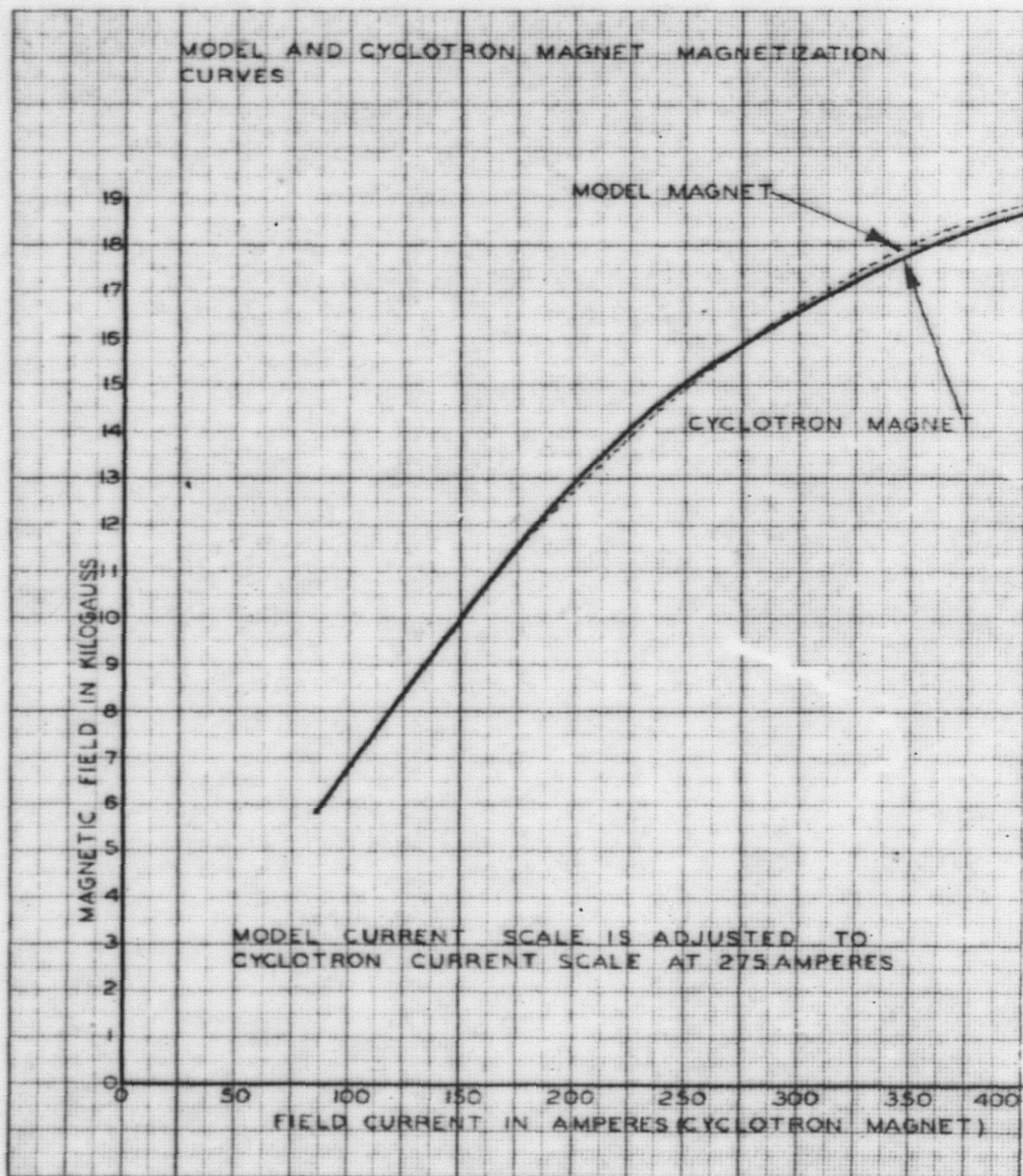


FIGURE 3.02

3.3 The Model Magnet

The first problem was the design of shims which would produce the desired radial dependence with sufficiently intense fields. A one-twelfth scale model of the magnet was constructed for experimental studies of shims. The advantages in using a model instead of the cyclotron magnet were: (1) A variety of shims could be constructed, installed, and tested with considerably reduced expense and working time; this point was emphasized by the possibility of using special alloys which are costly and require heat treatment after machining. (2) The investigation could be carried out before completion of the cyclotron magnet, thus accelerating the construction program. (3) Investigation with a model would remove these activities from the cyclotron itself and eliminate interference with other phases of construction and testing. (4) Some measurements of minor importance could be conveniently carried out with the model. (5) Since it is anticipated that the cyclotron may be radically altered in the future with the introduction of frequency modulation, further magnetic studies may be required which can be carried out with the model while the cyclotron remains in operation.

On the other hand, the use of a small scale model entails difficulties which can consume considerable time and effort. These are principally associated with: (1) the problem of obtaining high spatial resolution in the field measurements, and (2) the problem of heat dissipation in the coils.

In the model program the amount of testing required to arrive at a final shim design was much less than anticipated. This was due in part to the fact that the geometry of parts limited the possible variations more closely than was expected. The final design did not employ any special alloys. Considering all aspects it seems that the advantages

and disadvantages of using the model were fairly closely balanced.

3.31 Model Magnet - Core and Cover Plates

The core of the model magnet was constructed from forgings supplied by The Midvale Company in Philadelphia, Pennsylvania. The steel for both the cyclotron magnet and the model was poured from the same heat and it can be assumed magnetic properties are identical. Except for small details, such as bolts and carrying lugs, the model was a precise one-twelfth scale replica. Its weight is 227 pounds. The cover plates for the model were made of scraps from the plate that was used for the large covers.

3.32 Model Magnet - Coils and Excitation

Since only the gross distribution of the exciting current is important, the detailed structure of the model departs widely from the full scale coils. The construction features are compared in Table B.

TABLE B

SPECIFICATIONS OF MAGNET COILS

	<u>Cyclotron</u>		<u>Model</u>	
Width of Conductor	2.875	2.125	0.375	in.
Thickness of Conductor	0.125	0.1875	0.0625	in.
Number of Turns per Pie	110	76	20	
Number of Pie per Coil	6	2	3	
Number of Turns per Coil		736	60	
Number of Coils		2	2	
Total Number of Turns		1472	120	
Current (rated)		400	409	amp.
Magneto-Motive Force		588800	49070	amp.turn
Resistance		1	0.0733	ohm
Potential		400	30	watt
Power		160,000	12,270	watt
Temperature Rise		11	5	° C.

In scaling a magnetic device the gross current density varies inversely as the linear dimensions and the heat generation per unit volume varies as the square of the current density. Therefore, in the model the problem of heat dissipation is a serious one. Each coil was enclosed in a

tank and cooled by direct contact with water flowing at the rate of 10 GPM and the resulting temperature rise was only 5° C. with continuous operation. This effective cooling was achieved, however, at the expense of structural support and when tests were essentially completed, the supporting structure for the coils failed, presumably under the magnetic forces. The coils became distorted and short circuits developed. The coils will be rebuilt when shop time is available. The model magnet is shown in figure 3.03. A motor-generator set supplied the direct current. The differential method of measuring the field described below made close regulation of the current unnecessary and a manually operated field rheostat provided satisfactory control. Figure 3.04 shows the arrangement of the apparatus.

All field measurements with the model magnet were made with flip coils indicating on a fluxmeter (General Electric Fluxmeter Cat. #32C247, #32C248), and calibrated with a standard mutual inductance. Absolute values of the induction at the center of the gap were measured with an accurately constructed flip coil of 2 turns wound on a radius of 0.25 inches which is shown in figure 3.05. The measured values were about 20 per cent smaller than predicted on the basis of the Rowland ring measurements. This discrepancy was the result of short circuits which developed soon after the model was put into use. Limitations imposed by the generator did not permit increasing the current to compensate. However, the simple expedient of placing additional steel around the outer face of the magnet yoke raised the field in the gap to its proper value without affecting its shape appreciably and the model was used with this modification.

3.33 Model Magnet - Instrumentation for Radial Dependence of Field

An accurate determination of the radial dependence of the magnetic induction is important only out to the point where the induction has decreased

FIGURE 3.03

MODEL MAGNET

This photograph shows the core, coil tanks, and cooling water connections. The threaded nuts on the coil tanks are electrical terminals.

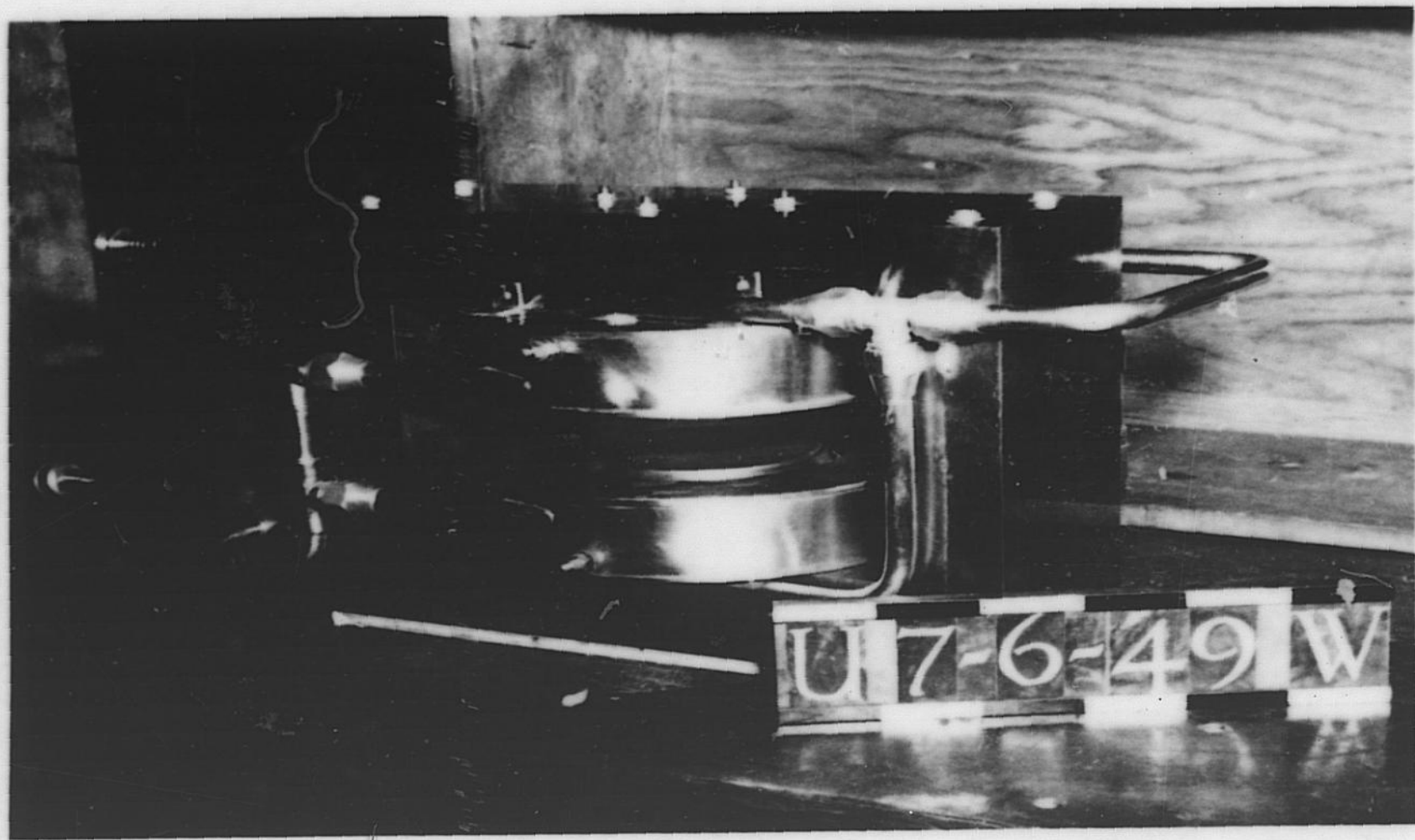


FIGURE 3.04

MODEL MAGNET OPERATING SET-UP

The photograph shows from left to right: generator (30 volt, 400 amp.), overload circuit breaker, resistance box in ammeter circuit, voltmeter, ammeter, model magnet, water cooling connections with thermometer and pressure gauge, and field rheostat.

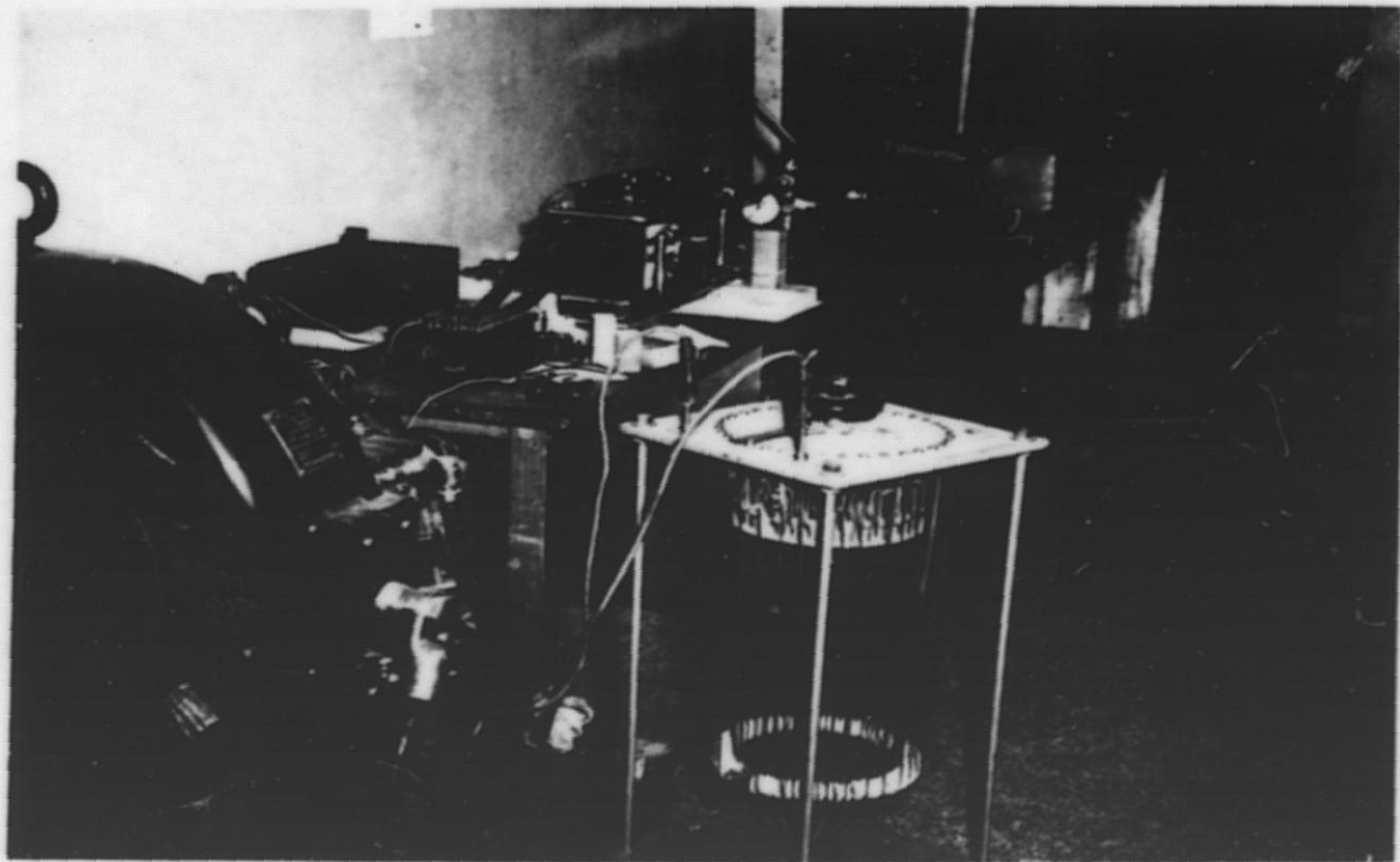
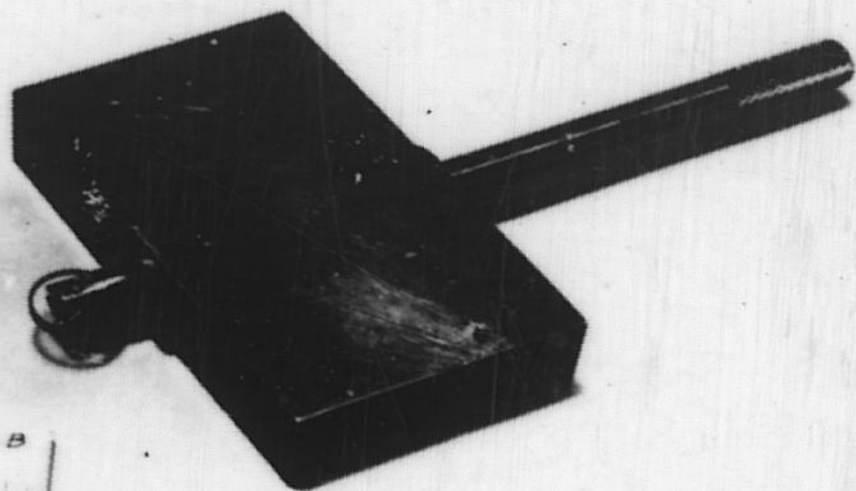
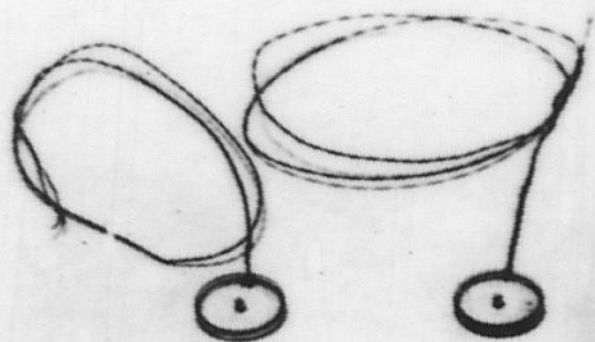


FIGURE 3.05

SEARCH COILS AND COIL HOLDER FOR MEASURING MAGNITUDE OF MODEL MAGNET
AND CYCLOTRON FIELDS

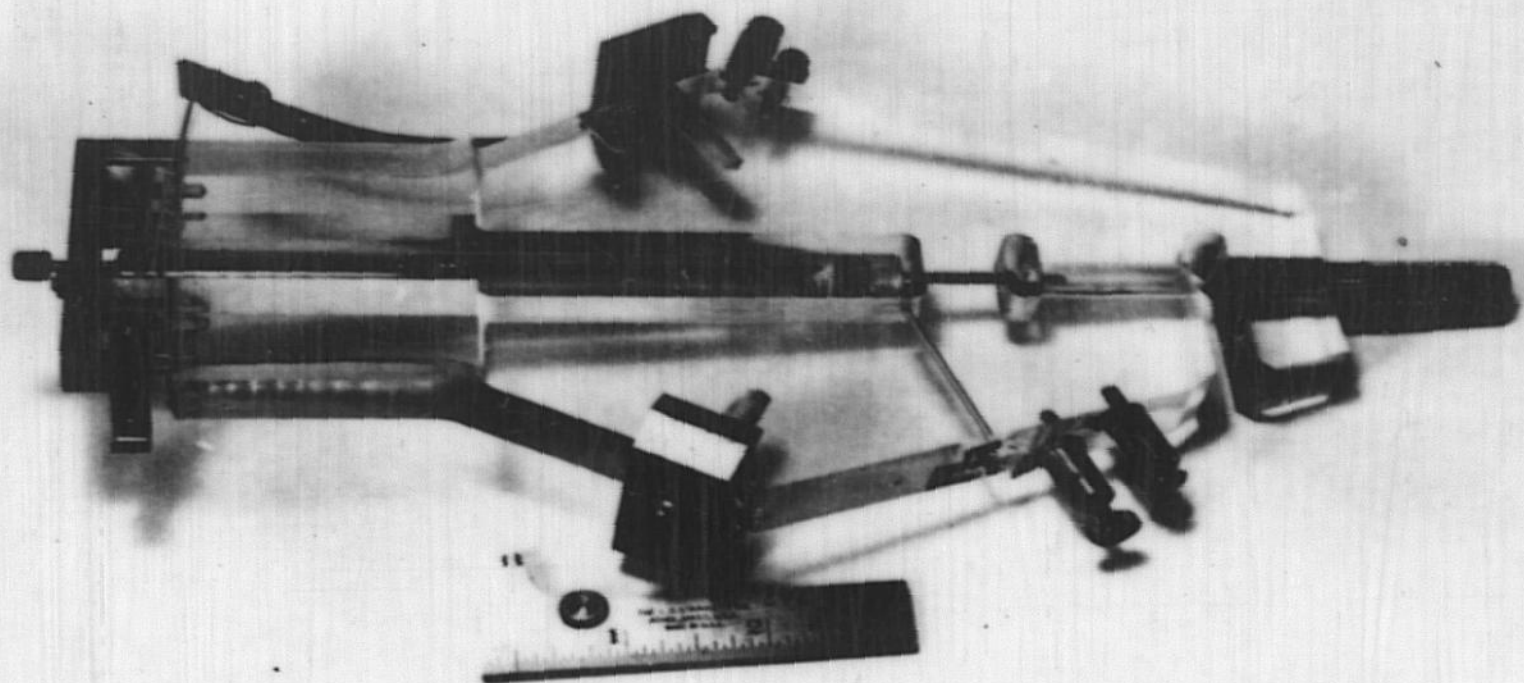
The coil is turned through 180 degrees by hand and the lead-
in wires are brought out through the hollow stainless steel tube.



by about 4 per cent from its value at the center. A precise measurement of relative values is required, but a moderately accurate measurement of absolute values is sufficient. The following differential method was therefore indicated: Two small flip coils were connected in opposition in a circuit with the fluxmeter. The flip coils were roughly spherical, with diameters of .17 cm, effective areas of 36 cm^2 , constructed as closely identical as possible, and finally adjusted to have nearly equal effective areas. The two coils were mounted in a shaft, whose axis was in the median plane, and consequently were rotated simultaneously through equal angles. One remained permanently at the magnet axis, while the second, sliding on ways along the axis of the shaft, was advanced to any selected radial distance by means of a lead screw carried in the shaft. The cancellation of the major portion of the electromotive force generated in each coil permits high sensitivity in the measurement. To establish a percentage scale it was necessary to make an observation using only the fixed coil and with reduced sensitivity. The mechanical construction prevented readings for points nearer to the axis than 0.4 inches, corresponding to 5 inches on the cyclotron magnet, but the data justified confidence in the extrapolation to zero radial distance. This differential method eliminates the importance of many instrumental imperfections which would seriously affect determinations made with a single coil, such as drifting of the exciting current, inaccurate flipping, inconstancy of the fluxmeter, and temperature effects. Difficulties were encountered in securing in the flipping mechanism the necessary strength and rigidity within the small available space and in making electrical connections with wire pairs which were tightly twisted, well insulated, light, and flexible. The experimental set-up is shown in figure 3.06.

FIGURE 1.06

Apparatus for Measuring Radial
Dependence of Field in Model Magnet



3.34 Magnet Magnet - Design of Shims

The experiences of other cyclotron groups and consideration of theoretical discussions led to the following preliminary formulation of the problem of shaping the magnetic field: (1) Inside the exit radius the field should be as uniform as possible and specifically it may decrease by 1 per cent from its value at the center. (2) If a central spike is used as described below, one must take as the value at the center an extrapolated value, in which the effect of the spike is ignored. (3) Between the center and the exit radius the decrease must be monotonic. (4) Outside the exit radius the field should decrease as rapidly as possible and specifically at the exit radius the parameter $n = -(r/B)(dB/dr)$ shall have the value 0.4. (5) The exit momentum, as measured by the value of B_r at the exit radius, shall be as large as possible and consistent with these requirements. The space available for shimming inside the vacuum tank was an annular ring against each vacuum tank cover plate. The inner radius was 25.75 inches, width 3 inches, and height 1 inch.

The first shim tested occupied the entire available space. It had a cross-section equivalent to 1 inch x 3 inches on the cyclotron magnet. This was followed by four other shims having cross-sections with smaller areas and various shapes. The field area near the exit radius was sensitive to both the area and the shape of the cross-section. External shims in the one-half inch gaps between pole faces and cover plates were found to have no appreciable added effect, and were not included in the shim design. These studies indicated for the optimum shim design a rectangular cross-section equivalent to $5/8" \times 3"$. With a field of 15,000 gauss the exit radius was 25 inches.

At the conclusion of the tests it became apparent that this solution would result in a value of the exit momentum larger than had

been originally anticipated and that this large value would demand a de-voltage above the value that could be expected with reasonable certainty. Unfortunately, with this shim design a reduction of the exciting current produced a minimum in the radial dependence, which is an objectionable feature. A compromise solution was therefore adopted. A 3 inch x 1/2 inch shim was used, and 25 inches was selected as the exit radius. With this shim the sharpness of the transition at the exit radius was reduced, but it is believed that the field will have a useable shape for values of the induction between 13,900 and 15,000 gaussess. At these fields the induction at the exit radius is reduced from its central value by 1.2 per cent and 2.2 per cent respectively.

3.35 Model Magnet - Incidental Measurements

The model magnet was useful in making two minor measurements:

(1) The stray field at the location of the oscillator tube was measured, which datum was the basis for the design of a magnetically shielding box for the tube. (2) The magnetic force on the cover plates, a matter of importance in connection with the structural design, was investigated and the results indicated a force greater than 35 tons for the cyclotron magnet. For comparison the force of atmospheric pressure is 24 tons.

3.41 Cyclotron Magnet - Radial Dependence of Field

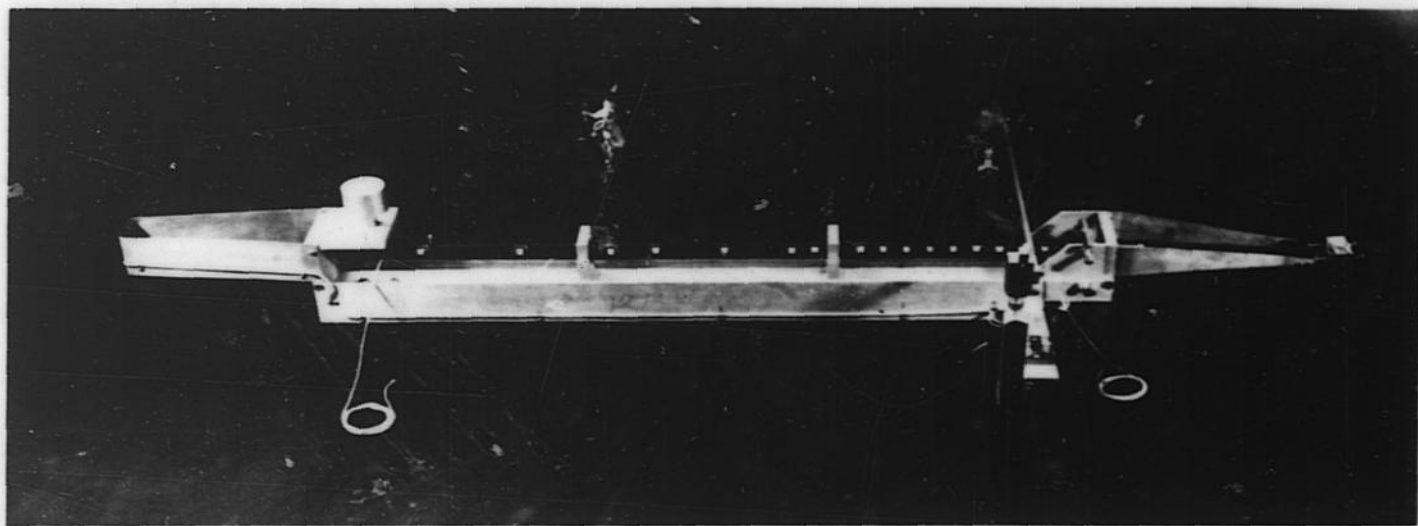
It was considered necessary to make field measurements of the radial dependence directly on the cyclotron magnet rather than to rely on the results of the model work. The same scheme, employing a pair of differentially connected flip coils, was employed. Figure 3.07 shows the apparatus. The coils were of 28 turns with an average radius of 0.607 cm. With the larger equipment the mechanical difficulties were greatly reduced.

The first measurements were of the radial dependence without shims. The results were in close agreement with similar data obtained

FIGURE 3.07

APPARATUS FOR MEASURING RADIAL DEPENDENCE OF FIELD IN CYCLOTRON MAGNET

The aluminum cylinders to the left are secured at the center of the gap and the brass framework to the right is engaged with the edges of the pole faces in order to position the apparatus in the gap. The search coils are inside the bakelite tube. The movable coil is shifted by means of the strings shown coiled at each end, and can be locked in place by the brass peg extending through the holes in the tube and into the coil. Lead-in wires are held at a constant tension and restrained laterally by the sheet brass holders at each end of the device. The bakelite tube turns through 180 degrees when the catch on the right is released.



from the model as may be seen from figure 3.08, and showed that the model data could be used as a basis of prediction with confidence. Shims for the cyclotron magnet were constructed in accordance with the design mentioned above. The predicted radial dependence was verified and the results were considered satisfactory.

3.42 Cyclotron Magnet - The Central Spikes

After the construction of the shims for the cyclotron magnet information was received from the University of California concerning the remarkable increase in beam current in the 18 1/2 inch cyclotron resulting from the introduction of central spikes. The function of the spikes is to produce a sharp increase in the induction at the center of gap without producing a minimum anywhere in the radial dependence. The space available for such a spike was limited, and it seemed certain that the largest possible spikes would still be smaller than the optimum size. Spikes were installed which essentially filled the available space. Each consists of a cone-topped cylinder with a radius of 1 1/2 inches and 1/4 inch height for both cone and cylinder. The final curves of the radial dependence presented in figure 3.09 show plainly the effect of the spikes.

3.43 Cyclotron Magnet - Measurements of Azimuthal Variation

With the field properly shaped in its main outlines it remained to discover and correct any appreciable asymmetries. Such imperfections might be expected to result from: (1) the unsymmetric shape of the magnet core, (2) a number of unavoidable small asymmetrical features of the steel construction, notably the bolts securing the one-inch thick sections of the cover plates, the screws holding the copper liners, and a gap where the shim is relieved to accommodate water lines, (3) accidental asymmetries in the construction and placing of the coils, and (4) non-uniformities in

MAY 12, 1950

CURVES ARE DISPLACED VERTICALLY FOR CLARITY

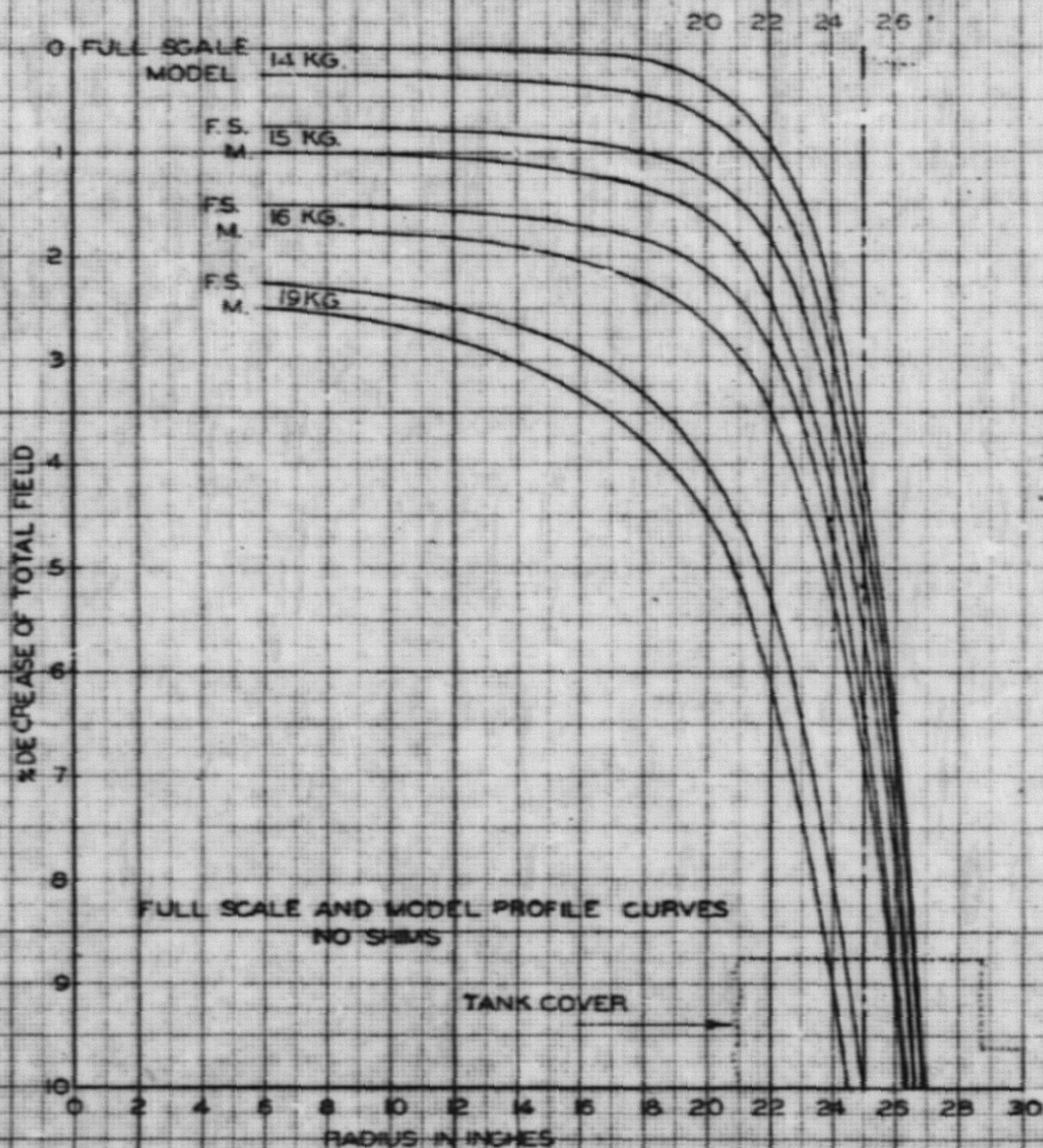


FIGURE 3.08

0.0% POINT OF EACH CURVE IS 0.25% BELOW THE PRECEDING CURVE
AND IS LOCATED AT 15 INCHES RADIUS

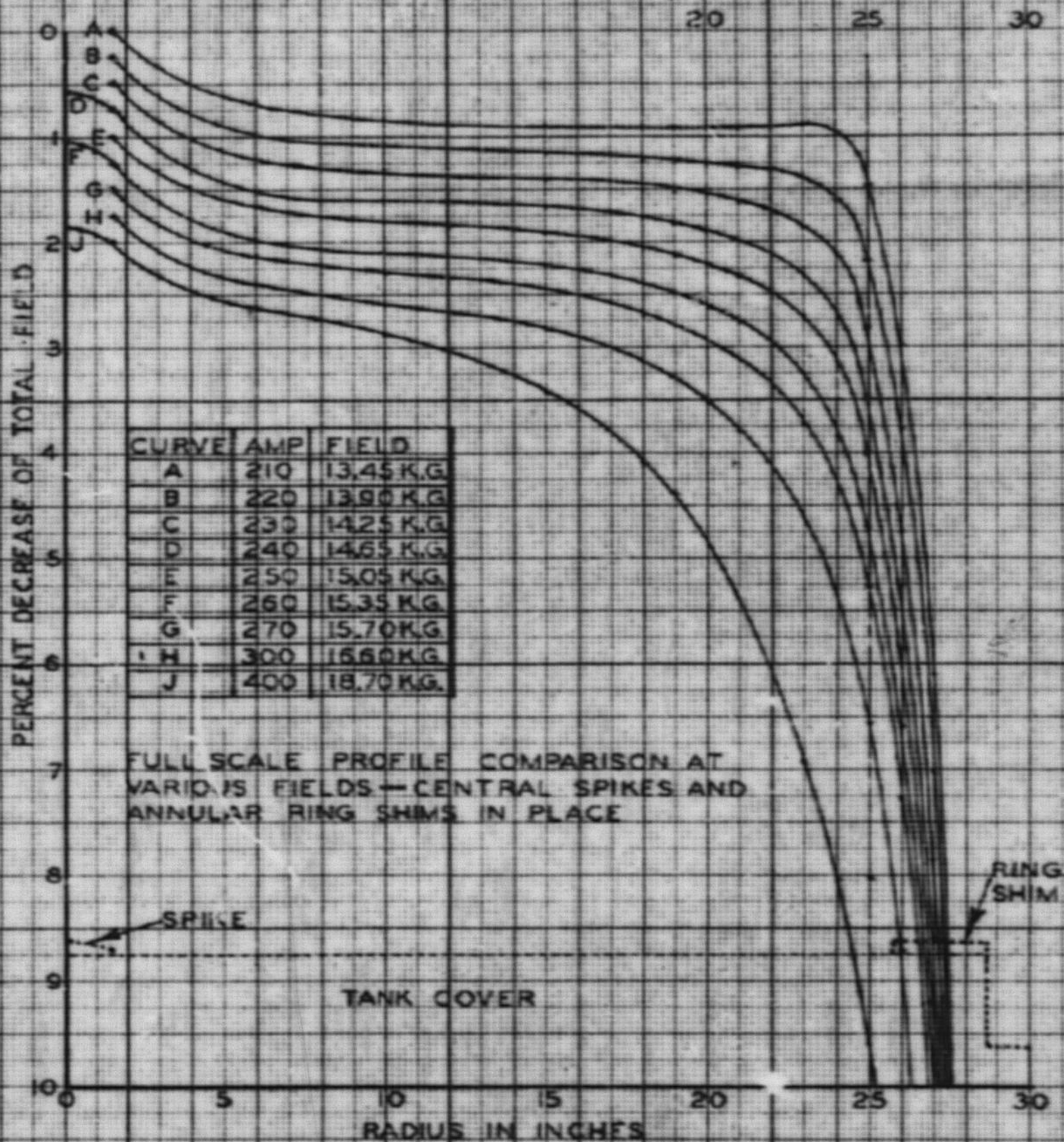


FIGURE 3.09

the steel of the core and the cover plates. To determine the azimuthal dependence of the field in the median plane at various radii the following instrument was constructed. It consists of a beam with suitable clamping and leveling attachments capable of rotating about an axis coinciding with the axis of the magnet. The beam carried a coil of 1000 turns wound on a 1-inch diameter spool, located in the median plane at a variable distance from the axis of rotation, and with its axis parallel to the axis of rotation. With the beam in rotation any azimuthal variation of the field generates an electromotive force in the coil. Also, where the field is uniform and connected in opposition, a similar coil mounted close to the axis served to cancel almost exactly any electromotive force induced by fluctuations of the exciting current. This part of the instrument is shown in figure 3.10. Connections were made through a pair of twisted leads running along the axis of rotation and out to a recording fluxmeter (General Electric Photoelectric Recorder Cat. #320114). The drive of the recorder was geared to one of a pair of selsyn motors as shown in figure 3.11. The other member of the pair through a gear and pulley system drove the rotating beam in coordination with the recorder tape. The period of rotation was 140 seconds. The device proved to be capable of detecting an increment of 0.01 per cent equal to 1.5 gauss in the magnetic induction with a resolution of one inch. With this device data was rapidly collected and immediately interpreted. A total of 100 runs were made.

Most of the measurements were made with the vacuum tank open, but in order to observe the effect of atmospheric loading on the vacuum tank, several measurements were made with the tank closed and evacuated. For these measurements the selsyn motor driving the beam was mounted in the des stem tanks within the vacuum system but outside the field. No

FIGURE 3.10

APPARATUS FOR MEASURING AZIMUTHAL VARIATION IN CYCLOTRON MAGNETIC FIELD

The horizontal beam carrying the search coil shown at the extreme right turns freely on its vertical axis which can be made perpendicular to the magnet pole faces by means of adjusting screws in the triangular base plate. The vertical position of the beam is adjusted by the horizontal arm at the top of the instrument. Lead wires from the coil are brought down through the hollow spindle and connect to a terminal strip on the base plate. To the left of the base plate is shown the selsyn motor and a small cylindrical drum which is turned by the motor shaft through reduction gears. The small cylinder is linked to the large drum by a dial cable. The selsyn motor can be mounted outside the magnetic field thus providing a means for synchronizing the rotation of the beam with the tape drive on the recorder.

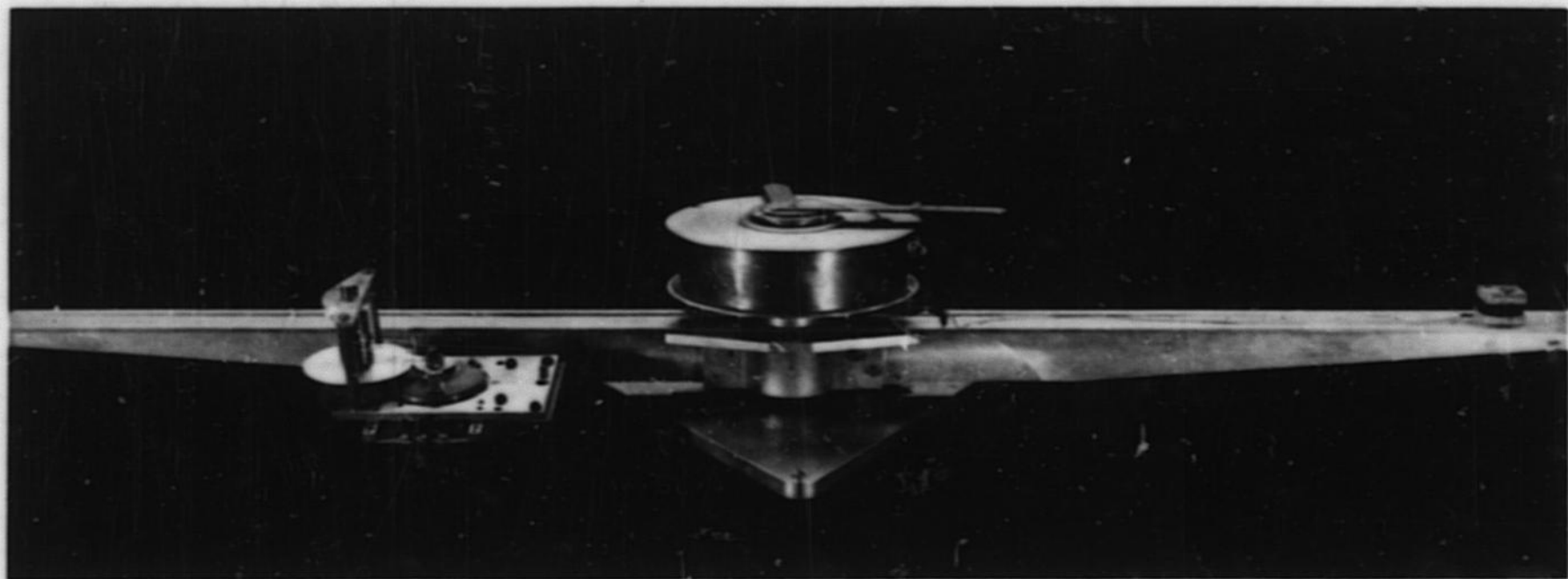
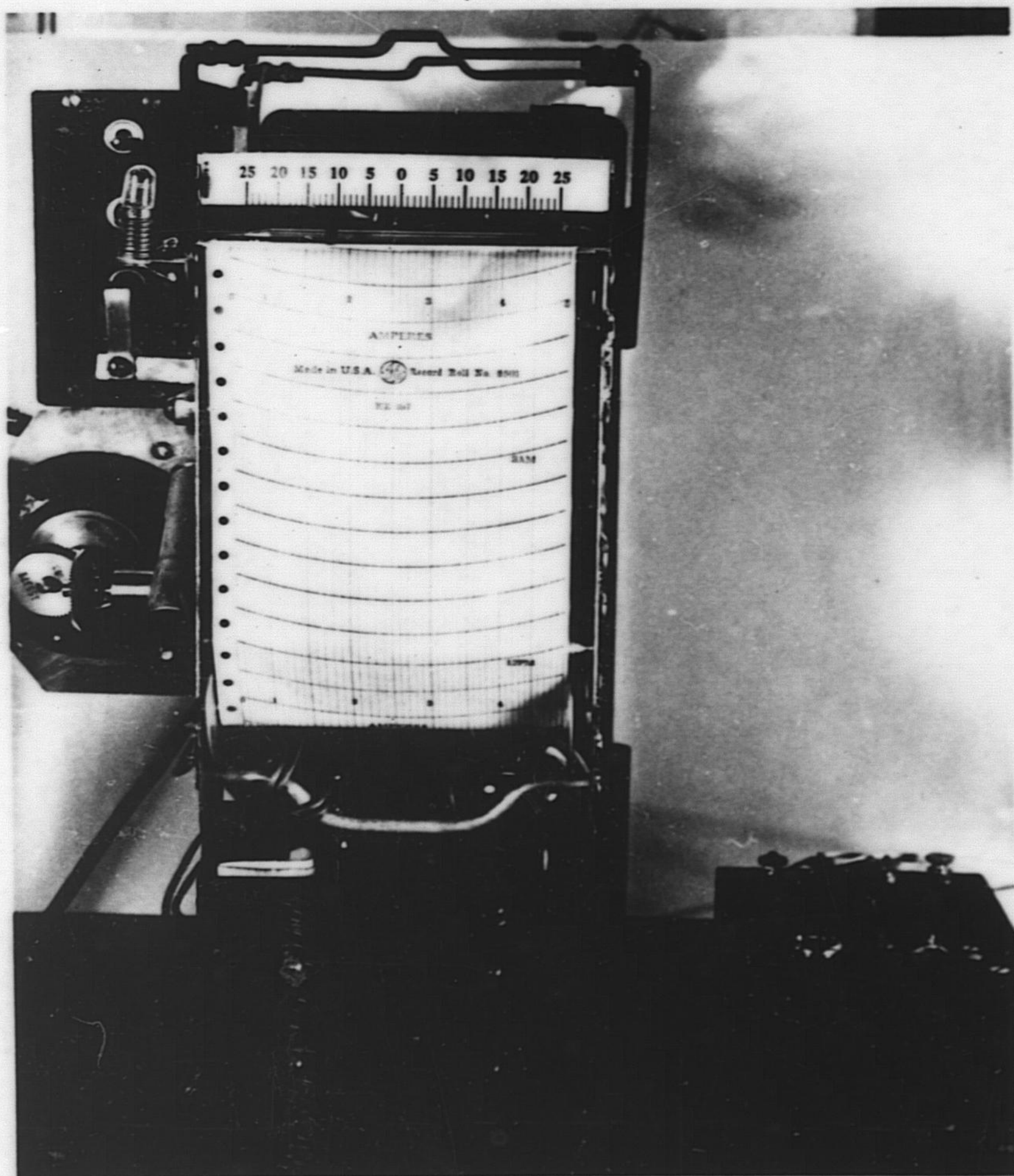


FIGURE 3.11

RECORDER WITH SELSYN MOTOR AND CONTROL BOX

A commercial General Electric photoelectric recording flux-meter has been modified to permit the clockwork to drive a selsyn motor. The control box shown on the right is used to correct galvanometer drift and to control the position of the tracing pen at the start of a measurement. The small electric lamp indicates the time at which the search coil is at the starting position.



effect associated with the evacuation was detected. Since the magnetic forces greatly exceed the atmospheric forces and pull the cover plates tightly into locations determined by spacing shims which had been inserted in the air gap, this was as expected.

3.44 Cyclotron Magnet - Correction of Azimuthal Variation

The first set of measurements revealed a consistent 180° variation of the magnetic induction which was qualitatively the same at all radii. These measurements indicated some nonparallelism between the faces of the poles and the cover plates. Previous mechanical measurements had shown that the pole faces were parallel within 0.007 inches while the cover plates deviated from parallelism by 0.031 inches in just such a direction as would account for the variation of the magnetic field. The correction of this condition had been delayed with a view toward using the adjustment to correct the field and this correction was made the criterion for final adjustment rather than reference to mechanical measurements. As a first attempt to correct the field, spacing shims which were designed to hold the inner faces of the cover plates accurately parallel were inserted into the air gap between pole faces and cover plates. The variation was greatly reduced, but a small component of the original gradient remained. This was successfully eliminated by additional spacing shims of the order of 0.001 inches in thickness which were estimated by extrapolating the effects of the first set of spacing shims.

Remaining imperfections in the field were corrected by the insertion of mild steel external shims into the one-half inch air gap between pole faces and cover plates. Eventually a condition was obtained beyond which further improvement was impossible because an attempt to correct the field at one point has extended influence. The effectiveness of these correction procedures is shown in Table C.

TABLE C

EXTREME AZIMUTHAL VARIATION OF MAGNETIC FIELD OF CYCLOTRON
Central Field = 15 Kilogausses

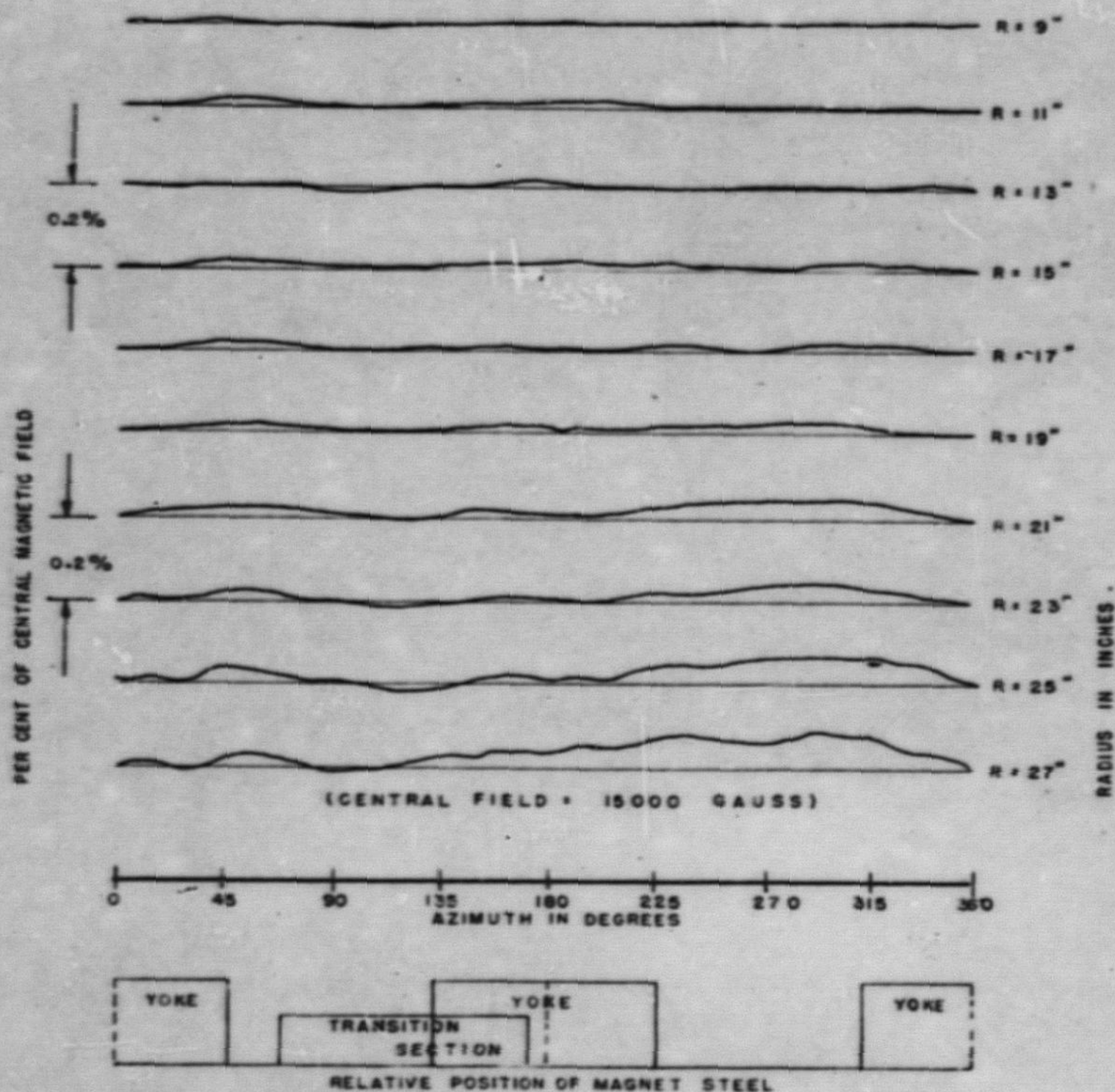
<u>Radius (in.)</u>	<u>Original Data</u> <u>Per Cent</u>	<u>Tank Covers Parallel</u> <u>Per Cent</u>	<u>Final</u> <u>Per Cent</u>
5	.045	—	—
7	.056	.027	—
9	.071	—	.002
11	.097	.036	.002
13	.137	—	.025
15	.146	.059	.027
17	.168	.064	.027
19	.199	.069	.032
21	.228	.090	.041
23	.291	.125	.074
25	.420	.231	.103
27	.496	.344	.132

The most significant value of the extreme variation probably corresponds to a radius of about 21 inches, because at smaller radii the field is uniform, while larger radii correspond to the conclusion of the acceleration process where misdirection of the beam does not have serious consequences. The azimuthal variations at various radii after final adjustment are presented graphically in figure 3.12.

3.45 Cyclotron Magnet Median Surface - Dipping Needle Observation

The median surface is the locus of points at which the magnetic induction is vertical. Ideally the median surface will be the plane parallel to and midway between the pole faces. Apparently, it is not unusual to find appreciable deviation from the ideal in an uncorrected gap. While it is not known what deviation may be tolerated, it is clear that any reduction of the deviation is highly desirable. Correction of the azimuthal variation will usually also improve the shape of the median surface; however, the two problems are basically separate and an azimuthally symmetric field may still have a dish-shaped median surface.

A dipping needle was constructed of a soft iron rod of a



AZIMUTHAL VARIATION OF MAGNETIC
FIELD IN MEDIAN PLANE

FIGURE 3.12

diameter of 0.10 inches and a length of 1.50 inches mounted on a horizontal silk thread under tension and carrying a small mirror. The rotation about the axis was determined by observing through a telescope the image in the mirror of a vertical scale. The field near the center of the gap was found to be very uniform and was taken as the reference direction. To measure the height of the median surface above the midplane the entire system was raised by means of screws until the scale reading indicated that the field was parallel to the reference direction.

The height was observed as a function of azimuth at a number of different radii and was plotted in figure 3.13. A consistent departure of the median surface from the midplane is in evidence, but it was considered that the small departure of 0.5 inch maximum would have no appreciable effect. Therefore, no attempt was made directly to improve the shape of the median plane. Later shimming to correct the azimuthal variations was entirely symmetrical with respect to the midplane and could have no appreciable effect on the median surface.

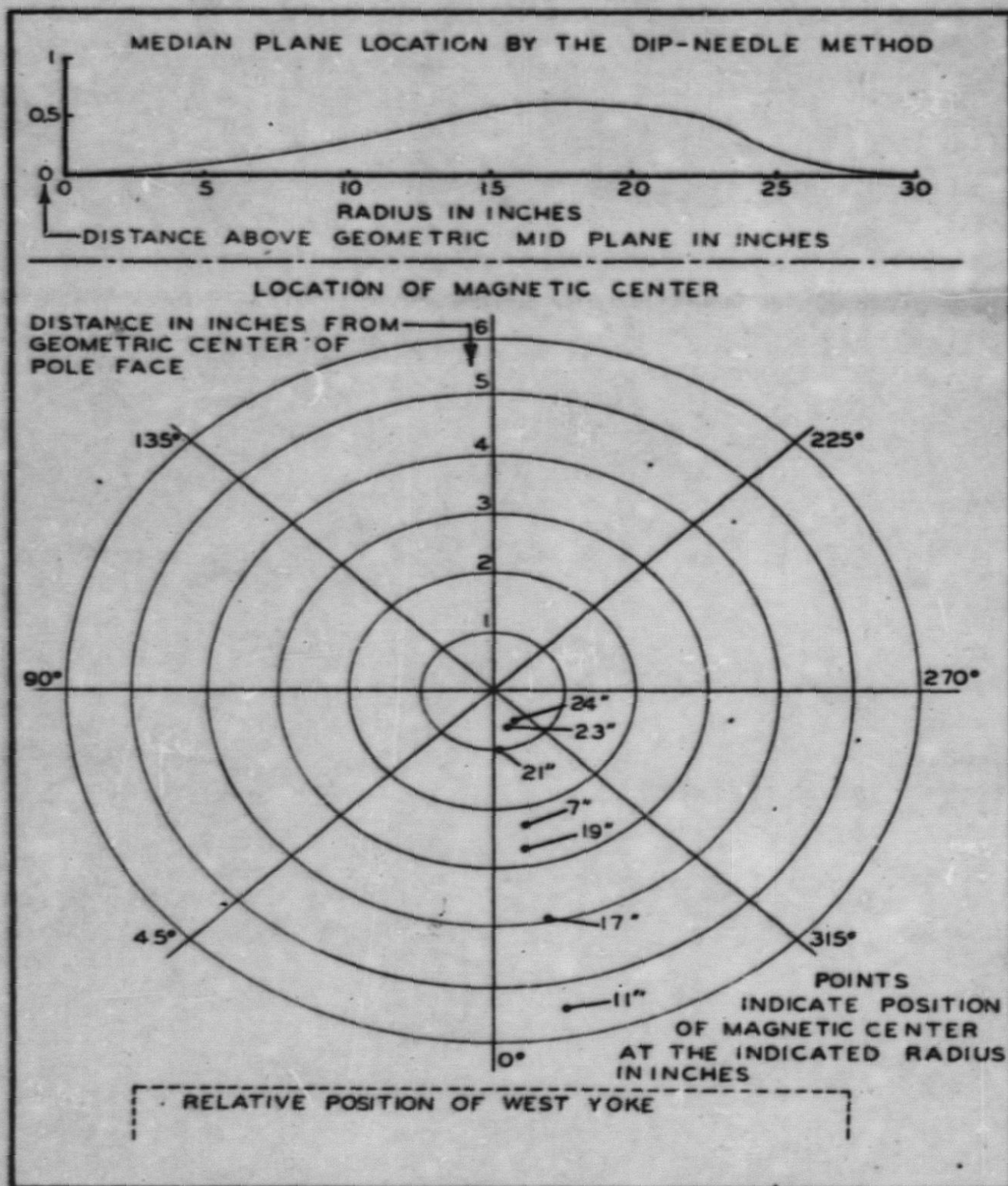


FIGURE 3.13

4. VACUUM TANK

The vacuum tank houses the accelerating electrodes, or dees, and also the ion source and capacity compensator. The finished tank is shown in photograph, figure 4.01. It is 5'-10" long, 6'-0" wide, and 17 inches high, having circular openings 4'-8" diameter in top and bottom. The tank was made of 2 1/2" thick 61S-T4 aluminum, heliarc welded (with argon gas) here, and machined in an outside shop. Aluminum was chosen over stainless steel because of its short half-life property. This tank with the 1" aluminum side covers has been repeatedly pumped down and found to be vacuum tight at 2×10^{-6} mm. of Hg. Berkeley standard double groove gaskets with pump outs were used on all joints.

The vacuum tank covers are of the same heat of mild steel as the magnet forgings and consist of a 4 1/2-inch thick plate with a 1-inch plate attached by screws. The covers are shown in figure 4.02.

FIGURE A.01

The Aluminum Vacuum Tank

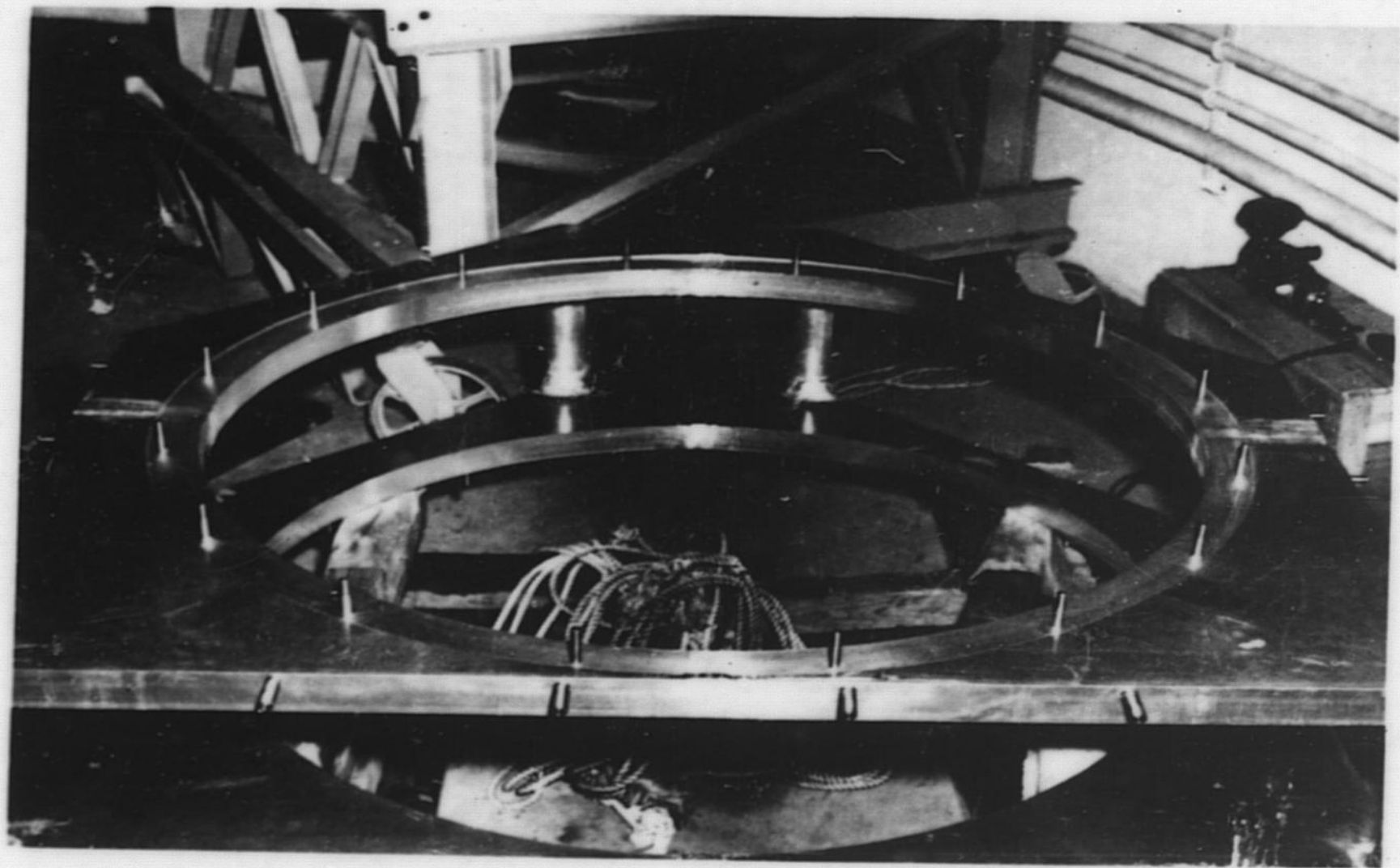
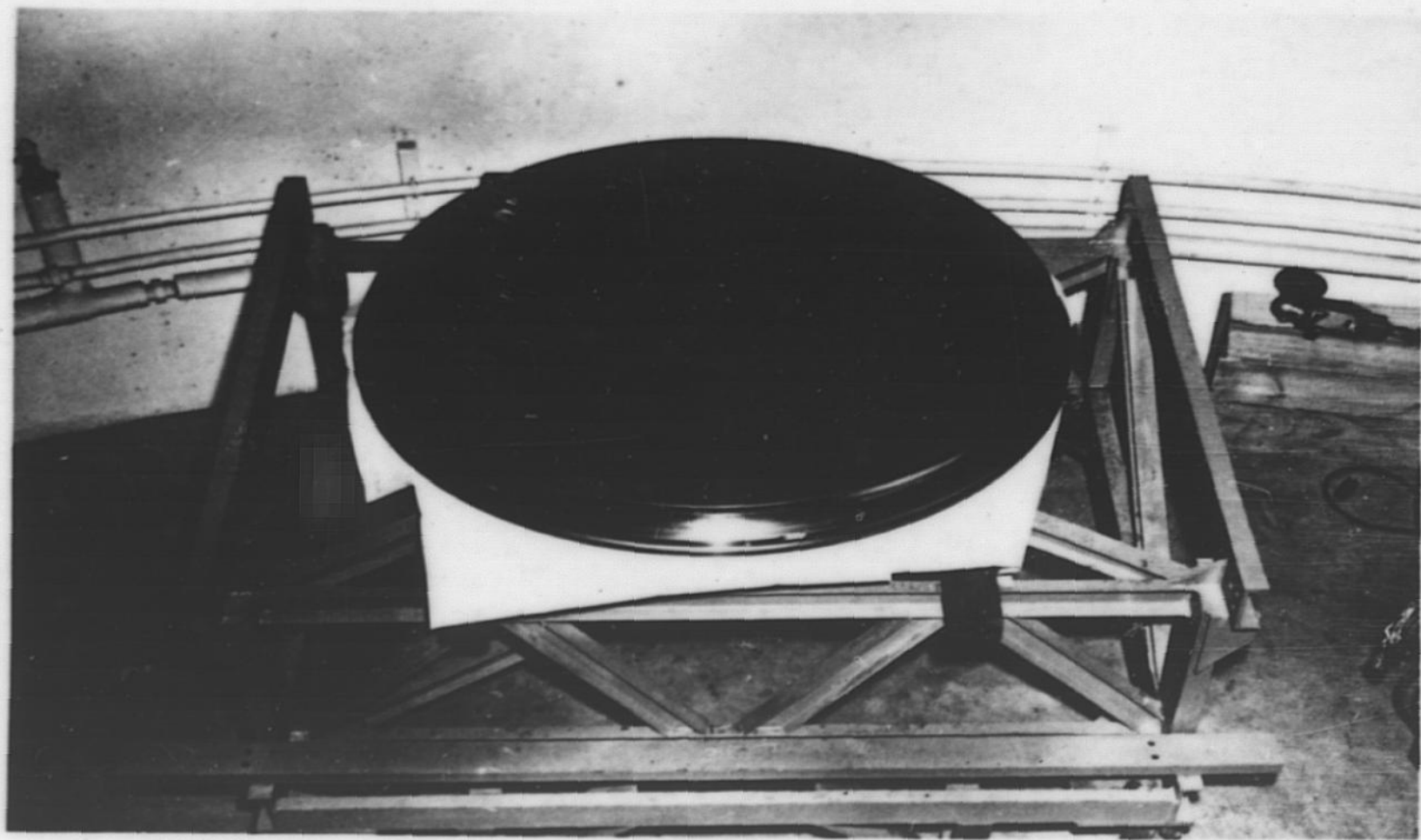


FIGURE 4.02

One of the Vacuum Tank Covers



5 VACUUM SYSTEM

5.1 Vacuum Envelope

The main vacuum envelope consists of the vacuum tank, a transition section, and two dee stem tanks. The general arrangement of these components is indicated in figure 5.11. The vacuum tank will support the deflector, probe target, ion source, target chamber, capacity compensator, and dee voltmeter pickups. The transition section is an externally ribbed, welded, stainless steel structure which connects the vacuum tank to the two cylindrical dee stem tanks and to the vacuum pumping system. The dee stem tanks are rolled and welded steel tubes. The volume of the entire tank is approximately 4800 liters.

5.2 Pumps and Piping

The vacuum pumping system consists of a 20-inch oil diffusion pump (D.P.I. MC-7000) and its associated 6-inch booster pump (D.P.I. MB-200), a Kinney DVD 8810 mechanical pump, and a Cenco Hypervac 23 mechanical pump which serves primarily as the so-called house vacuum system pump but which may be used if necessary as a holding pump for the oil diffusion pumps.

The valve and piping arrangement is shown schematically in figure 5.11. The piping from the MB-200 pump to the Kinney is made in sections of 3-inch seamless steel tubing welded to standard welding neck pipe flanges. The two air operated valves are electrically controlled by means of four-way solenoid valves and double acting air cylinders with regulators for setting the speed of valve motion.

5.3 Gaskets and Seals

Double gaskets with a pump-out space between the two gaskets are used wherever possible for making seals at the joints in the system. Single stuffing box type gaskets are used to seal around water lines,

ion gauge tubes, and the R. F. loop insulators and loops, and single flat gaskets are used under the larger viewport windows.

Double non-moving seals are of three general materials: (1) Garlock style 8474 hycar rubber, (2) molded hycar sandwich gaskets, and (3) standard O-rings.

Chevron seals are used on moving shaft seals although some smaller moving shafts are sealed with O-rings.

5.4 Operation and Performance

Initial testing of the system disclosed two leaks in welds, both of which were in stainless to mild steel joints. Leaks have also been found in two of the single gasket stuffing box type seals and in one of the single flat gasket seals, the latter being caused by failure of the rubber itself.

The lowest pressure attained during the initial testing of the system was 2×10^{-6} mm. of Hg. This pressure was reached without the aid of vapor traps or the refrigerated baffle. Installation of the copper tank liners, R. F. loops and loop insulators approximately tripled the interior surface area and the lowest pressure that has been attained under this condition is 4×10^{-6} mm. of Hg.

Some approximate pumping speed measurements were made in order to determine the optimum power input to the diffusion pump heaters. The results of these measurements for input powers of 3100 watts and 825 watts to the MC-7000 and MB-200 pumps respectively are shown in figure 5.41.

Total pump-down time is approximately 1 hour, 45 minutes being required for the Kinney pump to reduce the pressure to 50 microns and an additional 10 to 15 minutes being required for the diffusion pumps to reduce the tank pressure to less than 2×10^{-5} mm. of Hg.

VACUUM SYSTEM
PUMPING SPEED

FIGURE 541

Pressure (mm-Hg)	Pumping Speed (Liters/Sec.)
1.5×10^{-6}	~50
2.5×10^{-6}	~1100
5×10^{-6}	~2300
1.5×10^{-5}	~3000
4×10^{-5}	~3500

5.5 House Vacuum System and Gas Supply System

The principal elements of these systems and their valve and piping arrangement are shown in figure 5.51. All lines in these systems are of copper tubing with sweat soldered joints except where gasketed joints are necessary for ease of disassembly in case repairs should be required.

The gas supply switching loop is so constructed that when the loop is connected to any one of the three gas lines a microswitch is closed which will then permit operation of the corresponding leak and solenoid valves. The vacuum operated switch in the switching loop prevents opening of the main gas line solenoid valve when the loop is not evacuated. The leak valves are not yet completed but they will be motorized needle valves with slip clutch closing drive and positive opening drive.

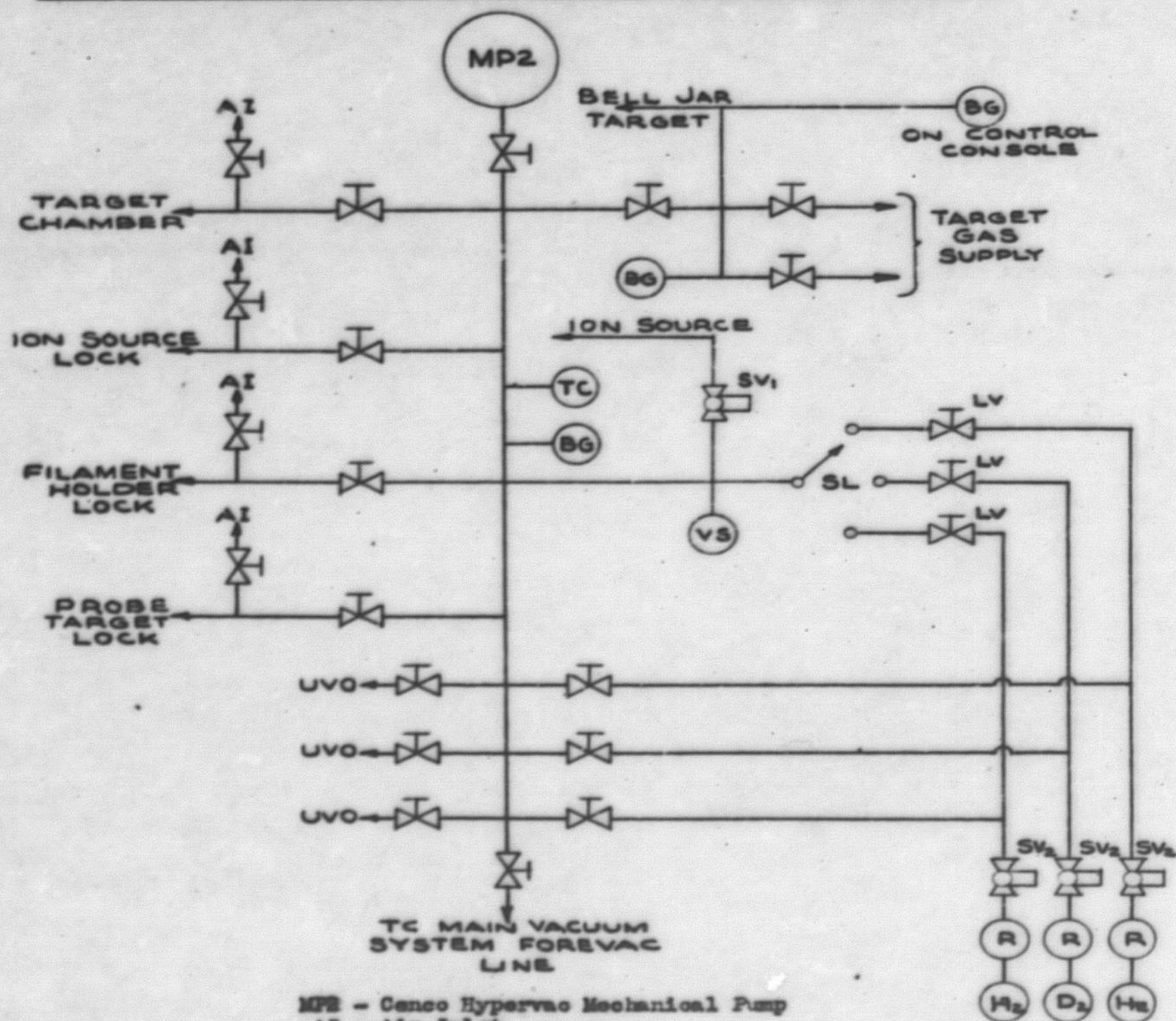
The house vacuum and gas supply systems are located on the west end of the magnet yoke. Also located on the same end of the magnet are control panels which permit operation of all remotely controlled components of the entire vacuum system. Duplicate controls for the main 20-inch valve and the diffusion pump heaters are located in the main control room as are indicator lights which show the condition of other components of the system.

5.6 Gauges and Protective Devices

Gauge locations are indicated in figures 5.11 and 5.51. A selector switch on the control desk allows one to read the output of any of the various thermocouple gauges either on the meter on the control desk or on a meter on the control panel located on the end of the magnet.

At the present time the diffusion pumps are protected by an ionization gauge protective unit which closes the main 20-inch valve

HOUSE VACUUM SYSTEM AND GAS SUPPLY SCHEMATIC



- MP2 - Cenco Hypervac Mechanical Pump
- AI - Air Inlet
- TC - Thermocouple Gauge
- BG - Bourdon Gauge
- SV₁ - Main Gas Line Solenoid Valve
- SV₂ - Individual Gas Line Solenoid Valve
- LV - Leak Valve
- SL - Main Gas Line Switching Loop
- VS - Vacuum Operated Switch
- R - Pressure Regulator
- UVO - Utility Vacuum Outlet

FIGURE 5.51

when the tank pressure becomes higher than a pre-set value. This method of protecting the pumps will be replaced by a geissler discharge protective device. Provision is also being made for a pressure operated interlock in the fore vacuum line which is protected at present only in case of failure of the Kinney pump motor. The entire system is protected by water flow interlocks wherever water cooling is required.

6 DEES AND LINERS

The dees and stems are shown in figure 6.01. The skin is of 1/8" electrolytic high conductivity copper with 1/4, 3/8, and 5/8" copper tubes silver soldered on the back side for water cooling. Each dee and stem is split longitudinal to facilitate repair, and the assembly is supported internally by a combination stainless steel and shelby tubing support tube. The support tube is attached to a bracket on the dee tank end plate, thus effecting cantilever support of the dees. The dees are 53" in diameter and the stems 9 3/4" O.D.

Through the end of each support tube are passed 18 copper cooling tubes which are fanned out and each connected to an individually controlled water cooling circuit.

The R. F. liner is of one piece construction except for the 8" x 61 3/4" bridge liner which is attached to the vacuum tank covers along the axis of the dees. Surfaces joining the split liner are silver plated. All liner material is of 1/8" electrolytic high conductivity copper and is 31" I.D. in the dee stem tank region. Aluminum bar backing strips are located in the space separating the copper and steel shells. The liner is shown in figure 6.02.

In the region traversed by the spider (shorting bar) aluminum bars are closely spaced to withstand the 100-pound pressure per lineal inch of contact imposed by the spider. The spider mechanism is shown in figure 6.03. Its purpose is to provide an electrical short between the dee stems and liners. Contact on the R. F. liner is effected by a mechanical arrangement of cable actuated levers on 42 spring loaded, copper fingers. Contact on each dee stem is made by 18 spring loaded copper fingers gear driven. A copper shield connects the fingers. The spider is externally controlled and is adapted for remote control.

FIGURE 6.01

The Copper Dees and Dee Stems

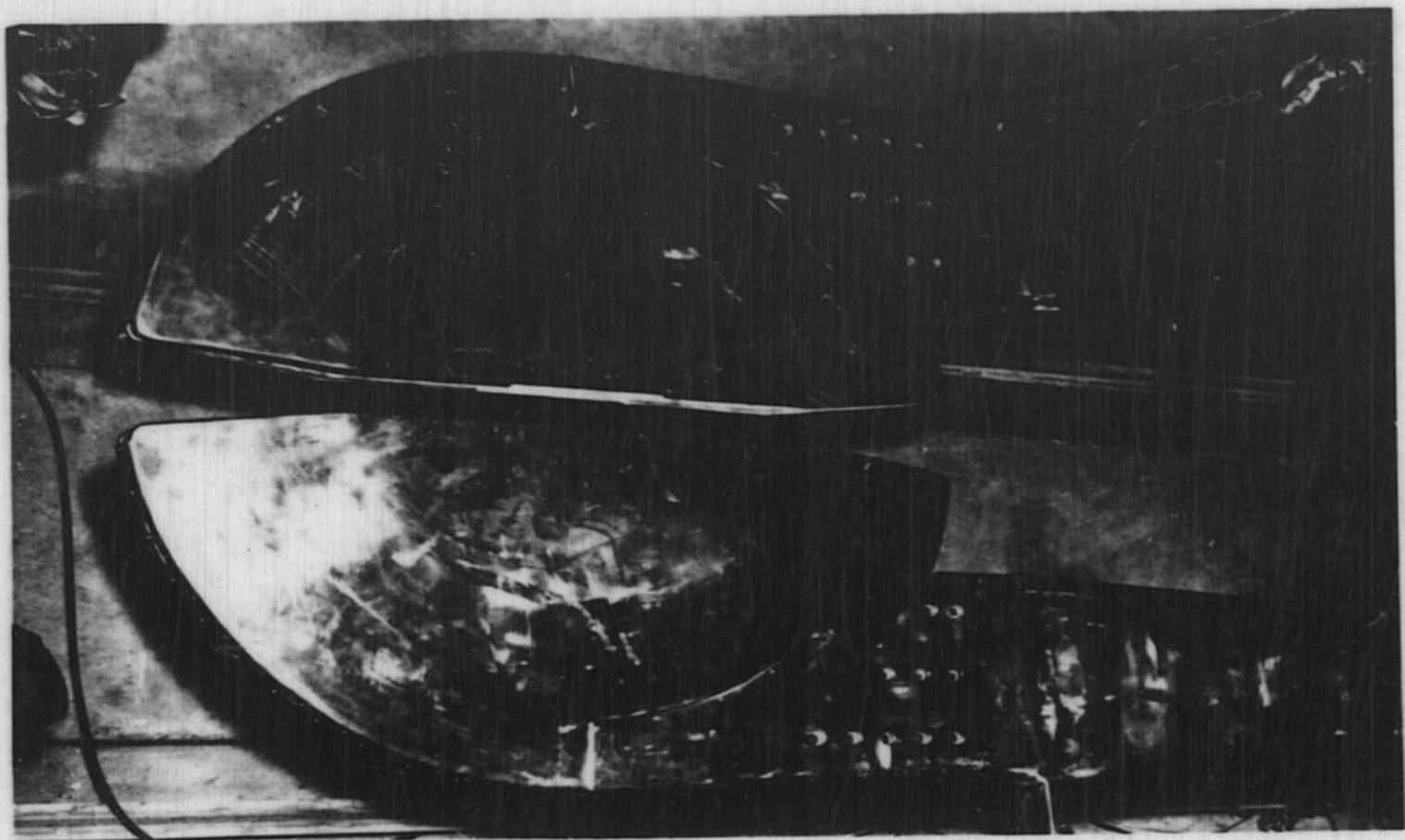


FIGURE 6.02

The Copper R. F. Liner

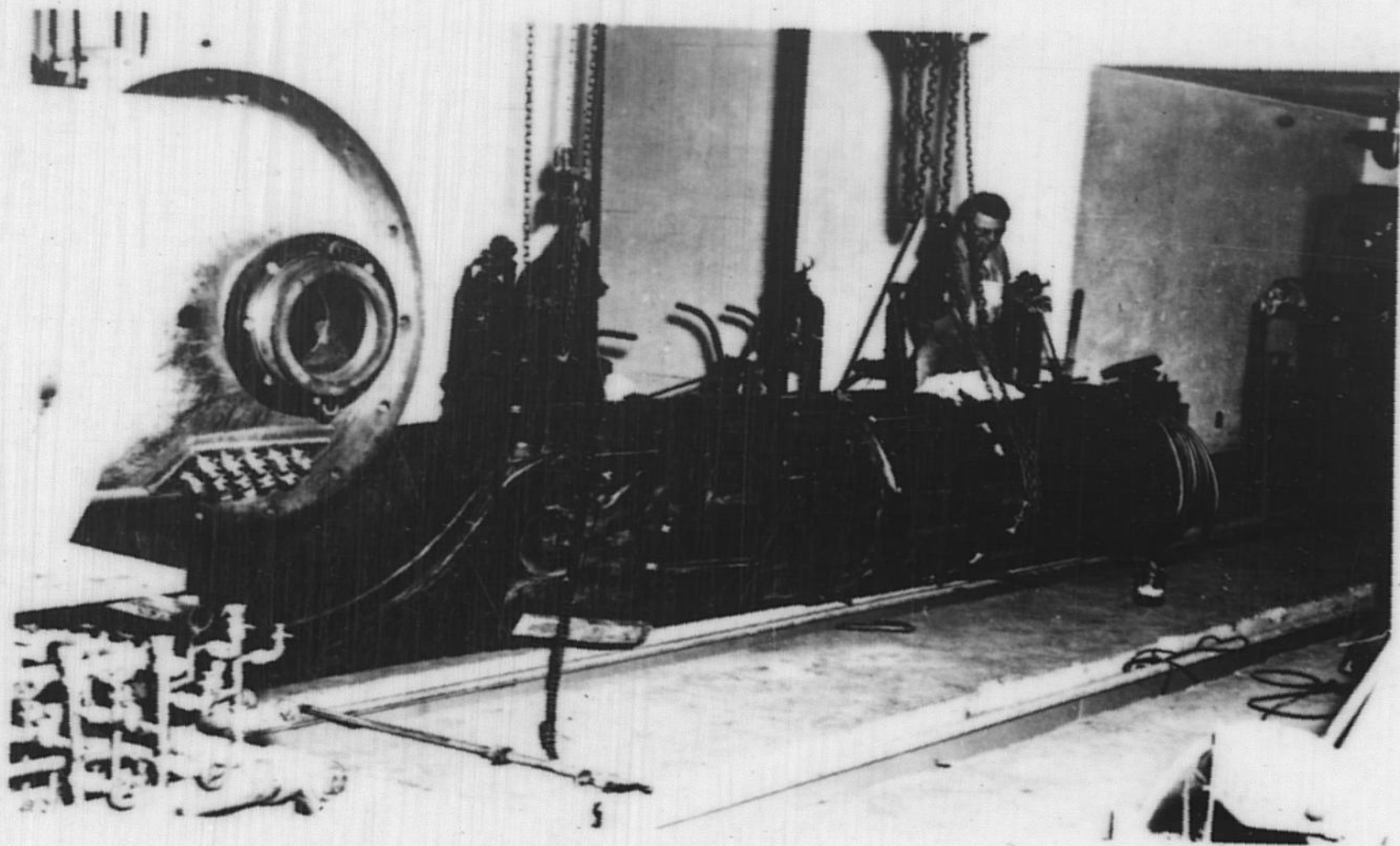
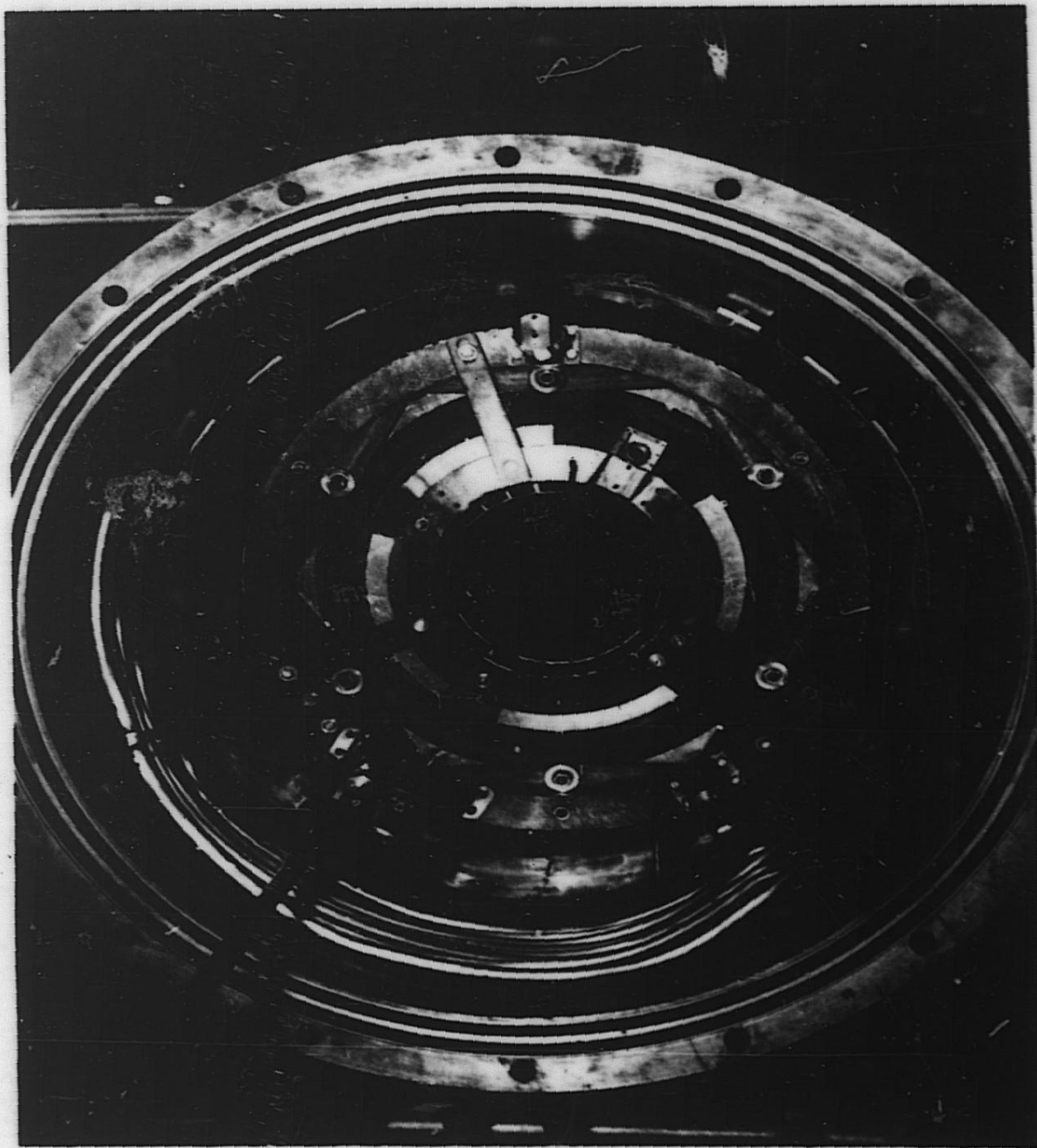


FIGURE 6.03

The Spider (Shorting Bar) Mechanism



7. ION SOURCE

7.1 Design and Construction

The ion source is the mechanism in the cyclotron which generates the protons, deuterons or alpha particles to be accelerated. This is done by bombarding hydrogen, deuterium or helium gas with electrons emitted by a hot tungsten filament. The ion source designed for this machine is basically the same as ion sources used at Berkeley.

Provision is made to extract the filament from the ion source assembly without disturbing the vacuum in the tank, by means of a filament vacuum lock. This allows convenient means for quick replacement of broken or burned out filaments. Also, an ion source vacuum lock is provided to make the replacement of the entire ion source assembly as convenient as possible. The ion source vacuum lock is of heliarc welded aluminum construction. It contains a swinging gate which closes against the end plate of the vacuum tank. The gate is actuated by toggle action, which applies enough pressure to the gate to cause the gate gaskets to seal.

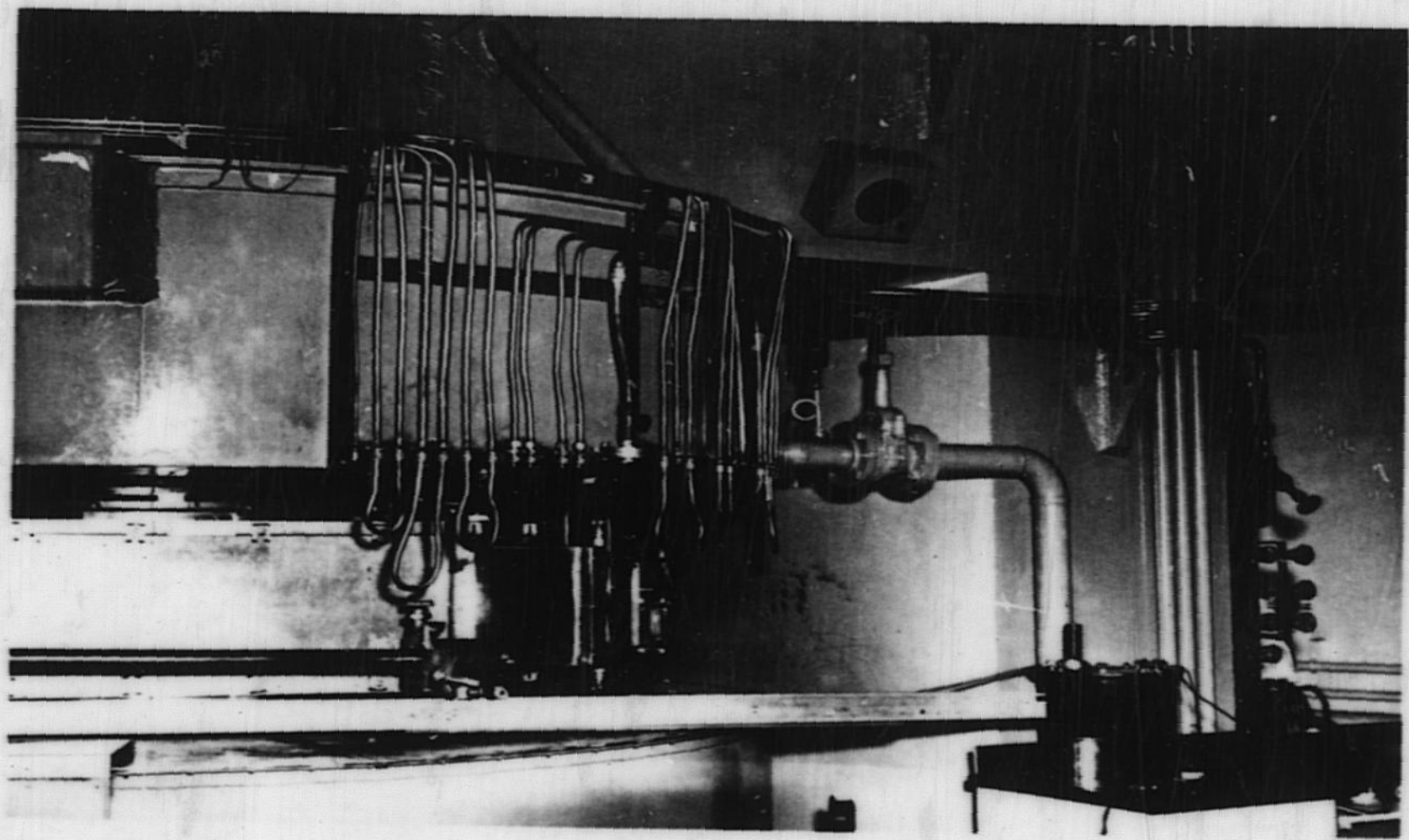
The ion source lock door clamps to the lock with toggle-action clamps. It supports, through three adjusting screws and a sylphon, the chevron seal which makes the vacuum seal on the ion source support tube. The three adjusting screws allow for positioning of the ion source in both the horizontal and vertical planes. The design for motorizing these adjustment screws for remote control is complete but construction of this system has not been started.

A 4" glass window has been located in the ion source lock door so that the space between the doors can be seen. A brass shutter is hinged behind the window to protect the glass.

Figure 7.11 shows the ion source lock in position on the vacuum

FIGURE 7.11

Ion Source Lock in Position



tank and the filament lock on the ion source guide track, immediately in front of the ion source lock.

Figure 7.12 shows the ion source assembly in position. From left to right in this photograph are shown the ion source and filament guide track, filament water connecting blocks, filament insulator vacuum seal supports, filament vacuum lock, and ion source vacuum lock.

Figure 7.13 shows the ion source cone and support tube as they pass through the chevron seal and ion source vacuum lock door. Two of the three ion source positioning screws can be seen between the vacuum lock door and chevron seal mounting plate.

7.2 POWER SYSTEM

Filament power for the ion source is supplied by a 3-phase, copper oxide, bridge type rectifier that has an output of 6 volts at 300 amp. d-c. It is a standard commercial plating rectifier.

The arc voltage is provided by a 3-phase, full wave bridge rectifier using G1 5558 mercury vapor diodes. The maximum output is 500 volts at 8 amp. The voltage is controlled by a motor driven powerstat in the primary of the transformer.

Arc current regulation is obtained by saturable reactors in the primary of the filament supply rectifier. Since the regulation is brought about by holding the filament emission constant, the arc voltage and current are independently variable.

FIGURE 7.12

Ion Source Assembly in Position

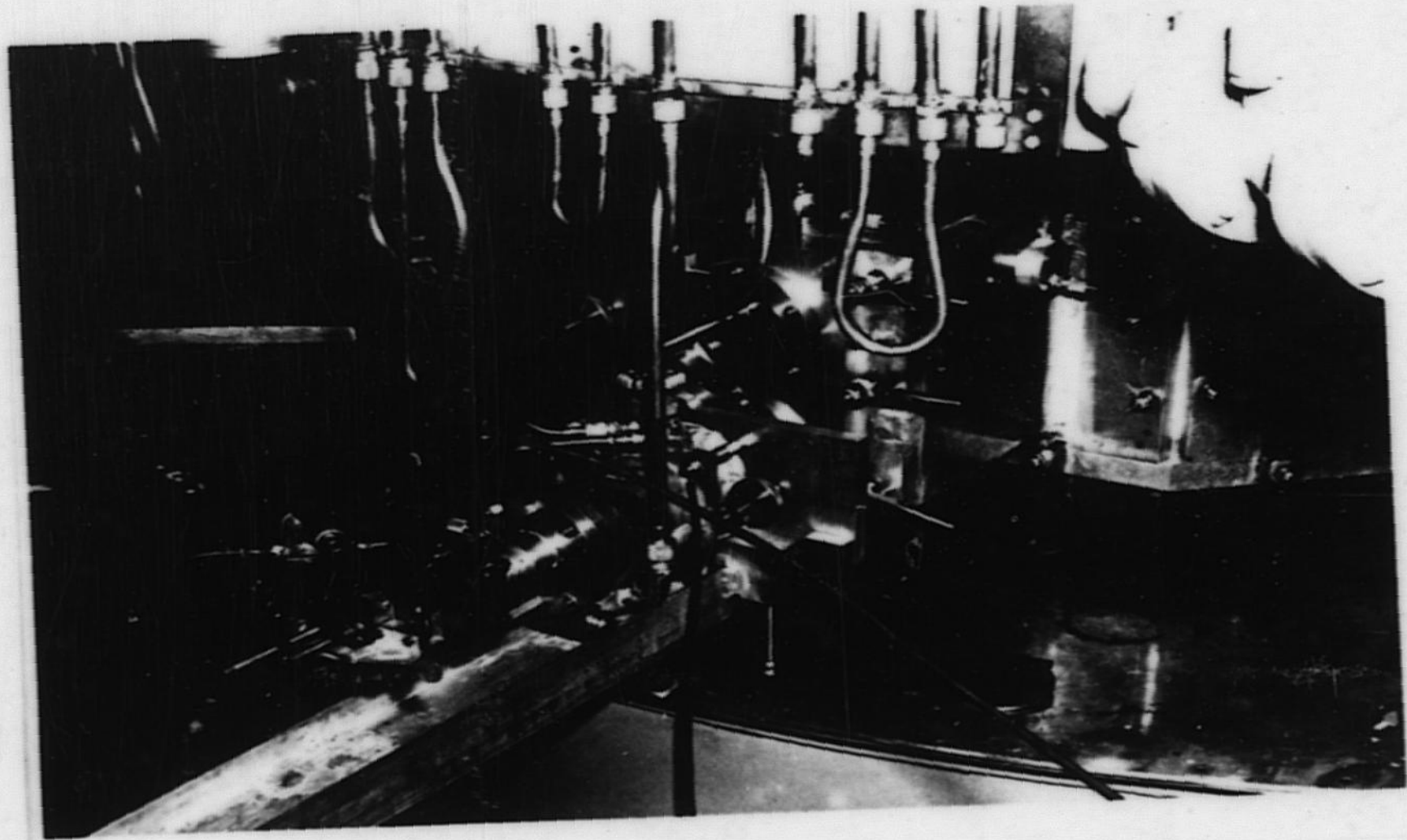
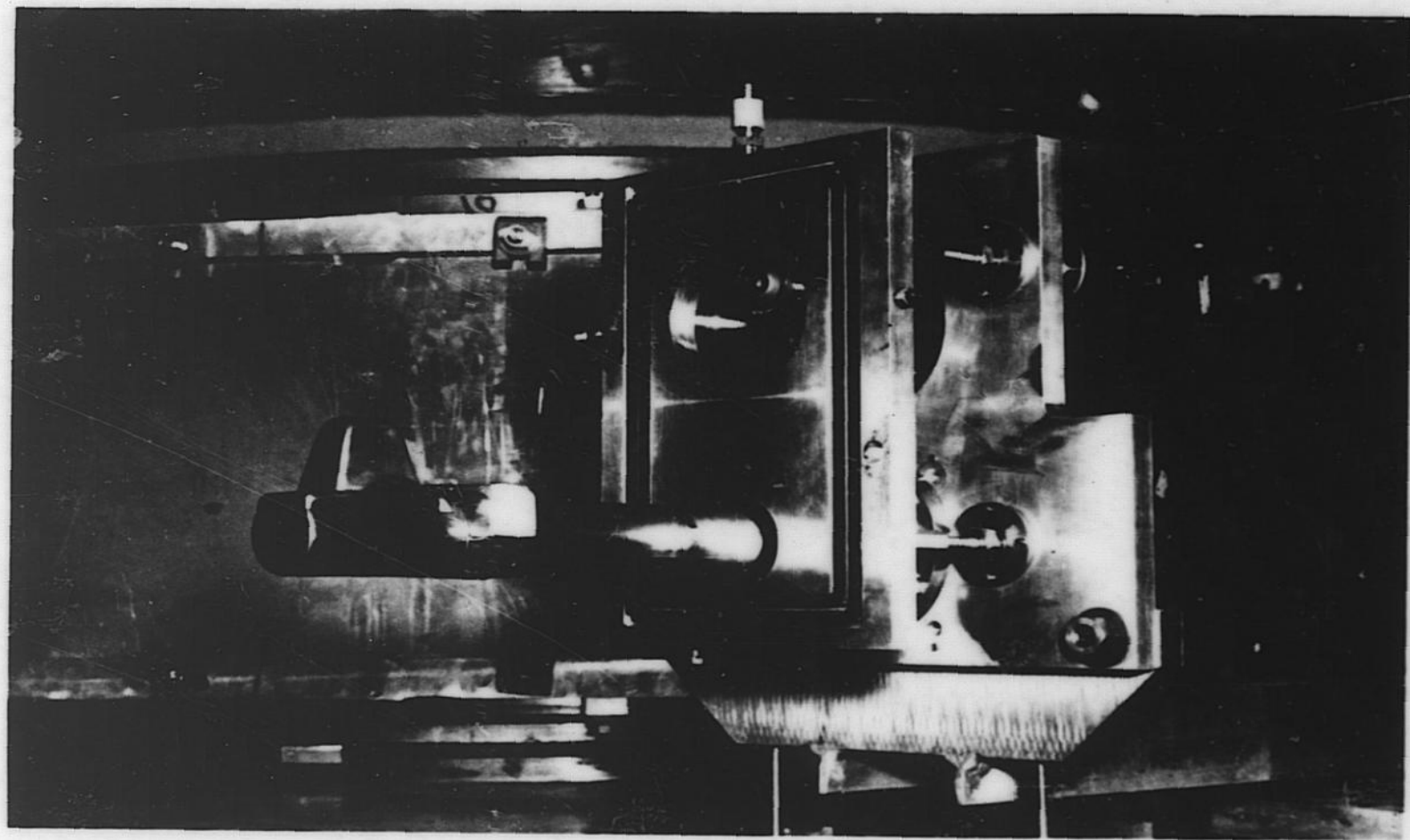


FIGURE 7.13

Ion Source Cone and Support Tube



8 OSCILLATOR

8.1 General Principles and Problems

The development of a suitable oscillator to supply the high voltage required on the dees is one of the major problems in cyclotron design. The problem is made difficult by the high voltage and frequency required and the low impedance of the dee capacity.

The frequency required for a charged particle in a magnetic field is given by $f = \frac{1}{2\pi} \frac{qH}{mc}$. For deuterons in a magnetic field of about 15 kilogauss this frequency is about 11.3 mc/sec. The capacity of the dee is necessarily large because of the geometrical factors involving the minimum dee height and maximum magnet pole gap that are allowable. In this machine the reactance of the dee is only about 40 ohms at the operating frequency.

It may be shown, that for a given magnetic field profile, there exists a minimum required peak voltage across the gap between the dees to accelerate each type of particle to the exit radius of the machine. Calculations based on magnetic field plots for a central field of 15 kilogauss and a chosen exit radius of 25.2 inches indicate that the minimum voltage is about 160 kv peak across the gap for deuterons and alpha particles. It is also apparent from the calculations that a much higher voltage would probably be necessary to get a large beam output.

The only suitable method to produce such high voltages across as low an impedance as 40 ohms is to connect sufficient inductance in parallel with the dee to make a circuit that is resonant at the desired frequency. To keep the power requirements as low as possible the inductance must have a very high Q value. For this reason a shorted coaxial transmission line is used. The Q of such an inductance is about 11,000. When losses in the dee and energy transferred to the ion beam

are included, the overall Q value is reduced to about 7500.

The equivalent lumped constant circuit of the dees and shorted line inductances may be drawn as in figure 8.11. C_D represents the

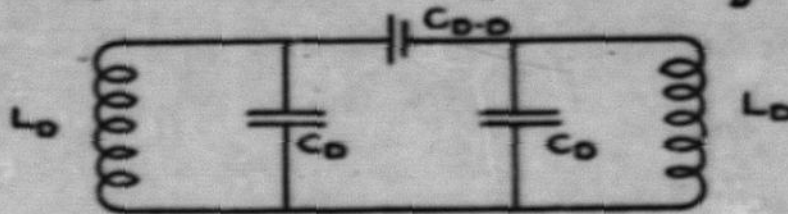


FIGURE 8.11

capacity of the dee; the L_D the shorted line inductance, and C_{D-D} the capacity from dee to dee. This circuit is one that contains two parallel resonant circuits that are capacitively coupled. Analysis of the circuit will show that there are two resonant frequencies.

$$\omega_1 = \frac{1}{\sqrt{L_D C_D}} \quad \text{and} \quad \omega_2 = \frac{1}{\sqrt{L_D (C_D + 2C)}}$$

At the frequency ω_1 , the voltages from both dees to ground (the voltage across the C_D 's in figure 8.11) are in phase and no voltage is developed across C_{D-D} . At the frequency ω_2 , the voltages are 180° out of phase producing a voltage across the gap that is twice the voltage from dee to ground. Thus ω_2 is the only frequency that is usable. Since ω_1 and ω_2 differ by only a few per cent, the first requirement is that the oscillator excite the system at ω_2 and not at ω_1 .

Further analysis of figure 8.11 will show that when the Q values of the resonant circuits are considered, the peak r-f voltage across the gap (C_{D-D}) will be

$$E_{pk} = 2 \sqrt{P Q X} \quad \text{where}$$

E_{pk} = peak gap voltage

P = total r-f power supplied

Q = Q value of the resonant circuits

X = reactance of the dee capacity

Using a value of $Q = 7500$, $I = 40$ ohms, and $E_{pk} = 160$ kilovolts the r-f power required is found to be about 21.2 kw. If the peak gap voltage required is raised to 250 kilovolts, the power requirement becomes 52 kw. If 150 kw of r-f power were provided, a peak voltage of about 450 kv would be produced across the gap. It is doubtful if the dee system could stand this large a voltage without arcing over.

However, upon considering the approximations necessarily made in this type of analysis, the figure of 150 kw maximum r-f power was selected. The dees with their connected inductive stems and the outer copper liner of the system have been designed to dissipate the 150 kw and the oscillator and power supply components were selected with sufficiently large ratings to handle a 150 kw oscillator. The type of load in a cyclotron oscillator is such that serious arcs may occur on the dees. When this happens the reaction on the oscillator may be very serious and the tube must be capable of withstanding heavy overloads without damage.

The last requirement is that the oscillator build up into oscillation when the plate power is applied. Electron oscillations in the vicinity of the dees and dee stems at low r-f voltages tend to absorb energy and prevent the oscillations from building up. The method planned to solve this problem is to use a small self-excited "booster" oscillator that does not depend on coupling through the dee system. This oscillator should provide sufficient power to raise the dee voltage up to a point where electron oscillations can no longer take place.

The problem thus becomes one that requires a high frequency oscillator that will excite the dees at the proper frequency, develop large amounts of r-f power, be sufficiently rugged to withstand severe operating conditions, and that will start into oscillation readily.

The next section of this report will give a more detailed description of the methods used to design an oscillator of the type described.

8.2 Theory of Design

A grounded grid oscillator with the plate loop coupled into one dee stem and the filament loop coupled to the other dee stem was selected. With this type of circuit it should be easiest to assure oscillation at the proper frequency with the two dee voltages 180° out of phase.

The basic requirements for oscillation in a grounded grid oscillator are that the voltages at the tube from plate to ground and filament to ground be in phase and have the proper ratio of magnitudes. If these conditions can be met, the circuit will oscillate. It is also important throughout the design to keep practical construction difficulties in mind.

The oscillator design described below is one in which a coaxial line about 2 meters long extends downward from the tube plate to one end of the coupling loop. The other end of the coupling loop is connected to a shorted coaxial inductive stub line whose length may be varied. The grid is maintained at r-f ground by vacuum capacitors, and another coaxial line connects the filament of the tube to one end of the filament coupling loop. The other end of the filament coupling loop is connected to an open coaxial stub which can be tuned to have either a capacitive or inductive impedance.

The oscillating conditions can best be determined by using a schematic equivalent of the system as an aid. Such a schematic drawing is shown in figure 8.21. The equivalent plate line is shown in figure 8.22 and the filament line in figure 8.23.

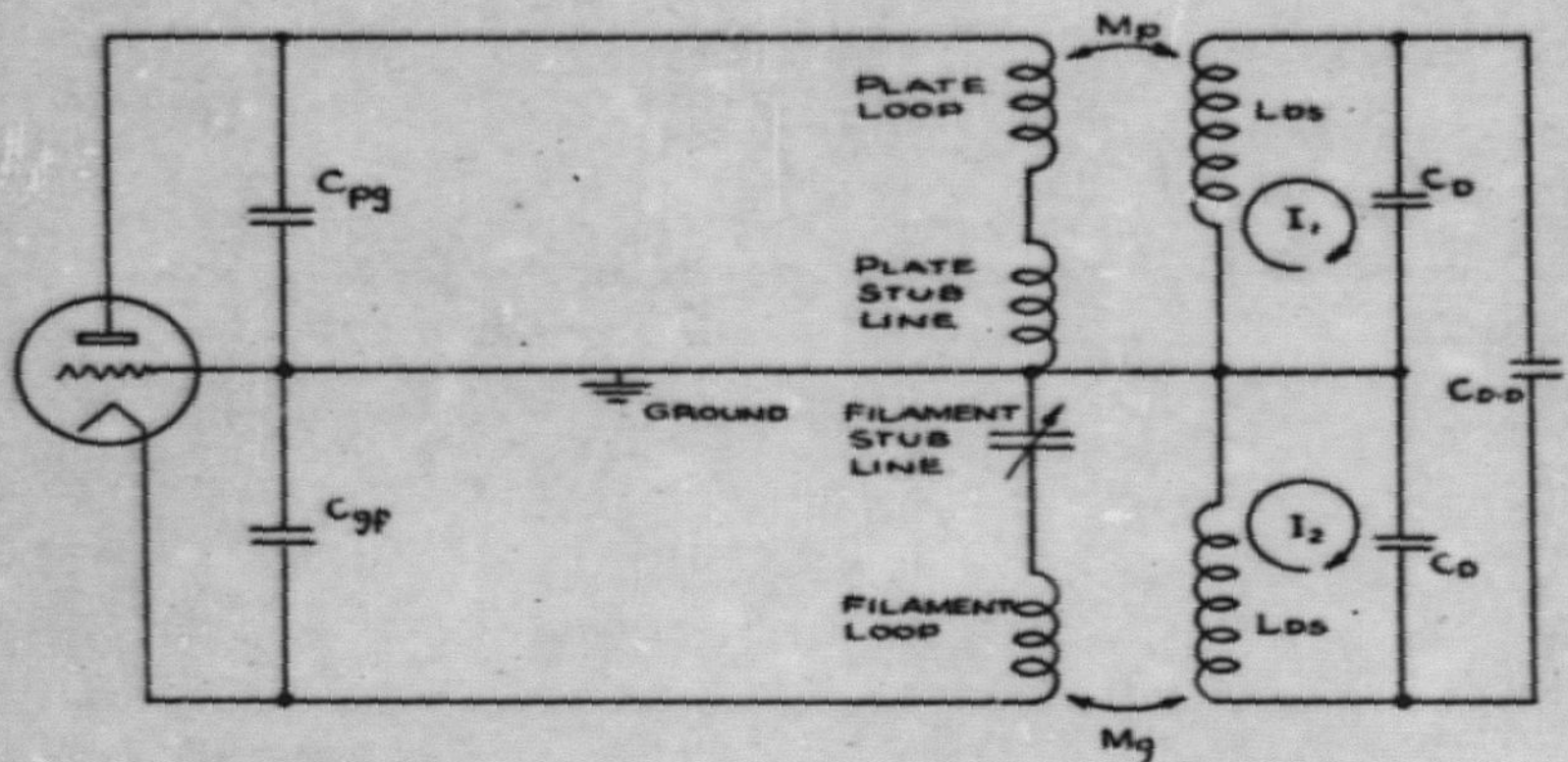


FIGURE 8.21

- C_{pg} = Interelectrode capacity plate to grid
- C_{gf} = Interelectrode capacity grid to filament
- L_{ds} = Inductance of dees stem
- C_D = Dees capacity to ground
- C_{D-D} = Dees to dees capacity
- M_p = Plate loop to dees stem mutual inductance
- M_g = Filament loop to dees stem mutual inductance
- I_1, I_2 = Dees circuit currents

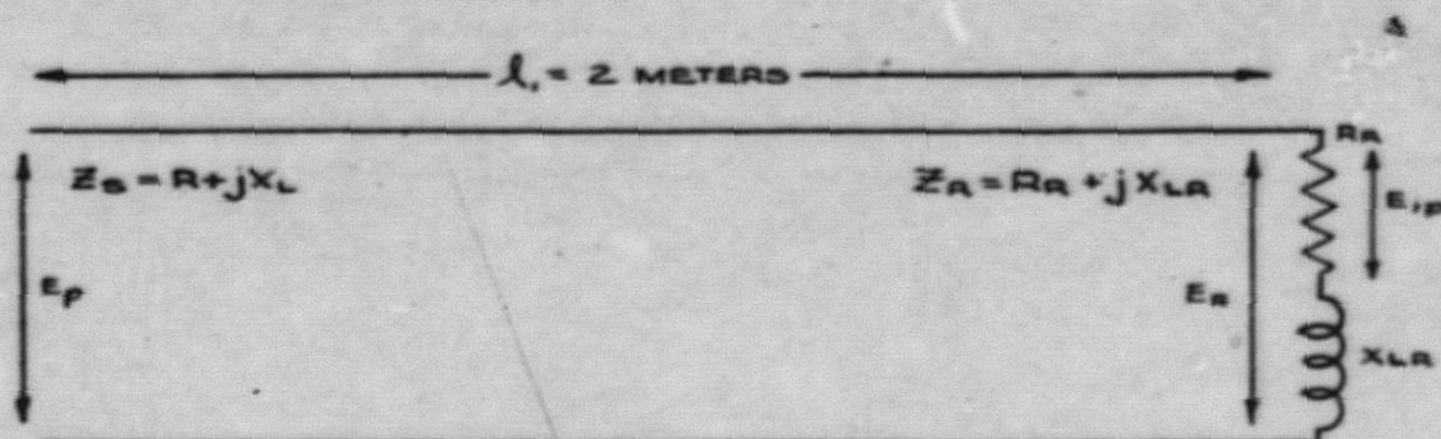


FIGURE 8.22

- E_{ip} = Induced plate loop voltage
- E_p = Plate to grid r-f voltage
- E_R = Loop to ground r-f voltage
- l_1 = Coaxial plate line length
- X_{LA} = Self inductance of loop plus inductance of shorted stub line
- R_R = Reflected resistance from dec circuit

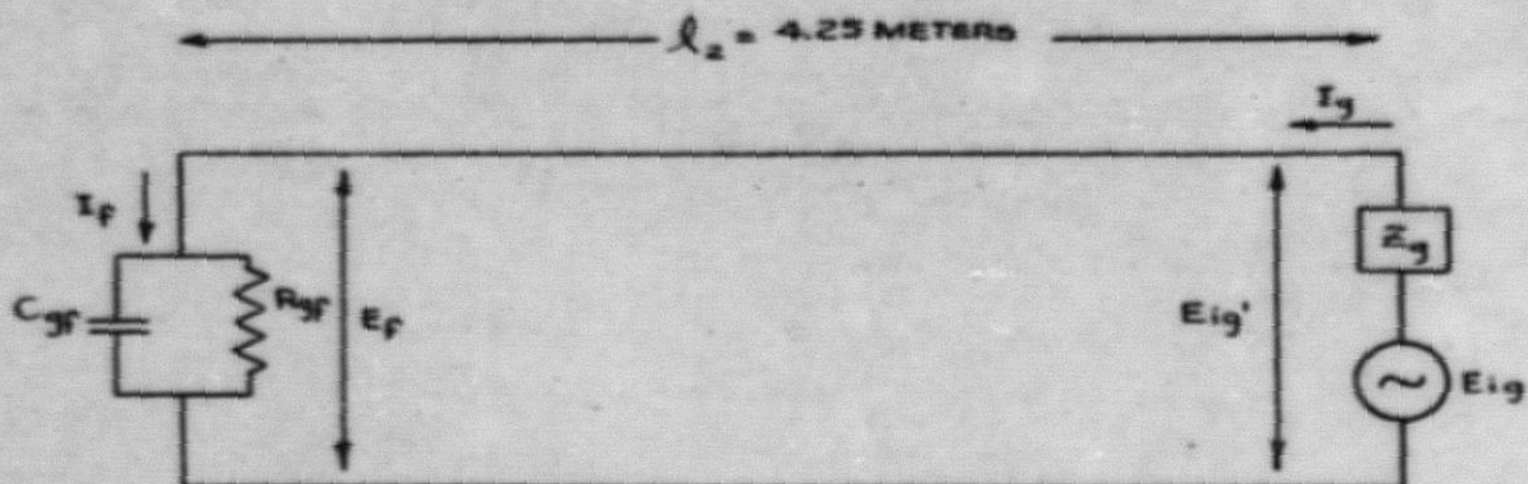


FIGURE 8.21

- E_f = Combined impedance of C_{gf} and R_{gf}
- C_{gf} = Interelectrode capacity filament to grid
- R_{gf} = Equivalent resistance due to driving power requirements in the tube
- E_f = Grid to filament r-f voltage
- E_{ig} = Loop to ground voltage
- E_{ig} = Induced filament loop voltage
- Z_g = Combined impedance of filament loop self inductance and filament stub line reactance

Referring to figure 8.21 E_{1p} , the induced plate loop voltage, is given by $E_{1p} = j\omega M_p I_1$ and E_{1g} , the induced filament loop voltage, is given by $E_{1g} = j\omega M_g I_2$. At resonance $I_1 = -I_2$ so that

$$\frac{E_{1p}}{E_{1g}} = -\frac{M_p}{M_g} \quad (1)$$

From figures 8.22 and 8.23 the requirements are that E_r and E_p must be in phase and in the proper ratio

From 8.23 (filament line)

$$E_{1g}' = E_r \cos \beta l_2 + j I_r \frac{E_g}{E_o} \sin \beta l_2$$

$$I_g = I_r \cos \beta l_2 - j \frac{E_r}{E_o} \sin \beta l_2$$

Substitution $\frac{E_r}{E_f} = I_r$ in both equations

$$E_{1g}' = E_r \left(\cos \beta l_2 + j \frac{E_g}{E_r} \sin \beta l_2 \right)$$

$$I_g = E_r \frac{\cos \beta l_2}{E_f} + j \frac{\sin \beta l_2}{E_o}$$

The above equations for E_{1g}' and I_g may be put into the equation

$E_{1g}' = E_{1g} - I_g E_g$. Upon doing this and collecting terms

$$\frac{E_{1g}}{E_r} = \cos \beta l_2 \left(1 + \frac{E_g}{E_f} \right) + j \sin \beta l_2 \left(\frac{E_g}{E_r} + \frac{E_g}{E_o} \right) \quad (2)$$

From figure 8.22 (plate line)

$$\frac{E_g}{E_{1p}} = \frac{E_g + j I_r E_r}{E_r} = \frac{E_g}{E_r}$$

$$E_p = E_r \left(\cos \beta l_1 + j \frac{E_g}{E_r} \sin \beta l_1 \right)$$

Combining these two gives

$$\frac{E_g}{E_{1p}} = \frac{E_g}{E_r} \left(\cos \beta l_1 + j \frac{E_g}{E_r} \sin \beta l_1 \right) \quad (3)$$

Combining (1), (2), and (3)

$$\frac{E_p}{E_f} = - \frac{E_p M_2}{E_R M_E} \left(\cos \beta l_1 + j \frac{E_2}{E_R} \sin \beta l_1 \right) \left[\cos \beta l_2 \left(1 + \frac{E_2}{E_f} \right) + j \sin \beta l_2 \left(\frac{E_2}{E_f} + \frac{E_2}{E_0} \right) \right] \quad (4)$$

into this equation one may substitute

$$\frac{1}{E_f} = \frac{1}{E_{gf}} + j\omega C_{gf} \text{ and } E_R = R_R + j\omega L \text{ and } E_E = jX.$$

This results in a rather long and awkward expression, but for this purpose it is sufficient to say that the result may be put into the form

$$\frac{E_p}{E_f} = R + jI \text{ where } R \text{ is the real part and } I \text{ is the}$$

imaginary part.

If E_p and E_f are to be in phase I must be zero. This sets the phase relation. The ratio of magnitudes is then R .

To use these equations all the variables concerning the plate line are fixed so that the oscillator will see its proper load resistance. Also, the load at the tube of the filament driving line may be determined from the grid to filament capacitance and the equivalent resistance R_{gf} representing the required driving power of the tube. When all these factors have been determined, the value of I , the terminating reactance on the filament loop, may be varied to bring about the proper phase relation and the ratio of depth of the plate and filament loops may be varied to bring about the proper magnitude relation.

Although the forms for the expression for I and $\frac{E_p}{E_f}$ are complicated, the values may be calculated quite readily by setting up the variable quantities in a tabular form and following a step by step process. This has been done over a frequency range from 9.25 to 13.25 mc.

The calculated values should not be considered as exact since there are many uncertainties in the determination of constants used, but the calculated values serve well as a guide in initial adjustment of the oscillator.

In some cases it has been found desirable to add capacitance at the tube in parallel with the interelectrode capacitance to reduce the construction problems on the inductive plate stub line and capacitive filament stub line.

8.3 Model Oscillator Work

A quarter scale model of the entire r-f system was built. This was used to find the required lengths of the dee stems and to test various methods of calculation used in the design of the main oscillator.

Since all dimensions were scaled down by a factor of four, the oscillator operated at four times the frequency of the full scale machine. The Q of the dee system was only half that to be expected in the full scale machine. Measured values of Q in the model were about 3500, a high value considering that no special precautions were taken to insure good joints or ideal surface conditions on the dee stems or liners.

It was found in the model that the calculated values of line lengths and terminations were sufficient to have the model oscillator work properly with only minor adjustments thereafter. This provided good experience for later work on the full scale job and provided a basis for confidence in the methods used in the design work.

Figure 8.31 shows a photograph of the model.

8.4 Construction

A discussion of the actual construction of the oscillator must begin with the selection of the tube to be used. The Machlett 354 has been chosen. It is a high power, water and forced air cooled triode with

FIGURE 8.31

The Model Oscillator



a rated plate dissipation of 75 kw and a maximum allowable power input of 225 kw. The tube is ruggedly built with heavy metal parts and all terminals co-axially aligned. The use of Kovar to glass seals greatly improves the mechanical strength of the terminals. The built-in water jacket on this tube also facilitates its mounting and replacement.

The tube is mounted anode down in a copper lined steel enclosure 34" x 34" x 52". Out of the bottom of this box a co-axial transmission line (4" diameter inner conductor and 12" square outer conductor) connects the plate of the tube to one end of the coupling loop. The other end of the coupling loop connects to a similar co-axial line that extends up alongside the oscillator box and is terminated in a short circuit.

Inside the box a metal shield is connected to the grid flange. Four 500 mmf vacuum capacitors serve to ground the grid for r.f. voltages.

Another co-axial line (2" diameter inner conductor and 6" square outer conductor) extends from the top of the box to one end of the filament driving loop. The other end of the filament loop connects to a short section of transmission line that is terminated in a box housing the filament r.f. chokes, filament transformer, phase correction vacuum capacitors, and the grid current and plate voltage metering equipment.

Cooling water for the oscillator is brought in through the inner conductor of the plate transmission line. Since the plate is operated at d-c ground, no insulation is needed in the water lines.

Filament power to the tube is brought in through the inner conductor of the filament transmission line. This permits the filament chokes to be placed at the end of the filament loop stub line.

8.5 Booster Oscillator

The booster oscillator to be used with the main oscillator is a converted BC 677 radar transmitter. The schematic is shown in

figure 8.51 and photograph in figure 8.52. A small oscillator running at half the cyclotron frequency is used to drive the BC 677 as a frequency doubling power amplifier. This will help to prevent energy being fed back into the booster when the main oscillator starts.

The driver oscillator frequency is controllable from the console by means of a selsyn driven variable condenser.

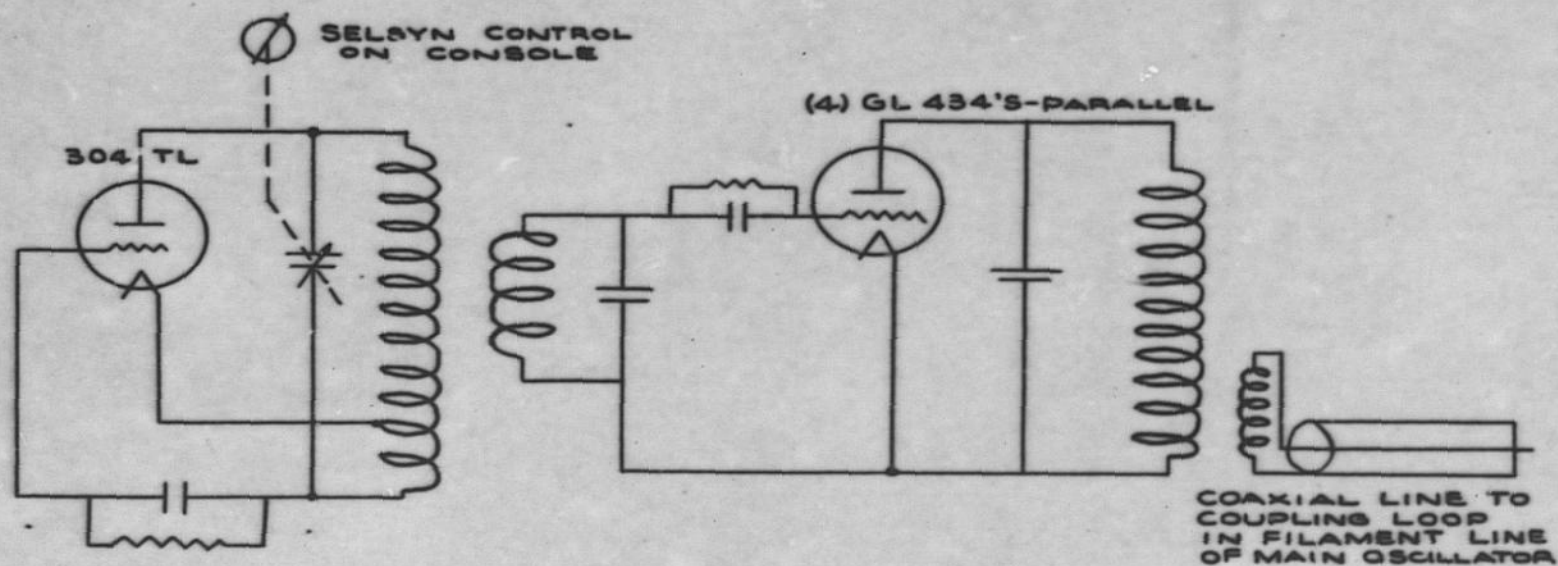
8.6 Instrumentation

The d-c plate voltage and current are measured using a standard high voltage multiplier for the voltage and a standard 50 mv shunt in the grounded side of the line for the current. The plate voltage and current will be shown on the control console and also on the duplicate oscillator control panels.

With the filament of the tube operated at high negative voltage, the grid current cannot readily be measured without having the meter at high voltage. To avoid this difficulty the grid current is passed through the control winding of a saturable reactor and the a-c winding is in an inductance bridge. The current in the control winding varies the inductance of the a-c winding and the voltage at the bridge terminals may be calibrated to indicate the d-c current. In this manner the high voltage is taken up in the insulation between the control and a-c windings.

Shunt type r.f. voltmeters with capacity pickups have been provided on the plate and filament transmission lines to facilitate testing and initial operation of the oscillator.

The dee voltmeters are series type peak meters that are coupled to the dees with small capacity probes that face copper paddles soldered to the dee edge. The probe leads are brought out through Kovar seals to the diode voltmeter units located in magnetic shield just outside the vacuum tank.

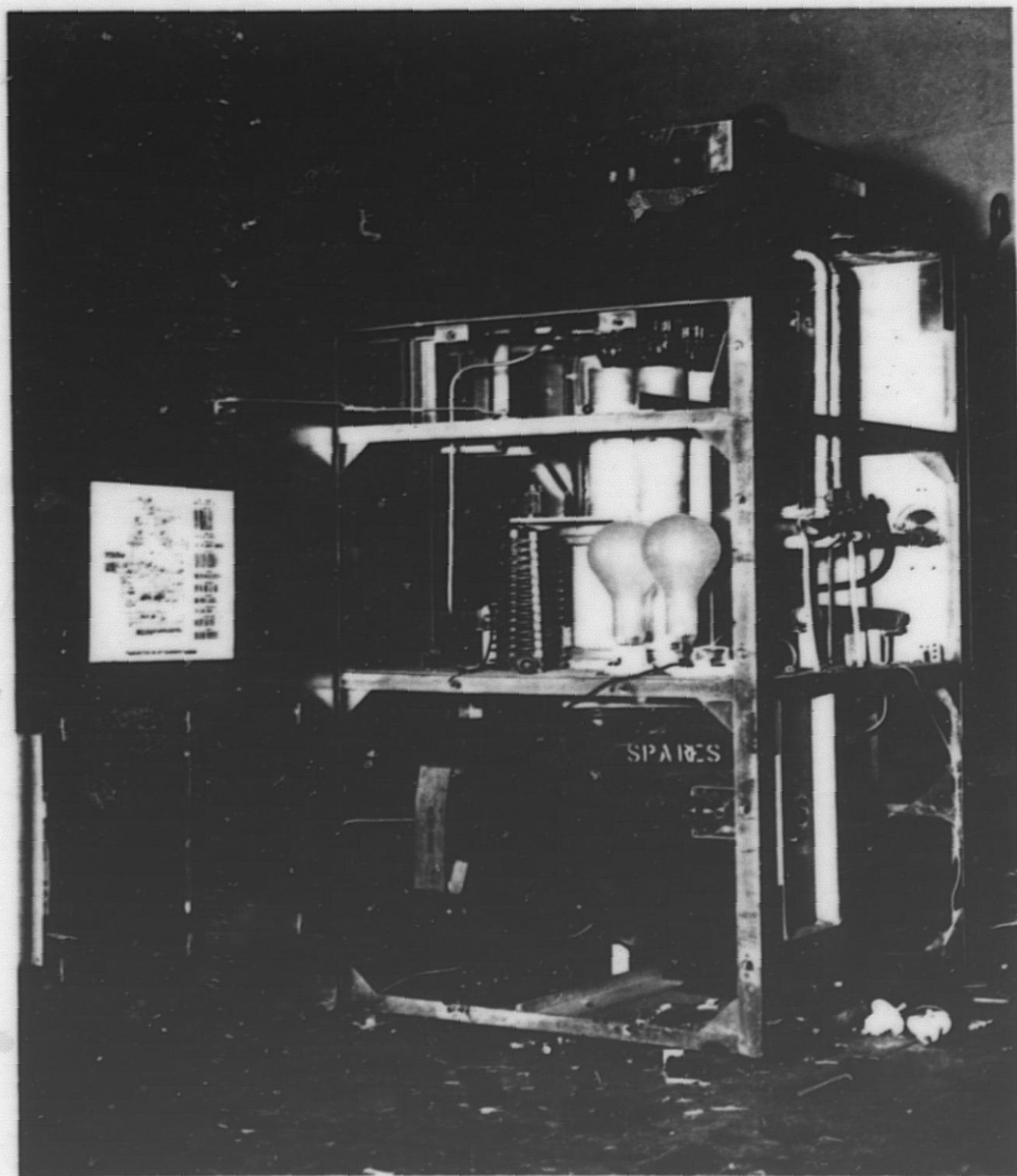


BOOSTER OSCILLATOR
SCHEMATIC

FIGURE 8.51

FIGURE 8.52

The Booster Oscillator
On Mastanine Floor



8.7 Power Supply

The power for the oscillator is supplied by a 3 phase, full wave bridge rectifier using type 869-B mercury vapor diodes, and is shown in figure 8.71. The a-c power system ahead of the rectifier consists of a fast acting circuit breaker in the 2400 volt line, an induction regulator having an output voltage range of 512 volts to 4100 volts and a 300 kva high voltage transformer with 14,400 volts output having two five per cent taps above and below this voltage. This combination provides for output voltages anywhere from 2 to 19 kv at up to 15 amps. This equipment is shown in the photograph, figure 8.72.

No constant current network has been employed in this power supply. The circuit breaker may be set to open at any current between 10 per cent and 110 per cent of rated load current. The plate dissipation of the tube is 75 kw and the breaker will open in 6 cycles or less. Upon taking into consideration these factors and planning to use a bank of glo-coil resistors for initial operation, the choice was made to eliminate the constant current network on the basis of cost.

The circuit breaker was supplied by the ITE Circuit Breaker Company and the induction regulator and transformer was supplied by the General Electric Company.

The filament power for the tube is supplied by a high reactance type filament transformer that is rated for 13 volts 225 amp. output. Its high reactance limits the starting current to 500 amp., the safe limit for the tube used. This transformer, built by the Sorgel Electric Company, is rated to stand the full d-c plate voltage from secondary to ground and secondary to primary.

FIGURE 6.71

3 Phase Full Wave Bridge Rectifier

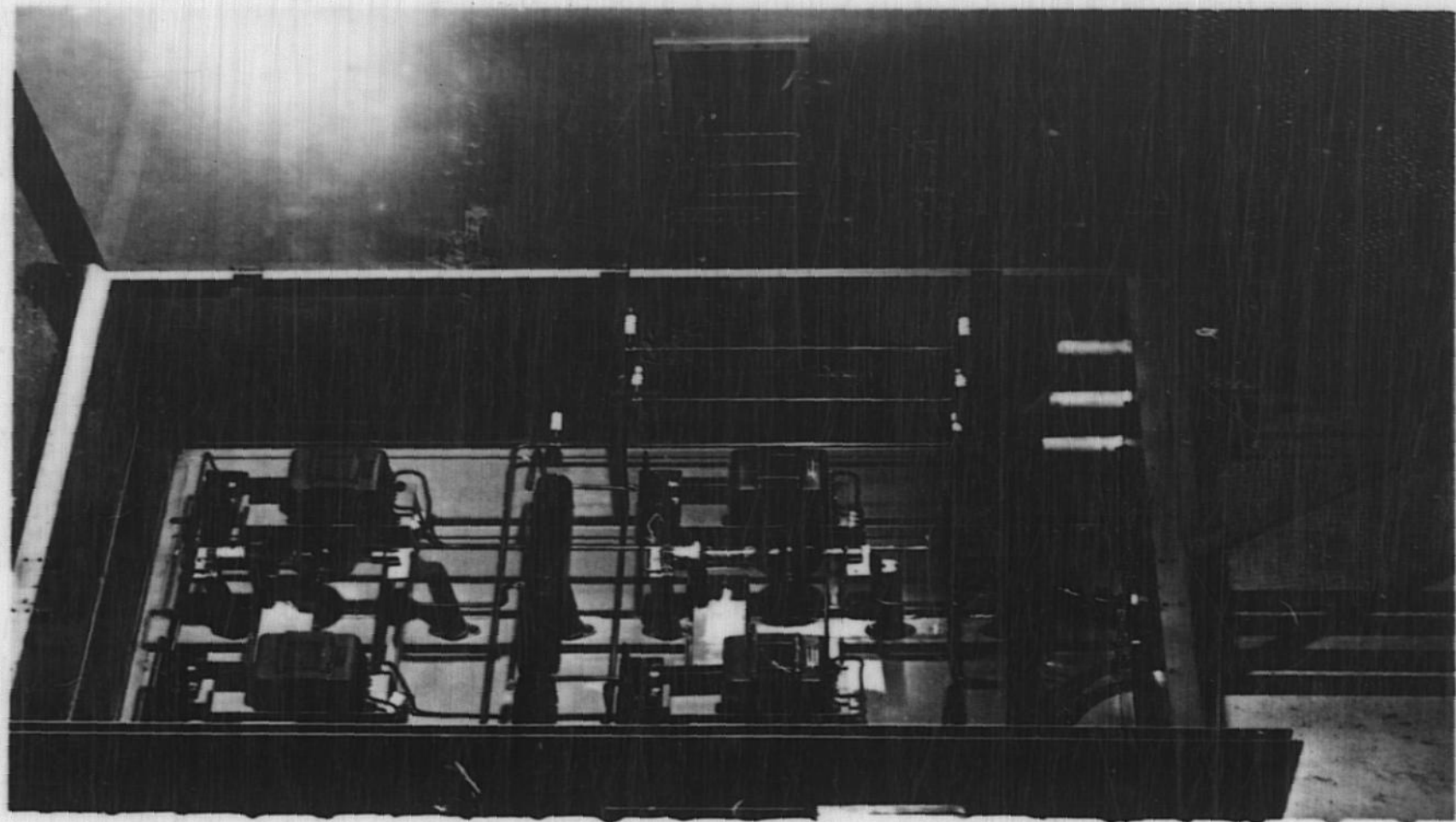


FIGURE 8.72

Circuit Breaker, Induction Regulator,
And Transformer



9. CONTROLS

9.1 Principles

The unified control system developed has followed closely other cyclotron systems. Major emphasis has been on making the system one that requires the least effort to operate the cyclotron while at the same time keeping the cost of installation and upkeep as low as possible.

The primary requisite of a control system for a machine of this type is that everything be so interlocked that serious damage to equipment will not occur in the event of any type of fault, whether it be operator error, loss of water, vacuum leak, etc.

The control system finally adopted provides for starting all major equipment from the control room in a definite sequence of operation. Sufficient pilot lights are used to show the exact state of operation and to determine the reason for failure of any unit to operate. Figure 9.11 shows a photograph of the control panels in the control room. Provision has been made for the addition of other units into the control system with a minimum of effort and rewiring.

9.2 Master Key and Switch

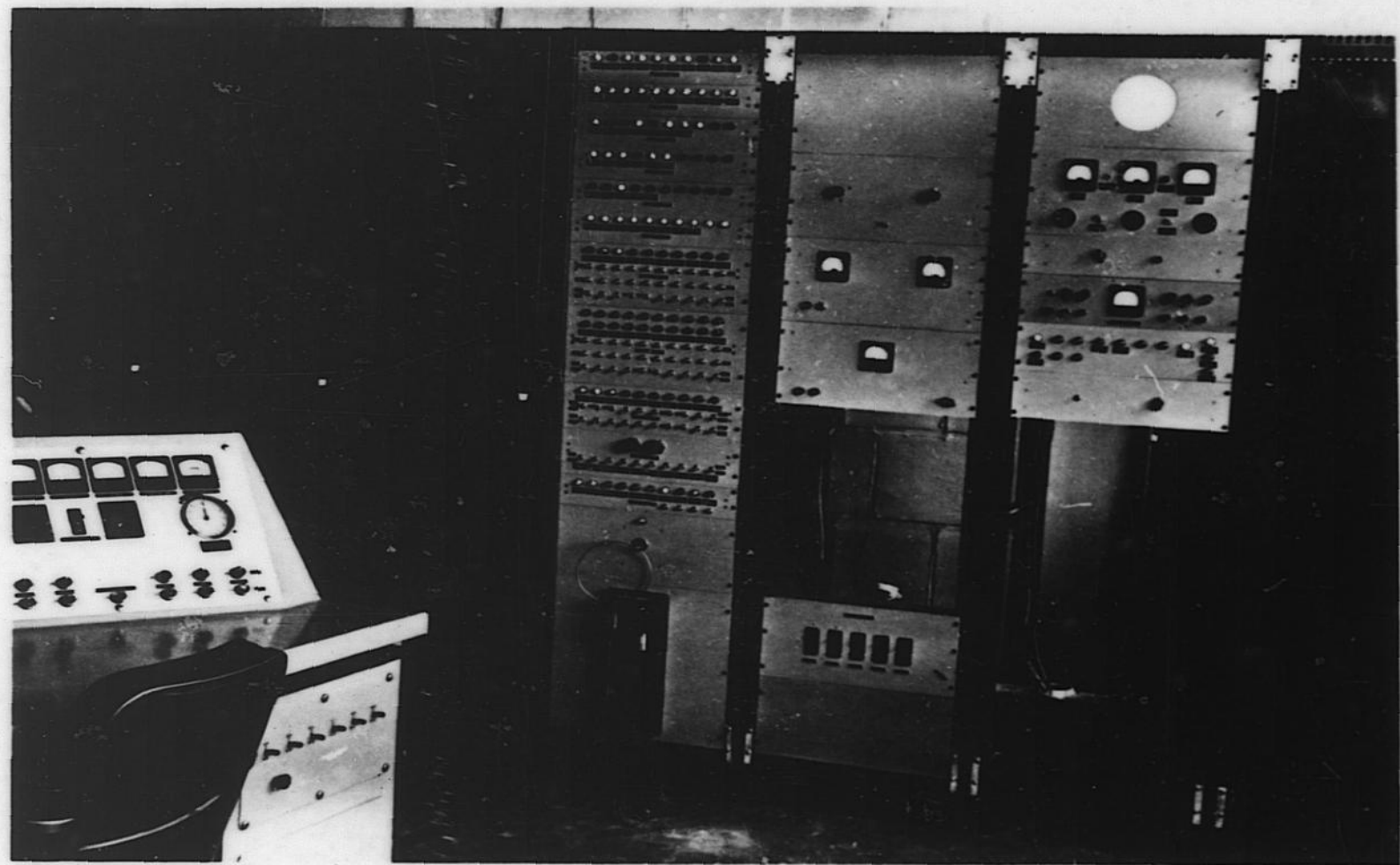
The control power for all cyclotron equipment except the vacuum system is supplied through a key type switch located in the main control board and a toggle switch on the control console. When both of these are turned on it is possible to begin the process of starting the cyclotron. Also the master switch on the console provides a means of turning off all equipment in case of an emergency.

9.3 Preliminary Gang

Next in the start-up process are the preliminary gang units. This group includes the thermocouple and ionization gauge control circuits, beam current integrator, beam amplifier, dee voltmeters, magnet current

FIGURE 9.11

Control Panels in Control Room



regulator, and are current regulator. These units may be operated as a gang or separately by switches on the main control board that place any desired units into gang or separate operation. All units that have been switched to gang operation may be turned on and off with one switch on the console. If any unit is in separate operation and turned off, a red light on the console lights when the gang switch is turned on.

9.4 Main Gang

After turning on the preliminary gang the main gang is ready to start. This group is divided into two sub-groups. The first contains:

Cooling towers

Cyclotron cooling water pump

Oscillator and deflector cooling water pump

Magnet oil pump

Magnet MJ set

The second contains:

Main oscillator rectifier filament

Main oscillator filament

Booster oscillator filament

Arc voltage supply filament

Ion source filament

Deflector voltage supply filament

This second group of units have time delay relays in their interlock chains and are therefore set aside from the first group.

Selector switches on the main control board permit either gang or separate operation of all units. With these switches set in gang operation a push button switch on the control console turns on the gang. This is done with a three step time delay relay to divide the instantaneous starting load. The first step starts only the magnet MJ set, the next

step starts the cooling towers and the water and oil pumps, and the third step starts all the remaining main gang units. As with the preliminary gang, a red light on the console will light if any main gang unit fails to start or is turned off in separate operation. The main gang "off" button on the console operates a shut-down time delay that keeps the cooling towers, water pumps, and oil pump running five minutes after all other units are shut off.

9.5 Console Operation

With the main and preliminary gang units in operation it is possible to proceed with operation of the cyclotron. Figure 9.51 shows a photograph of the control console in the control room.

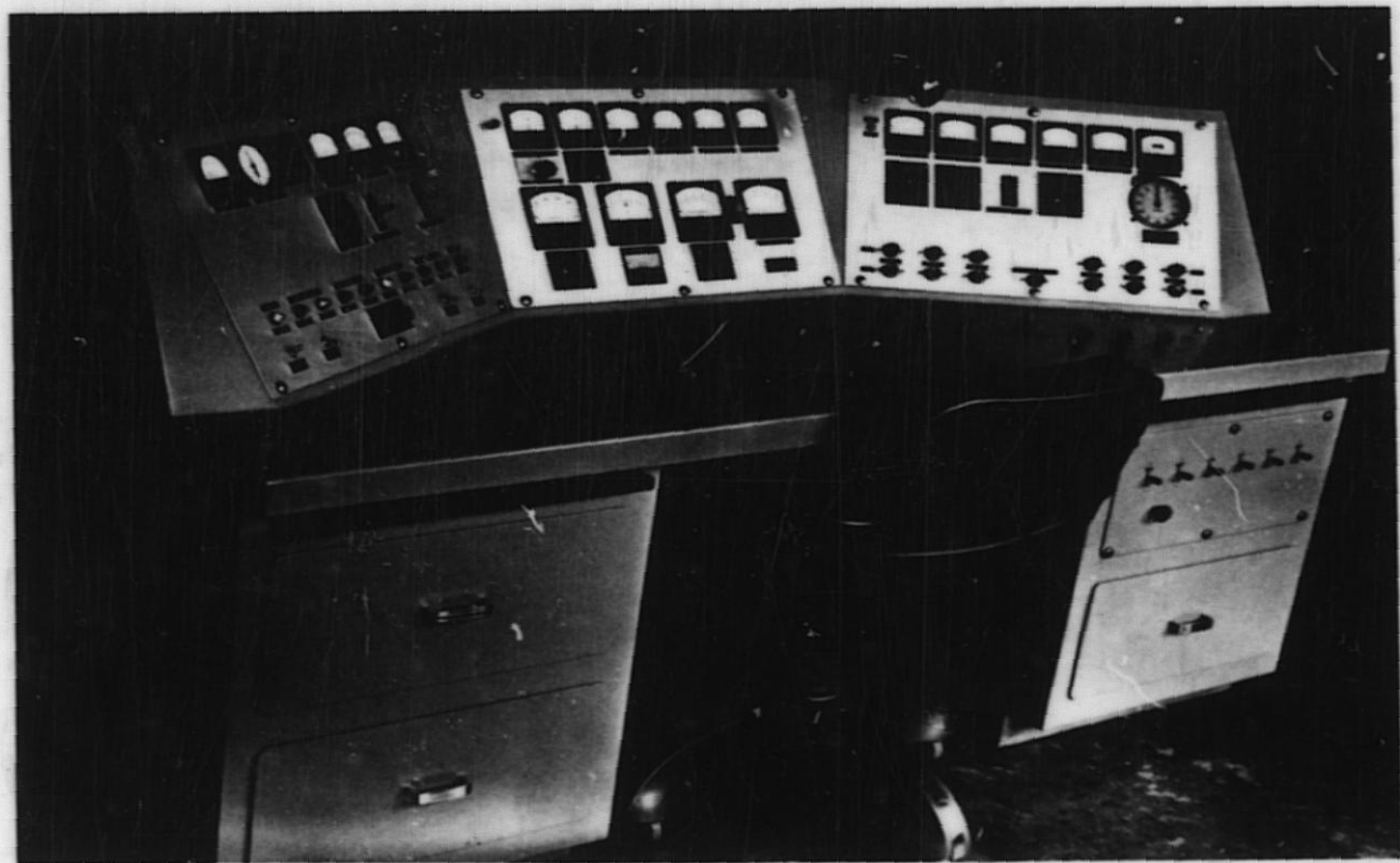
On the right hand panel of the console are a set of six combination push buttons and lights. The lower button is the "off" button and the upper one the "on" button. The green light in the "off" button serves as a ready light and when it is on, it is safe to push the "on" button. When the "on" button is pushed, the unit is turned on, a red light in the "on" button lights, and the green ready light goes out.

The first of these push buttons is the set for the main gang described above. When the main gang is on and all the necessary interlocks are actuated, the ready lights for the magnet current, ion source gas valve, deflector, ion source arc voltage, and oscillator will come on. Then it will be possible to go down the line pushing buttons until the last button puts plate voltage on the oscillator and then the cyclotron is in operation.

Also it is possible to control from the console the other equipment of the cyclotron. These controls include the arc current and voltage and the gas flow in the ion source, the main oscillator plate voltage and booster oscillator frequency, the magnet current, the deflector voltage,

FIGURE 9.51

Control Console in the Control Room



and the position of all equipment with motor drive.

The console also contains all the necessary meters to determine the state of operation of the machine.

9.6 Vacuum System Controls

Since the vacuum equipment will be required to operate on a 24 hour per day basis, the controls for it have been separated from the rest of the control system. The control power for the vacuum system is supplied through a circuit breaker in the control room that is left on all the time.

The vacuum equipment control is divided between the control room and a small vacuum control panel on the west end of the magnet frame which is shown in the photograph, figure 9.61. Diffusion pump and main gate valve controls are duplicated in both locations. Starting controls on the mechanical vacuum pumps are located adjacent to the pumps so that the operator may see that the pumps start properly.

Pressure measurements are made on the fore-vac side with thermocouple gauges. A selector switch on the console permits reading any of the four gauges in the fore-vac system or the house vacuum gauge from the console. On the high vacuum side of the system standard ionization gauges patterned after those used in Berkeley are used. A protective unit is used that turns off the gauge tube filament and closes the main gate valve if the pressure rises above a pre-set level.

9.7 Duplicate Oscillator Controls

A complete duplication of controls for equipment necessary to operate the oscillator as well as special components for testing have been provided in panels on the balcony of the cyclotron room adjacent to the oscillator and are shown in the photograph, figure 9.71. This should facilitate the initial operation of the oscillator as well as being helpful

FIGURE 9.61

Vacuum Control Panel and
Gas Supply System

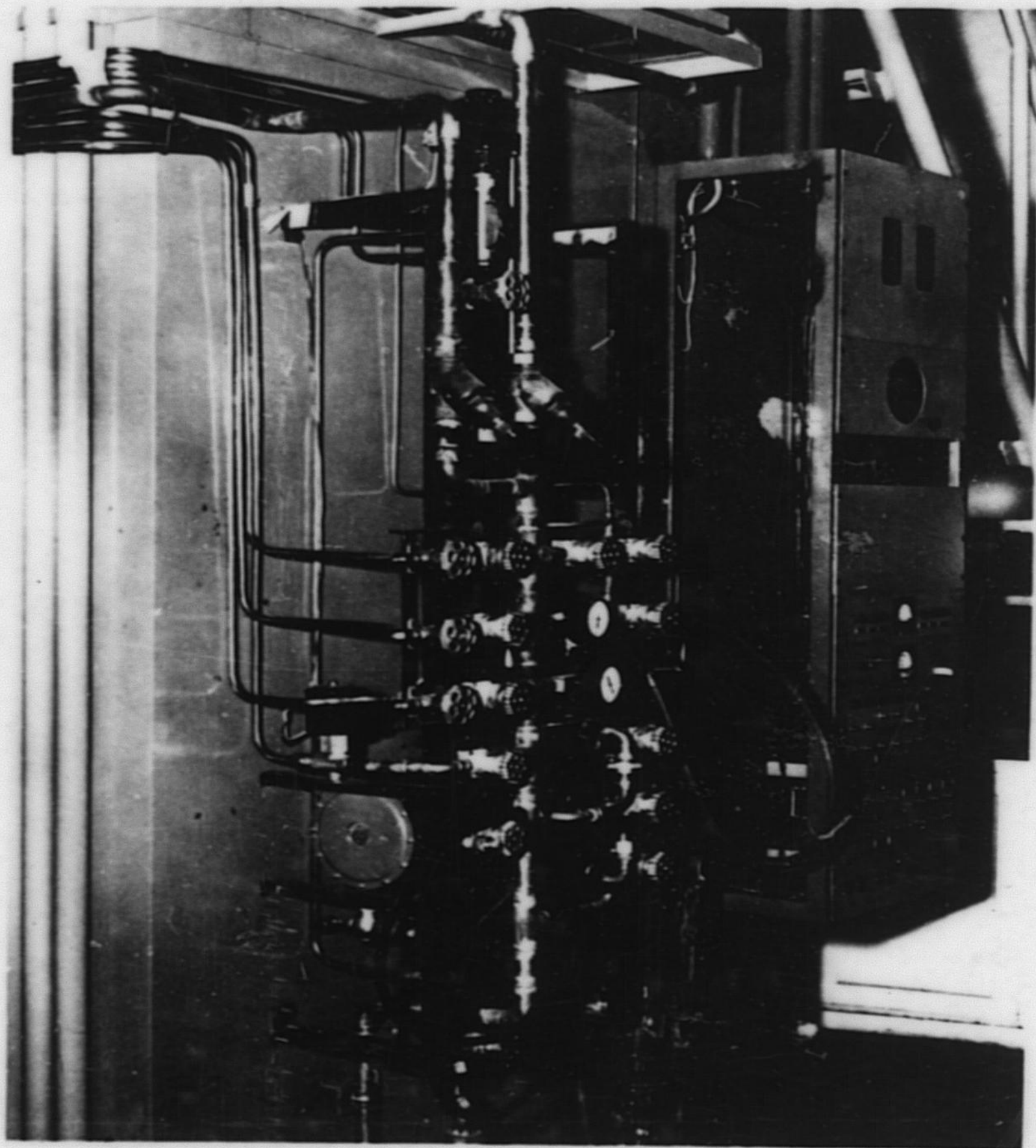
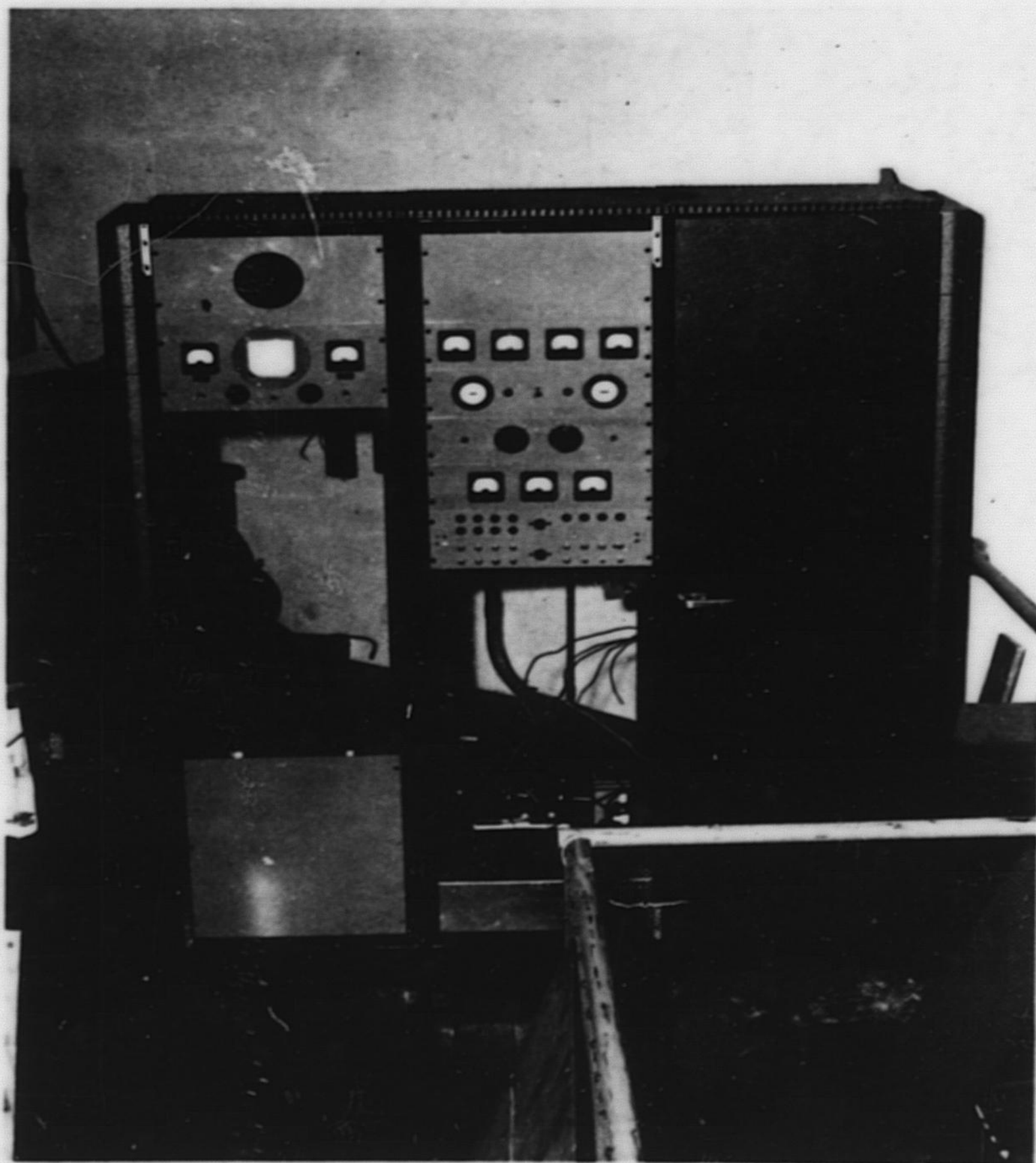


FIGURE 9.71

Duplicate Oscillator Controls on
Balcony of the Cyclotron Room



later for routine test procedures.

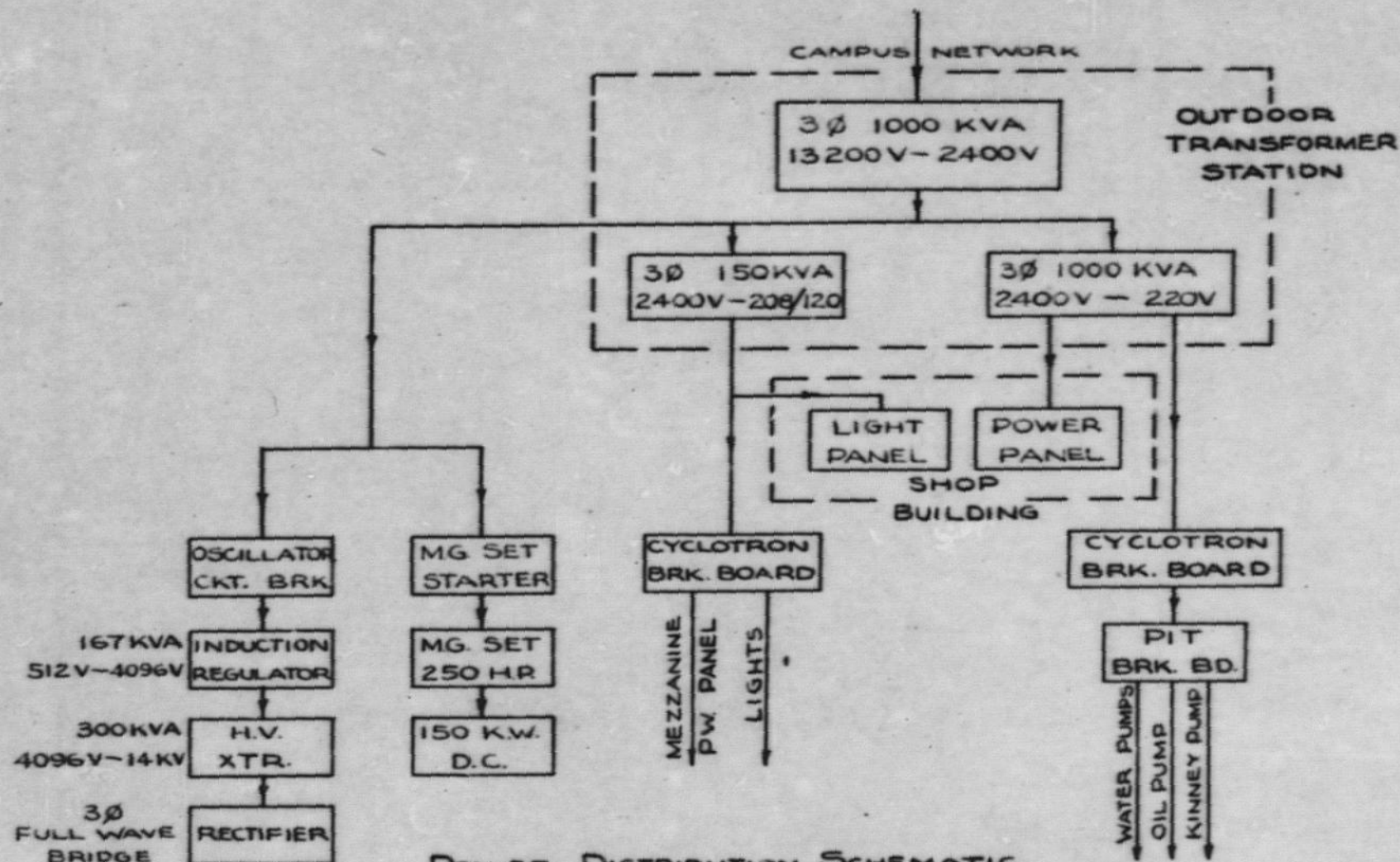
9.8 Wiring Procedures and Drawings

The general plan for wiring has been to use a cross-connect system with main terminal boards in the cyclotron, control, and motor generator set rooms. All control wiring from room to room goes through this network. Terminal strips are provided in the control console and on each panel unit in the main control board. Wiring diagrams for each unit show the designation of the terminal strip on the unit and the destination of all wires leaving the strip.

One complete schematic drawing showing the relation of all units and the location of connecting wires is maintained up to date. Book records keep track of vacant terminals and wires in the cross-connect network and vacant relay contacts in the relay panels.

9.9 Power Distribution

The power distribution system is straight forward and standard. Figure 9.91 shows all the major features of the system.



POWER DISTRIBUTION SCHEMATIC.

FIGURE 9.91

10 COOLING SYSTEM

The cyclotron cooling system consists of two distinct parts:

- (a) Magnet coil cooling system
- (b) Cyclotron - components cooling system

In each system the heat is absorbed by a coolant in the machine and the coolant then pumped underground to the outdoor cooling towers shown in figure 10.01. Cooling is effected by evaporation of spray water from the surface of tube bundles. The tower on the left cools the magnet oil and the tower on the right the cyclotron water.

DESIGN & OPERATING CHARACTERISTICS
OF CYCLOTRON COOLING

System	Coolant	System	Installed Capacity	Circuits	Pumps	Design Temp. Deg. F.	
						Out	In
Magnet Cooling	Oil Menco "C"	Open	170 KW	Upper Coil Lower Coil	175 GPM 200' Hd.	120	100
Cyclotron Components	Water	Closed	340 KW	33 Laterals & Spares	250 GPM 200' Hd. (Total 2 Pumps)	120	100

Circulating pumps are shown in figure 10.02, and are located in the service pit below the magnet. Beginning from left to right there is the 75 GPM water pump, which supplies 50 GPM of water to the oscillator tube, next is the 175 GPM water pump for general cyclotron component cooling and on the right is the 175 GPM oil circulating pump.

Heat is absorbed from the inner surfaces of the cyclotron by water flowing through 1/4, 3/8, 1/2, and 5/8" diameter copper tubes silver soldered to the copper surfaces. Each water circuit cools a given area and the flow is set and flow conditions indicated by means of a modified G.E. flow switch which is interlocked with the electrical control system. A flowrator with valves and interlock is specially provided for the .

FIGURE 10.01

The Outdoor Cooling Towers

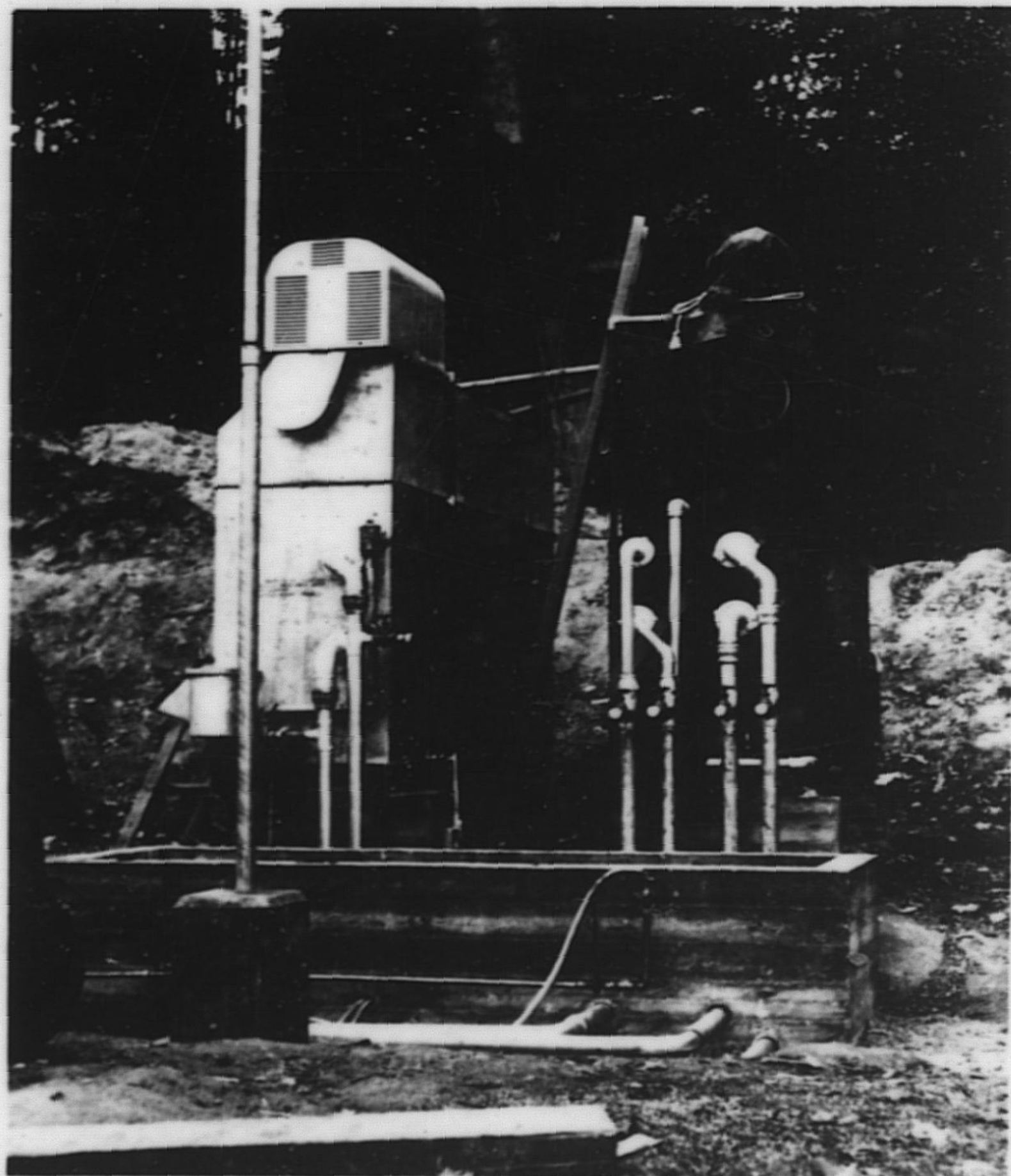
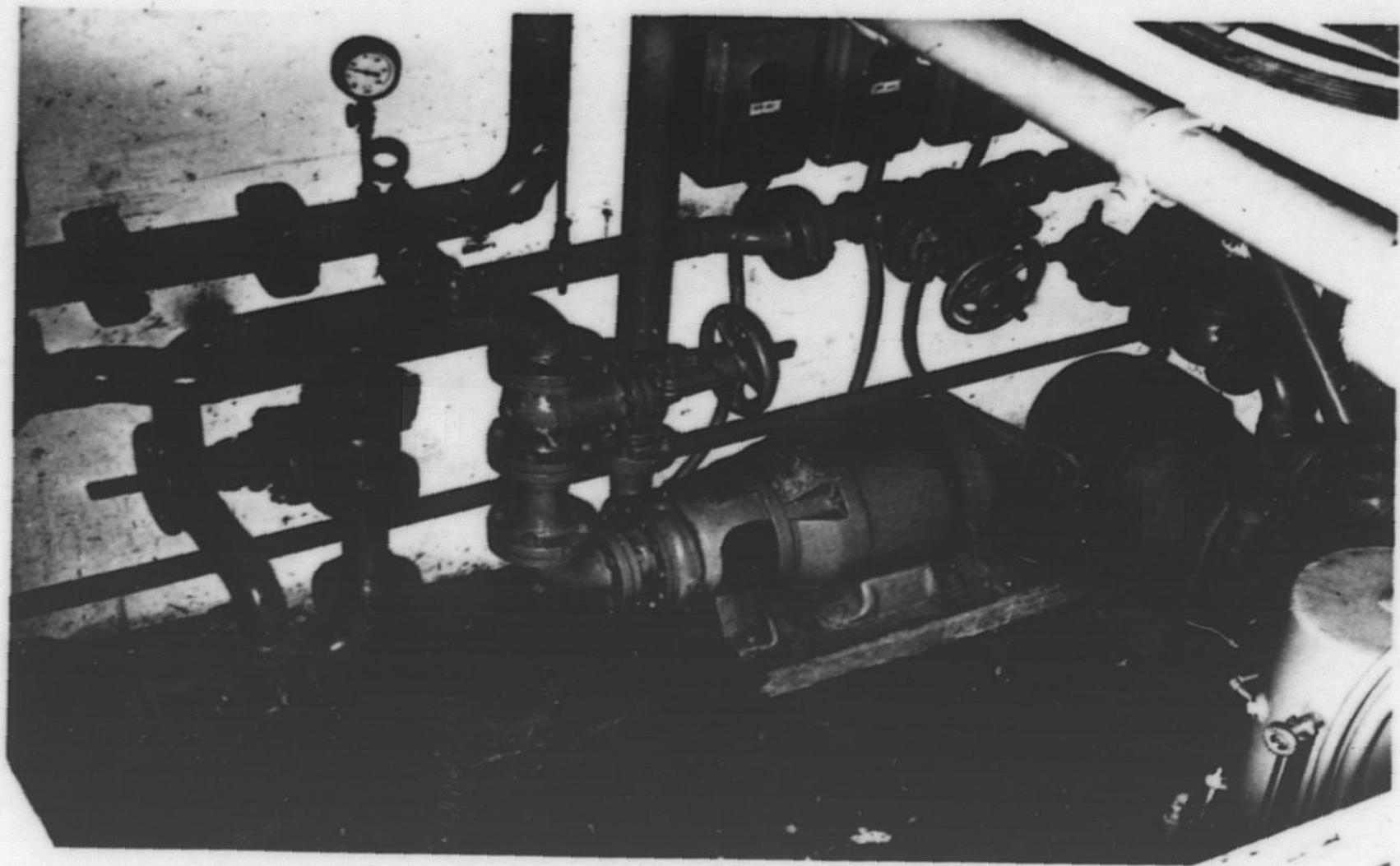


FIGURE 10.02

Circulating Pumps in Pit



oscillator tube located on the mezzanine. The tube requires 50 GPM.

Primary cooling at the towers is dependent upon the outside wet bulb temperature. The system was designed on the basis of 65° F. W. B. which occurs in July and August. A minimum W. B. of 36° F. occurs in January. Provisions have been made for future installation of an automatic temperature regulator to maintain uniform temperatures when required. A flow diagram of the system is shown in figure 10.03.

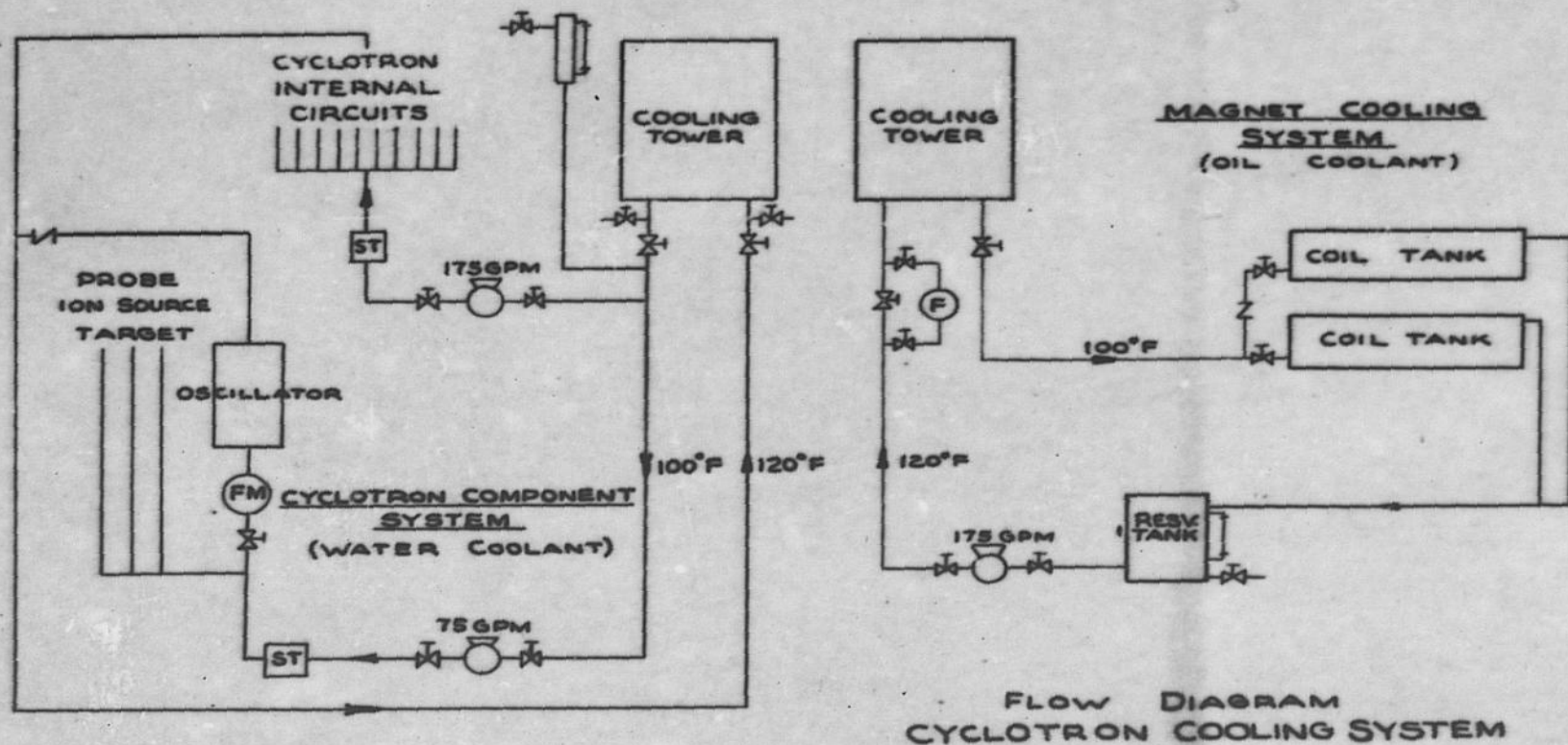


FIGURE 10.03

11 MISCELLANEOUS

11.1 Deflector

Removal of the ion beam from the vacuum chamber is effected by the deflector which is placed at the end of the acceleration cycle and causes the beam to enter the region of weak magnetic field. Upon the completion of magnetic field plots the preliminary design of an external type of deflector was completed. Machining work will begin after the oscillator is operating and an internal beam produced.

The deflector will have a variable groove and will operate with both d-c and r.f. current. A power supply of 60 kv and 20 ma. will be installed.

With the completion of the internal and external magnetic field measurements, it has been possible to design the beam deflector, and to calculate the expected phase, energy, and intensity characteristics of the beam. The original plan of 90° deflector has been modified in order to give greater mechanical stability to the deflector control mechanism. Calculations show that a deflector of 70° length, starting 60° beyond the dee gap in the west dee, will be able to deflect all types of ions used. The deflector will be designed to take advantage of the r.f. electric field, which may be supplemented by the addition of a d-c field when the cyclotron is operated with a smaller oscillating voltage than 120 kv. The deflector plate is kept at r.f. ground and the ions enter in such a phase that they feel the force of deflection from the field between the plate and dee edge during the entire deflection.

A study of the phase characteristics of a deuteron beam indicates that a minimum of 80 kv dee to ground r.f. potential is necessary in order that the ions do not enter the region of decelerating phase at any time within the dees. This will mean a necessary addition of 34 kv

d-e to the deflector in its present design. For protons, which require a smaller deflecting field, the width of the deflector channel may be increased by remote control. The mechanical mobility of the deflector plate insures the adjustment of the channel width to meet all expected circumstances of deflection. In the event that a greater ion flux is desired, the channel may be widened at the exit, or even along its entire length. For a greater energy selectivity, the deflector channel may be narrowed to a constant width of 0.90 cm.

Under the most favorable circumstances, an energy spread of about 1.5 MeV about a mean energy of 21 MeV is expected for the deuteron beam at the deflector exit. The most energetic ions will exit towards the outer part of the beam. It may be shown however that there is an intensity gradient across the emergent beam which tends to greatly diminish the flux of the ions of extreme energies. The beam with useful intensity may thus be limited to around 1 MeV spread. The external velocity selector will be expected to resolve this beam into a somewhat smaller energy spread with a corresponding loss of total ion flux.

A plot of the path of the beam has been made extending into the target chamber region, and out into the cyclotron room. It is now possible to complete the design of the external apparatus such as the target chamber and various pieces of research equipment directly associated with the beam.

11.2 Probe

Machine work has started on a probe assembly using an internal target. A water cooled tube extending through a vacuum lock runs above the west dee to a variable target location between the dees. The position of the target may be varied from approximately 10" to 25" magnet radius by remote control.

The beam current may be measured in either of two methods. One may measure the temperature difference of incoming and outgoing water and thereby find the power absorbed by the target from the beam, or one may insulate the probe from ground and measure the beam current on the target directly by measuring the current from the probe to ground. The latter method is preferable because it is a direct measurement, and secondly, because the temperature difference for an appreciable flow of water is very small and more difficult to measure.

12 STAFF

The following is a list of personnel active on the Cyclotron Project since July 15, 1950.

PERSONNEL

Project Director

Utterback, C. L.
Executive Officer
Department of Physics

Engineering Staff

Donnelly, F. K., Sr. Engineer
Engelbrecht, H. J., Ass't. Electronic Eng'r.
*Garnett, A. A., Ass't. Electrical Eng'r.
*Brand, E. H., Ass't. Mech. Eng'r.
*Musatko, Harold, Ass't. Mech. Eng'r.
*Thompson, E. J., Draftsman

Secretary

Laird, Mrs. Dorothy

Electronic Technicians

Orth, J. W.
Elliott, Robert

Accelerator Technician

Morgan, Ted

Cyclotron Committee (Physicists)

Henderson, J. E., Chairman
Schmidt, F. H.
Streib, J. F.
Farwell, G. W.

Research Assistants (Graduate Students)

*Gross, W. E.
Livdahl, P. V.
Wegner, H. E.
Stencien, J. O.
Penning, J. R.
Harlow, F. H.
Meyer, D. I.

Machinists

Bennett, H. E., Shop Foreman
Knutsen, Clarence, Lead Mach.
Savage, Stanley
Willman, Allen
Bergman, Ralph
*Pursell, Weldon
Grubb, Robert
Sorensen, A. G.
*Carlson, S. O., Mach. Helper

* No longer on Staff due to reduction in force.

DEPARTMENT OF PHYSICS CYCLOTRON PROJECT PERSONNEL

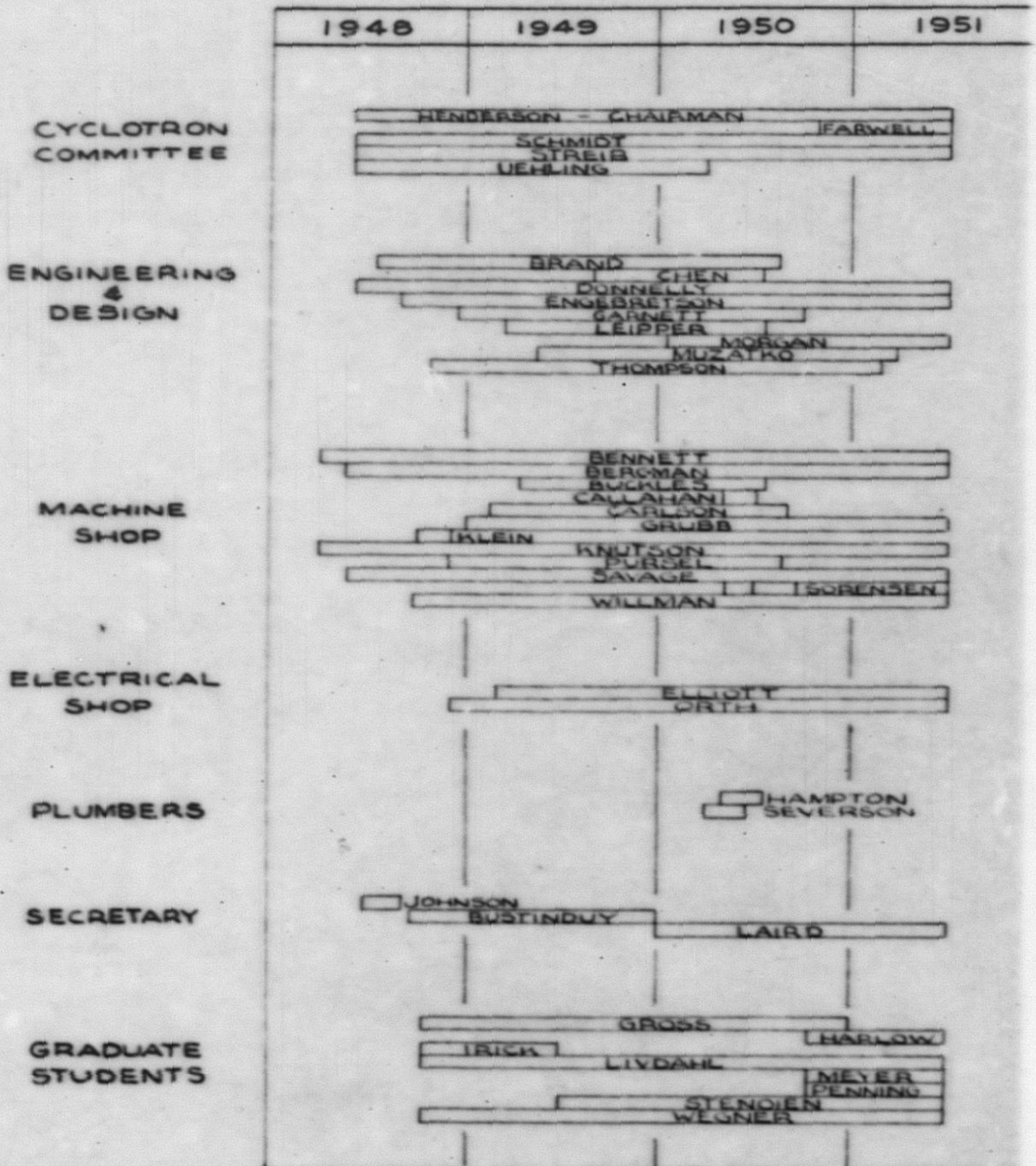


FIGURE 12.01

DEPARTMENT OF PHYSICS CYCLOTRON PROJECT PERSONNEL - GROUPS

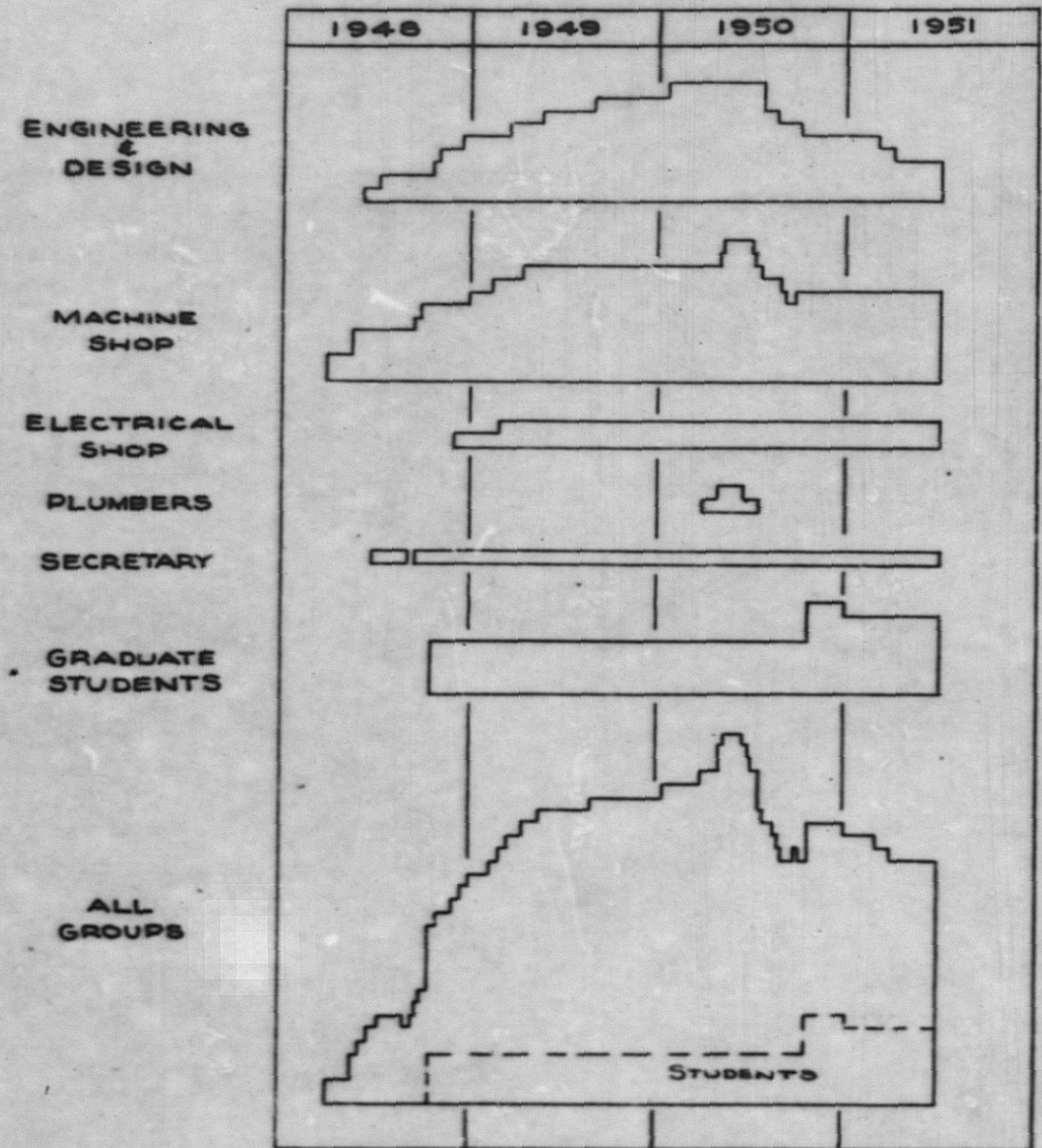


FIGURE 12.02

APPENDIX

AL LIST OF PREVIOUS REPORTS

All Reports were submitted to O. N. R.,
San Francisco, and Nuclear Physics Branch,
O. N. R., Washington D.C. relative to
Contract NS-ONR-520, Task Order I

1. Quarterly Progress Report No. 1 for Period August 15 to October 1, 1948
2. Quarterly Progress Report No. 2 for Period October 1, 1948, to January 1, 1949
3. Quarterly Progress Report No. 3 for Period January 1 to April 1, 1949
4. Quarterly Progress Report No. 4 for Period April 1 to July 1, 1949
5. Quarterly Progress Report No. 5 for Period July 1 to September 30, 1949
6. Quarterly Progress Report No. 6 for Period October 1 to December 31, 1949
7. Quarterly Progress Report No. 7 for Period January 1 to March 31, 1950
8. Final Status and Quarterly Progress Report No. 8 for Period April 1 to June 30, 1950

A2 FINANCIAL SUMMARY

A2.1 Consolidated Expenditures

Review of Expenditures to April 15, 1951
on Joint Program
(Exclusive of U. of W. Overhead &
Physics Department Staff Salaries)

University of Washington Expenditures

Buildings	\$225,000	
Materials & Supplies	201,500	
Payroll - Salaries & Wages	14,000	
	\$440,500	\$440,500

O. N. R. Contract NS-ONR-520

Payroll & Miscellaneous	\$150,000	\$150,000
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A. E. C. Contract A.E.C.(45-1)-293

Payroll & Miscellaneous	\$51,500	\$51,500
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TOTAL EXPENDED (Approx.)		\$642,000

A3 CYCLOTRON SPECIFICATIONS

DESIGN SPECIFICATIONS
UNIVERSITY OF WASHINGTON
60" CYCLOTRON

GENERAL

Maximum useful radius	26 1/2	inches
Available energy range		
Deuterons	14 to 28	mev
Alpha	28 to 56	mev
Protons	7 to 14	mev
Average beam currents (expected)		
Deuterons	100-300	μa
Alpha	5-30	μa
Protons	50-100	μa
Maximum Mag. Field	19,100	gauss
Oscillator Frequency	9.25 to 13.25 mc	

MAGNET FRAME

Pole Gap	22	inches
Thickness of Dee Tank (Top and Bottom Plates)	5 1/2	inches
Pole Gap (Nominal)	11	inches
Air Gap (Each, Top and Bottom)	1/2	inches
Pole Diameter	60	inches
Pole Diameter (useful)	53	inches
Magnetic Field (Center-Maximum)	19,100	gauss
Relative decrease mag. field at 15,000 gauss at 25 1/2"		2%
Iron (Forgings) (The Midvale Company)	200	Tons

MAGNET COILS

Excitation	624,000 ampere turns	
Turns	1560	
Material	18 Tons of 1/8" x 2 7/8" Copper Bar	
Current	400	amperes
Resistance	1	ohms
Voltage	400	volts
M-G Set	Fairbanks Morse 250 h.p. Synch. Motor Fairbanks Morse 150 kw d-c Gen.	
Oil Cooling		
Wemco "C" Transformer Oil		
Capacity of System	900	gals
Flow Rate	175	gpm
Operating Temperature	100°	F.
Temperature Rise	20°	F.
Cooling Tower - (York Rezonizer EV-9)	593,000	BTU/hr

OSCILLATOR

Main Oscillator

Oscillator Plate Voltage d-c	15	kv
Oscillator Plate Current d-c	15	amps
Oscillator Power Input	225	kw
Oscillator Tube Type	ML 354 (Machlett)	

OSCILLATOR - Cont'd.Main Oscillator - Cont'd.

Oscillator Tube Plate Dissipation	75	kw
Oscillator Tube Cooling Water	50	gpm
Oscillator Plate Peak rf	13	kv
Oscillator Grid Bias	-813	volts
Oscillator Grid Leak (Approx.)	365	ohms
Oscillator Filament Voltage	13	volts
Oscillator Filament Current	223	amps
Dee Capacity	350	mmf
Q of System	6,000 (Est.)	
Frequency Range	9.25 to 13.25	mc
Dee Voltage (Peak, to Ground)	150	kv

Booster Oscillator

Remodeled BC-877 Transmitter		
Power Output	2	kw

Oscillator Power Supply

Circuit Breaker ITE Type MV-50		
Induction Regulator GE	133	kva
Transformer GE	300	kva
Rectifier - 3 Phase Full Wave Bridge		

ION SOURCE - ARC TYPEFilament

Material	Tungsten	
Current (Max.)	300	amps
Voltage (Max.)	6	volts

Arc Voltage

Voltage (Max.)	500	volts
Current (Max.)	8	amps

Arc Regulator Emission limit regulation by saturable reactors in filament rectifier primary

Gas Control

Deuterons and Protons	Motorized Needle Valves
Alphas	Motorized Needle Valve

DEE SYSTEM

Dee Stems - 1/8" Electrolytic Copper	9 5/4" O.D.
R.F.Liners - 1/8" Electrolytic Copper	31" I.D.
Capacity Compensator, Copper, 3" x 30" (motor driven)	One
Spinnings - 1/8" Copper, 4 1/4" Height x 53" Dia.	

DEE SYSTEM - Cont'd

Spider - Mechanically operated, externally controlled Two
 Deflector - Variable Groove, 1/4" to 1", d-c and r.f. 60 kv and 20 ma

VACUUM SYSTEMMechanical Pump

Kirney, Model No. DVD 8810, Speed 110 cfm

Oil Diffusion Pumps

D.P.I. MD-7000 (20") Liters/Sec. at 10^{-4} mm 3500

Oil - Myvane 20 2 Gal
 Heater 3.5 kw
 Refrigerated Baffle. Design Temp. -20° F.

D.P.I. MB-200 (6") Liters/Sec at 10^{-5} mm (Booster) 200

Oil - Myvane 20 1000 cc
 Heater 1 kw

Liquid Air Traps 2

MISCELLANEOUSWater Cooling

One 1 1/2 RVH 7 1/2 Ingersoll Rand Pump
 (Oscillator, Probe, Ion Source, Target
 Chamber, Capacity Compensator) 75 GPM
 One 2 RVH 15 Ingersoll Rand Pump (Dee System) 175 GPM
 One Trans KH-1812 Evaporative Cooler
 Capacity 1,161,000 BTU /Hr
 Water In 120° F.
 Water Out 110° F.

Radiation Protection

Cyclotron in 40' - 0" Dia. Circular Room with
 10' - 0" Earth on Perimeter and 24"
 Water above Ceiling

Vacuum Tank

All 61S-T4 Aluminum, 2 1/2" thick, Heliarc Welded

Gas Flow

Operating Pressure in Dee Tank 2 to 4 x 10^{-5} mm Hg.

END