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DESCRIPTION OF FACILITIES AND MECHANICAL COMPONENTS MEDICAL RESEARCH REACTOR (MRR)

JULES B. GODEL

February 1960

BROOKHAVEN NATIONAL LABORATORY
Associated Universities, Inc.
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Abstract

The Medical Research Reactor (MRR) is a heterogeneous, tank-type reactor designed exclusively for medical and biological studies. It is housed in a 60-ft-diameter cylindrical gas-tight steel building connected to the Brookhaven Medical Research Center by air locks. The core contains a clean critical mass of 2.24 kg U^{235} in 17 fuel elements of standard curved-plate design. The MRR operates at power levels up to 3 Mw and is cooled by the forced circulation of water. The control rod system consists of three B_4C filled safety rods and one stainless steel regulating rod which fit between fuel elements. Nuclear instrumentation includes a safety system which will set back or scram the reactor if two out of three identical channels are tripped. Heat generated in the dry graphite reflector surrounding the reactor vessel is removed by the flow of filtered air.

Experimental facilities include two shielded rooms equipped with special treatment ports and vertical 20-ton shutters. The measured radiation at the treatment port for 1-Mw power is 2.03×10^{10} neutrons/cm^2-sec (thermal) with an associated gamma flux of 37 r/min. A broad beam experimental area located at the end of a thermal column is used for whole-body irradiation investigations. These facilities, plus three 4-in. horizontal thimbles, two tangential and one radial to the core, make the MRR a versatile research tool.

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DESCRIPTION OF FACILITIES AND MECHANICAL COMPONENTS MEDICAL RESEARCH REACTOR (MRR)

I. Introduction

1. GENERAL

On March 15, 1959, the Medical Research Reactor satisfied all the conditions of a self-sustaining chain reaction. This event was the culmination of almost seven years of planning, design, and construction and brought to completion the first reactor of its type – one devoted exclusively to medical and biological studies.

The Medical Research Reactor (MRR) is an important adjunct to the Medical Research Center (Figure 1), which houses the divisions of the Medical Department including the Hospital, Biochemistry, Experimental Pathology, Physiology, Microbiology, Medical Physics, and Industrial Medicine.

The unusual hospital arrangement to the right in the photograph is formed by four circular nursing units at the corners of an open quadrangle, with a combined floor area of 44,000 ft^2. In each circular unit, twelve individual rooms are arrayed around a central nursing station from which each patient may be seen through the door of his room. The large rectangular building to the left in the photograph is the 58,000-ft^2 laboratory area. Here, in a layout using a basic 11 × 11-ft module for economy and flexibility, are offices and laboratories as well as special facilities such as controlled temperature and humidity rooms, shielded counting rooms, veterinary service areas, and areas for the storage and processing of radioactive materials.

The MRR is housed in a 60-ft-diameter gas-tight container which is seen, with its adjacent 150-ft-high stack, towards the back of Figure 1.

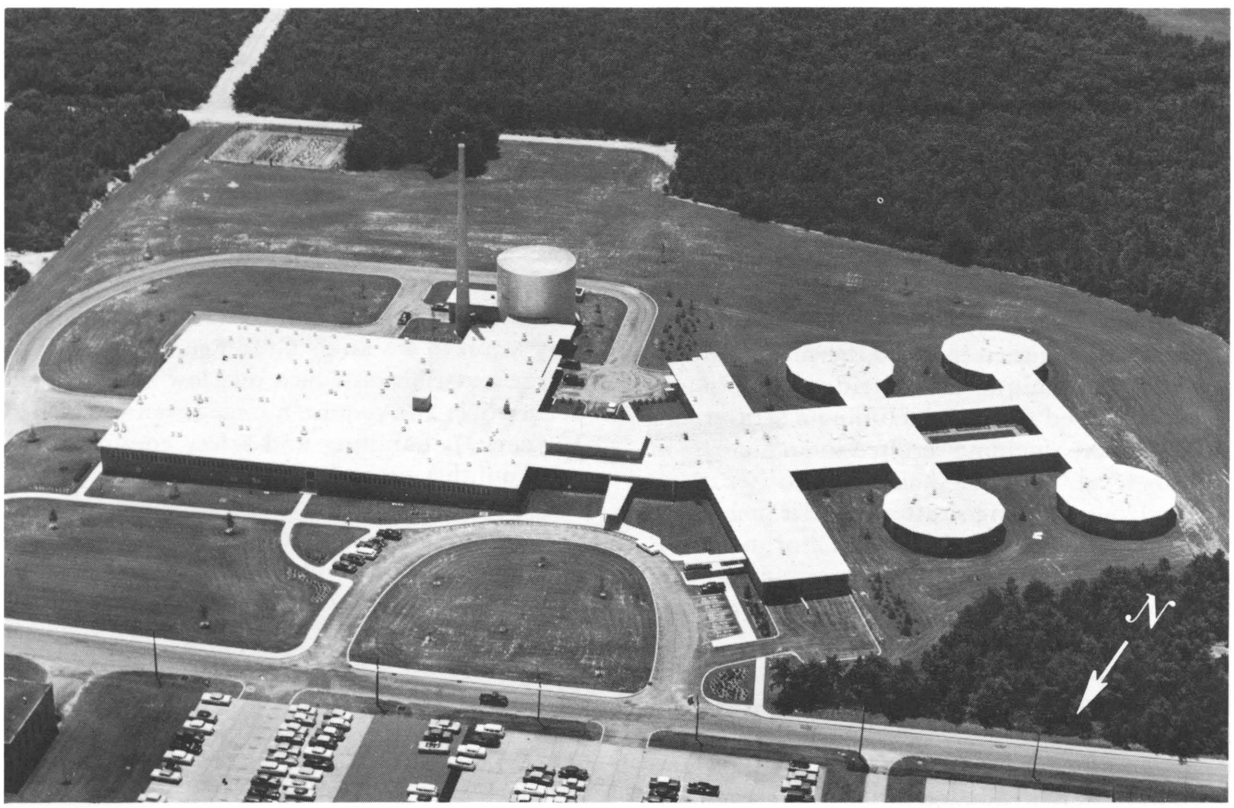


Figure 1. Aerial photograph of Medical Research Center.

The reactor building is connected to the laboratory and hospital areas through an air lock and a wing that contains operating, anesthesia, and preparation rooms. The MRR, with its variety of experimental facilities, is an integral part of the Brookhaven Medical Research Center and serves as a diagnostic and therapeutic instrument.

(Detailed drawings are included near the end of this report, Figures 42 to 44.)

To insure that the MRR would be an effective medical research tool, and would also conform to the highest standards of operational and reactor engineering practice, the close cooperation of many disciplines from the Medical, Nuclear Engineering, and Reactor Operations groups was required. The design, erection, and operation of this reactor were the responsibility of the Project Engineer and the Design Committee (see Appendix C) which served as an advisory group during the initial design phase.

2. EARLY REACTOR EXPERIENCES

Almost five years of medical experience at the Brookhaven Graphite Reactor preceded the construction of the MRR. An important part of this experience comprised neutron capture therapy experiments[1-15] on more than 30 patients, in which thermal neutrons absorbed by an element having a high capture cross section induce heavy-particle (alpha) radiation in a brain tumor mass. The investigations were conducted at the top of the reactor in a facility initially having a fixed cone geometry and capable of a flux of 2×10^8 neutrons/cm^2-sec. Exposure time was controlled by scramming the pile, but this technique was unsatisfactory because it induced thermal stresses in the natural uranium fuel cartridges then in use.

An improved design[16] including a shutter and more effective shielding resulted in an increase in the flux level to 3×10^9 neutrons/cm^2-sec. Also, the horizontal rolling shutter made it possible to conduct experiments with the reactor in continuous operation, so that some experiments, especially irradiations of small animals, could be done during the normal working day.

The Graphite Reactor was used for many other Medical Department needs. Isotopes having short half-lives were manufactured in the pneumatic tubes, and longer-lived elements such as sodium or gallium were irradiated in the production conveyor. Neutron phantom studies were conducted at the west face by using a collimated beam and a special cave. A water cooled facility was used in the irradiation of thermally unstable or organic compounds. Thus, a wide range of experience was gained at the Graphite Reactor which could be applied to the design of the MRR.

3. NEED FOR A MEDICAL RESEARCH REACTOR

It became apparent to the Medical Director and his staff that a facility should be designed for the specific needs of the Medical Department. The general criteria and objectives of a medical reactor have been comprehensively set forth in the *Bulletin of the Medical Department*, July 1, 1959, as follows:

"A. Maximum clinical convenience of the surrounding arrangements and service features, including the contiguous hospital.

"B. Control of program schedule and operation, both as to time and power level, directly on the basis of demands of the medical research program.

"C. Design of the core and reflector to provide the required quantity and quality of radiations.

"D. Design of the shielding, shutters, and other radiation control elements for adequate delivery and limitation of radiation fields in the treament rooms.

"E. Inclusion of isotope production tubes for the instant use of short-lived radioactive materials *in vivo* or for activation analysis of biological materials."

As early as 1954 study contracts were completed by Nuclear Development Corporation of America (NDA), White Plains, N.Y., in which a reactor was recommended as a source of neutrons. Their investigations included reactors, accelerators, and radium-beryllium or polonium-beryllium sources. Accelerators in use at that time could provide only a marginal neutron flux and involved problems such as heat dissipation at the target and high energy input to a Van de Graaff generator. Active source materials provide a very low neutron yield per particle and require a large inventory (10^8 to 10^9 curies); handling and safety considerations ruled out this method.

A preliminary reactor design study followed which covered both nuclear and experimental facilities as well as some aspects of heat transfer and air flow in the core, reflector, and thermal shield. These reports [17-20] proved to be a valuable and important basis for the final design of the MRR.

4. REACTOR DESCRIPTION

The BNL Project Engineer and his staff, with the assistance of many groups at Brookhaven, developed a facility to meet the requirements of the Medical Department. A thermal flux approaching 1×10^{11} neutrons/cm^2-sec at the treatment port was best accomplished, it was concluded, by a modified tank reactor using plate type, fully enriched fuel elements.

The core is cooled by an upward flow of water. The primary cooling circuit was designed with a capacity greater than the original published figure of 1 Mw, and recently permission has been received to operate at 3 Mw. Most core components including the reactor vessel and cooling water system are aluminum.

Space not occupied by fuel elements, control rods, or instrumentation within the cylindrical vessel is filled with graphite blocks which, along with the water, serve as a moderator. One regulating rod and three safety rods with a total worth[21] of 9.7% $\Delta k/k$ are used for control. The rods fit between fuel elements so as not to interfere with fuel handling.

A reflector structure of graphite blocks surrounds the core. The graphite is air cooled; the effluent is discharged through an iodine trap and absolute filters to a 150-ft-high stack. The reflector is contained within a biological shield of steel plates lined with boron carbide, followed by dense concrete containing limonite ore and steel punchings.

The above components presented no difficult development problems as their nuclear characteristics and high degree of safety were well known. The layout and design of experimental facilities involved many studies, including a mock-up of a treatment port in a critical experiment. There are two identical treatment ports, each within a shielded room, on opposite faces of the reactor and as close to the core as minimum patient shielding will permit. The ports consist of openings through the biological shield for the emerging beam, covered by shutters that move up and down to give precise control of irradiation time. The ports are designed for maximum flexibility; filters, moderators, and shields can be rearranged to meet the needs of different experiments.

The Broad Beam Facility, a $5 \times 5 \times 5$-ft space equipped with retractable screens that alter the components and spectrum of the beam, can be used for large mammalian studies. Full access to this facility is possible during shutdown periods by opening a large shielding door. Three horizontal thimbles complete the experimental facilities of the MRR. One of these terminates in the Patient Treatment Room and another is connected to the Animal Treatment Room. Isotopes manufactured in these tubes can be immediately used for *in vivo* experiments.

II. Critical Assembly Tests and Reactivity Measurements on the MRR

G.A. Price

The basic design of the reactor was formulated by Advance Technology Corporation (now NDA) in their final report in January 1955.[19] It specified a tank type reactor employing Bulk Shielding Facility type fuel elements with water moderation and cooling and graphite reflection on four sides.

1. CRITICAL ASSEMBLY TESTS

The initial critical assembly measurements were made at the BNL Critical Assembly Facility under the supervision of Kenneth Downes[41] during the period November 1955 to January 1956. For this purpose a versatile assembly was erected in a pit below ground level, which included four cable-driven control rod drives and a water dump system. Enough neutron detectors were installed to permit reactivity measurements and also to actuate a reactor scram system. Most of the measurements were done at 1-watt nuclear power or less, which made it possible to work on the assembly immediately following any of the measurements without undue radiation hazards.

A 1-g radium-beryllium neutron source provided neutrons to the assembly while it was subcritical and during the approach to critical. Once it became critical, however, the source was removed so that it would not hamper reactivity measurements. Reactivity values were obtained by the so-called "period method." Three sensitive neutron counters were used to observe the rise in neutron level as a function of time. The exponential rise in neutron level was then correlated to reactivity by the general in-hour relationship. Large reactivity changes, such as whole control rod worths, were measured by the "control rod drop" method. A special fuel element with removable fuel plates permitted small increments in fuel loading.

Criticality was achieved with 17 elements plus 7 plates, or 2418 g U^{235}, with 58 in.^{2} water between the loaded core and the graphite reflector. This is in good agreement with the predicted[19] value of ≈2.5 kg uranium.

"Square inches of water" is defined as the area of water between the fuel elements and the graphite reflector, as seen in a horizontal cross-sectional view at the centerline of the reactor. The presence of water channels between the fuel elements and the graphite reflector proved to have considerable effect on reactivity (see Figure 2). The area of water could be increased or decreased in the critical assembly by removing or adding long bars of graphite at the periphery of the loaded core. These bars were coated with an epoxy resin to prevent water penetration.

Figure 3 shows the effect of the worth of fuel plates on reactivity. Each fuel element contains 18 fuel plates with 7.77 g U^{235} per plate, or a total of 140 g U^{235}.

The effect of temperature on reactivity is shown in Figure 4, with 80.5 in^2 water between the core and the reflector. Temperature changes in the critical assembly were accomplished by circulating the reactor water through an external heat exchanger. It should be noted that the temperature coefficient of reactivity, α, is negative over the whole temperature range, and becomes more negative as the temperature increases.

Several control rods were tested by dropping them in a water-filled channel near the center of the assembly. Their shutdown reactivity worths are listed in Table 1.

2. RADIATION MEASUREMENTS IN THE CRITICAL ASSEMBLY

Neutron and gamma radiation measurements were performed on the critical assembly under the supervision of H.P. Sleeper, Jr.[42] Thermal neutrons were measured with dysprosium foils, indium foils, and BF_3 counters. Fast neutrons were measured with a Hornyak button scintillator and a Hurst type fast neutron dosimeter. Gamma-rays were measured with self-reading dosimeters and ion chambers, inside a 1-in.-thick lithium metal shield to eliminate the response of the pencils to

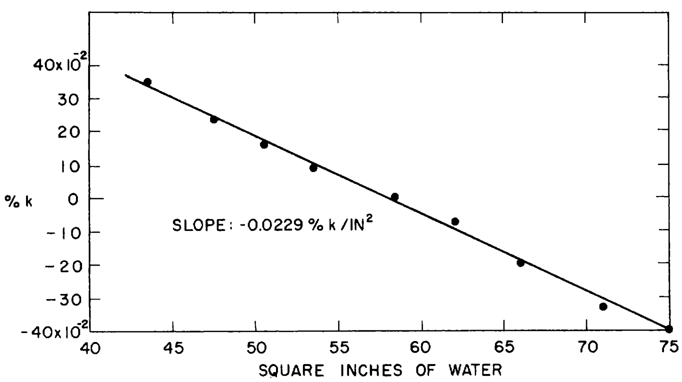


Figure 2. Effect of water on activity.

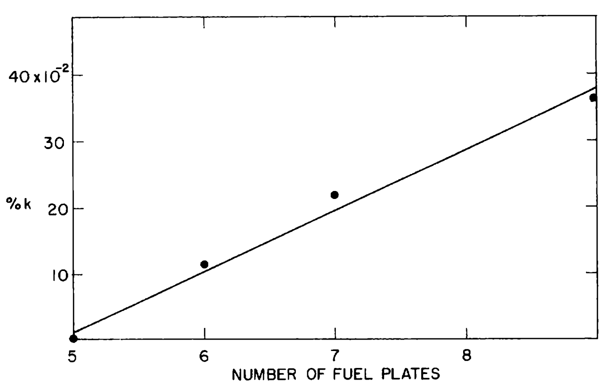


Figure 3. Worth of fuel plates. Loading: 17+ elements.

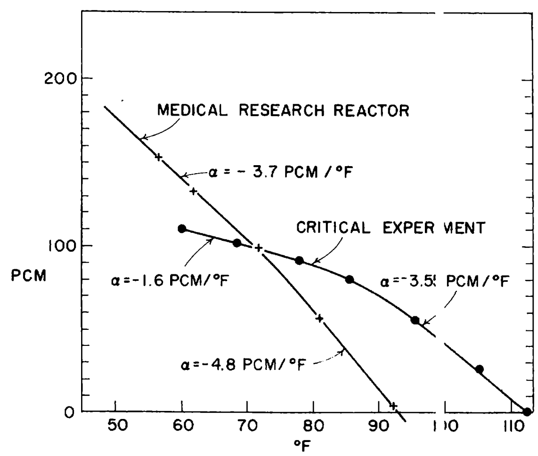


Figure 4. Reactivity vs water temperature.

Table 1

Control Rod Values

Size, in.	Material	% Δ k/k
0.030×2×30	stainless steel	0.08
¾×2×30	stainless steel	0.42
¾×2×30	Cd-Pb alloy	2.3
1×2×30	Cd sheath	1.9
1×2×30	Cd sheath filled with B_4C	2.8

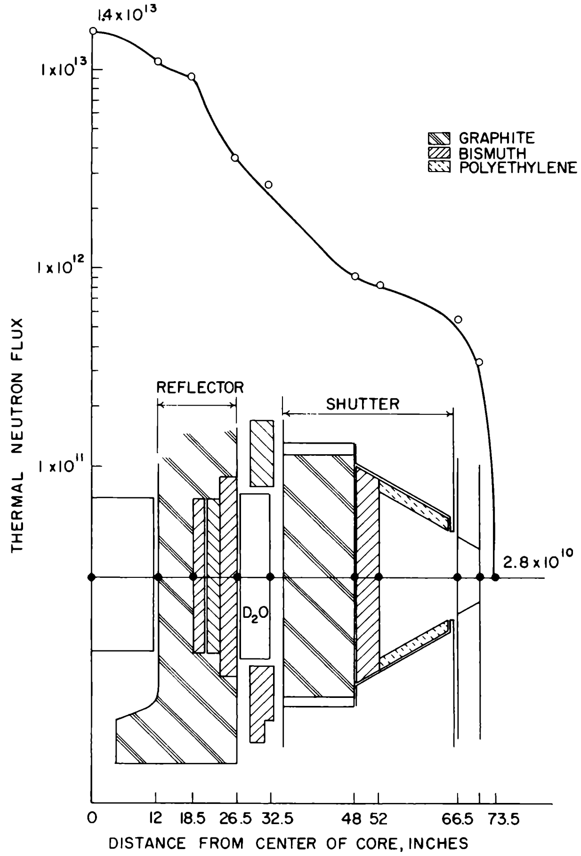


Figure 5. Flux distributions in MRR critical assembly (extrapolated to 1 Mw).

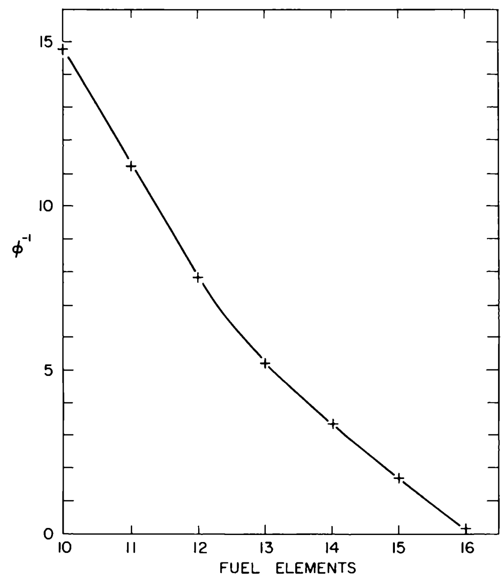


Figure 6. MRR critical approach; BF_3 No. 1.

Table 2

Patient Treatment Data from BNL Medical Reactor Mock-up Critical Assembly Tests (April 4, 1956)

A. Power Level of Critical Assembly

Measured peak thermal neutron flux: 6.83×10^{6} n/cm²-sec
Measured peak-to-average flux ratio: 1.68
Average thermal neutron flux: 4.06×10^{6} n/cm²-sec
Computed average flux at 1 Mw: 9.6×10^{12} n/cm²-sec
Computed critical facility level:
$P_c=4.06\times10^{6}/9.6\times10^{12}=0.42$ watts

B. Patient Treatment Head Exposure*

Critical Assembly

Radiation	2-in. Lucite lining	No Lucite lining
Thermal flux,** n/cm²-sec	4.42×10^{4}	2.63×10^{4}
Fast neutrons,† rep/hr	9.51×10^{-4}	9.10×10^{-4}
Gamma-ray dose,† r/hr	$9.8\ \times10^{-3}$	$11.8\ \times10^{-3}$

Scale-up factor to 1 Mw, $S=10^{6}/0.42=2.38\times10^{6}$

Medical Reactor, 1-Mw Operation

Radiation	2-in. Lucite lining	No Lucite lining	High density graphite used in cone 2 in. Bi + ⅛ in. Pb
Thermal flux, n/cm²-sec	1.05×10^{11}	6.25×10^{10}	3×10^{10}
Fast neutrons, rem/hr (rbe = 10)	2.26×10^{4}	2.16×10^{4}	400 r(rbe = 1)
Gamma-ray dose, r/hr	$2.3\ \times10^{4}$	$2.8\ \times10^{4}$	1000

*Complete port mock-up, including 4-in. Bi wall.
**Measurements made on surface of phantom "head."
†Measurements made 2 in. from steel cone exit.

thermal neutrons. A "phantom" head, made of a plastic mixture reputedly duplicating the nuclear characteristics of a human head, facilitated neutron measurements under expected operating conditions.

Figure 5 indicates the composition of the critical assembly thermal column, and also the distribution of thermal neutron flux for that particular configuration, extrapolated to a power of 1 Mw.

Table 3

MRR Criticality Data

Fuel element	BSF type, 18 plates, 140 g U^{235}
Moderator	water
Coolant	water
Reflector	graphite
Aluminum-to-water volume ratio	0.592:1
Critical mass	2249±13 g U^{235} (16.09 fuel elements)
Uniform temperature coefficient of reactivity, pcm/°F	
at 55°F	−3.7
at 90°F	−4.8
Void coefficient of reactivity, pcm/% water void	
center	−247
outer	−168
average	−186
	pcm
Worth of 3¾×3¾×6-in. Cd box	
in NE experimental hole	−37
in central experimental hole	−173
in NW experimental hole	−22
Raising east shutter	32
Filling D_2O tank	2
Replace Al clad core piece by SiC clay core piece	68
	%Δk/k
Remove Al clad core piece at A-3	0.6
Remove outer fuel element	−1.7
Replace graphite core piece by fuel element	1.1
Control rod worths	
Regulating rod	0.3
No. 2 rod	4.2
No. 3 rod	2.6
No. 4 rod	2.6

Table 2 gives the results of thermal neutron, fast neutron, and gamma radiation measurements in the critical assembly at 0.42-watt nuclear power, and also the same results scaled up to 1-Mw nuclear power.

3. CORE PARAMETERS

No program has been designed to calculate in detail the neutron parameters of this reactor core, but the following estimated values of core parameters are considered to be reasonable

Prompt neutron lifetime, μsec	170
Fast fission factor, ε	1.00
Thermal utilization, f	0.805
Resonance escape factor, p	1.00
Fission neutrons/capture, η	2.07
Infinite multiplication factor, k_∞	1.67
Effective multiplication factor, k_{eff}	1.00
Thermal diffusion area, L^2, cm^2	6
Fermi age, τ, cm^2	54

Similarly, the excess reactivity requirements of the reactor are estimated to be as follows:

Xenon	2.0%
Burn-out, etc.	1.0
Temperature	0.1
Experiments	0.0
Control	0.25
Total	3.35%

4. REACTIVITY MEASUREMENTS ON THE MRR

At the time of the initial loading and start-up of the reactor on March 15, 1959, a series of reactivity measurements were made which verified, in part, the earlier critical experiments and also provided a basis for safe operation.[21] Three low-level neutron detectors were used in addition to the normal reactor instrumentation during the initial start-up. An antimony-beryllium source provided neutrons while the reactor was subcritical, but this had to be removed during precise reactivity measurements because it interfered with them. Reactivity worths were measured by means of positive reactor periods, assuming Keepin's delayed neutron fractions.

Figure 6 is a plot of reciprocal neutron flux vs number of fuel elements during the initial critical approach. The temperature coefficient of reactivity was kept uniform by circulating the cooling water through the heat exchanger and observing the corresponding change in reactivity while the reactor was kept at ≈1-watt nuclear power. The void coefficient of reactivity, observed by inserting small plastic bags between the fuel plates and inflating them with air, was found to be negative but larger than had been predicted by Pigford.[43] The results of the reactivity measurements are given in Table 3. The unit of reactivity, pcm, is defined as $10^{-5}\ \Delta k/k$.

The reactivity effects of xenon poison have been calculated as a function of time and of power and are shown in Figures 7 and 8.

III. Core Components

1. GENERAL DESCRIPTION

The core assembly consists of 17 plate type fuel elements having nozzles that fit into holes in a grid plate. The grid plate itself is accurately located within the reactor tank and has additional holes of the same size and lattice spacing into which fit 8 fuel element-shaped graphite pieces, 5 specially shaped graphite pieces, and two hollow graphite blocks containing a source and a fission chamber. These core components fill the inside of the 23½-in.-i.d. reactor vessel as shown in Figure 9. The active fuel height is 23⅝ in. The core midpoint coincides with the horizontal centerlines of many of the experimental facilities.

Three safety rods and one regulating rod are used in the control rod system. These rods operate in aluminum sheaths located between fuel elements. Each rod is electromagnetically coupled to an extension rod suspended from the drive unit at the reactor top.

Nuclear instrumentation is discussed in detail elsewhere,[25,40] and is described in Section XI of this report.

2. REACTOR TANK

A. Functions

The reactor tank is a stepped cylindrical vessel 20 ft, 7½ in. long (Figure 10) designed to fulfill the following functions:

1. Support and position the core.
2. Contain the coolant and moderator.
3. Provide a holdup volume for water that has passed the core to allow decay time for the entrapped N^{16} before the water leaves the vessel.
4. Furnish a temporary underwater storage shelf for one spent fuel element during operation or for the entire core, if necessary, while the reactor is shut down.

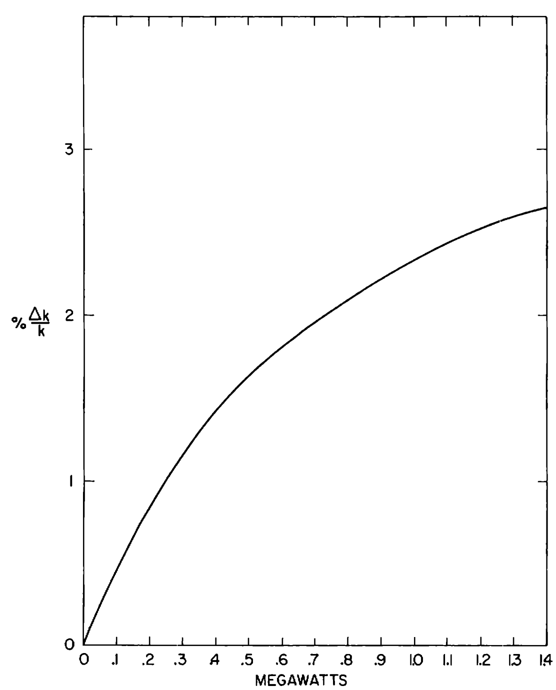


Figure 7. Saturated xenon poison vs reactor power in the MRR.

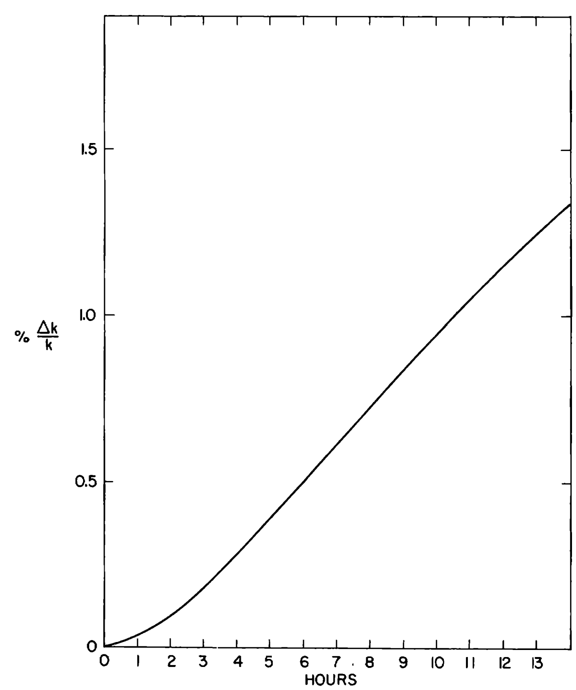


Figure 8. Xenon poison vs time at 1 Mw in the MRR ($\bar{\phi}=0.8\times10^{13}$ n/cm^2-sec).

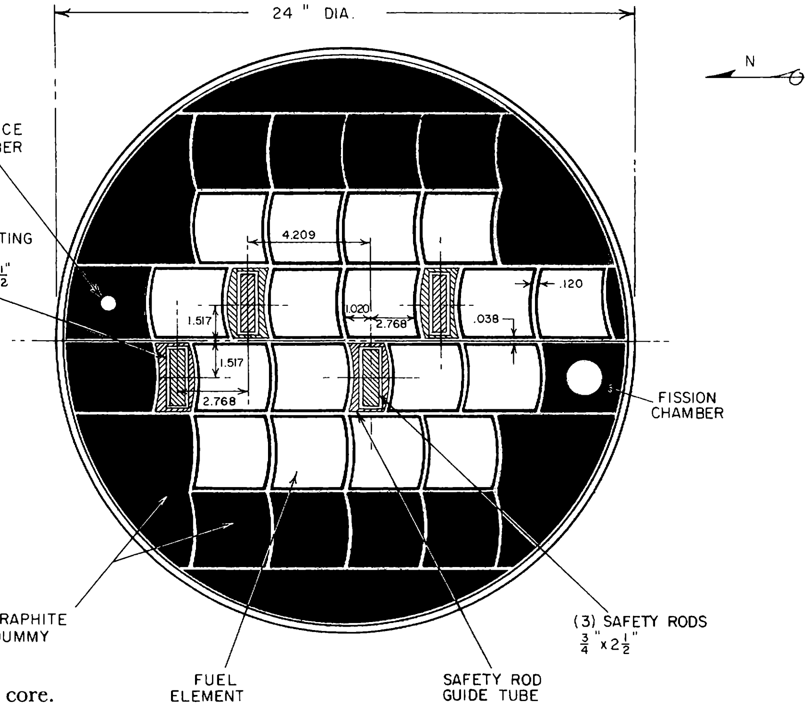


Figure 9. Section through core.

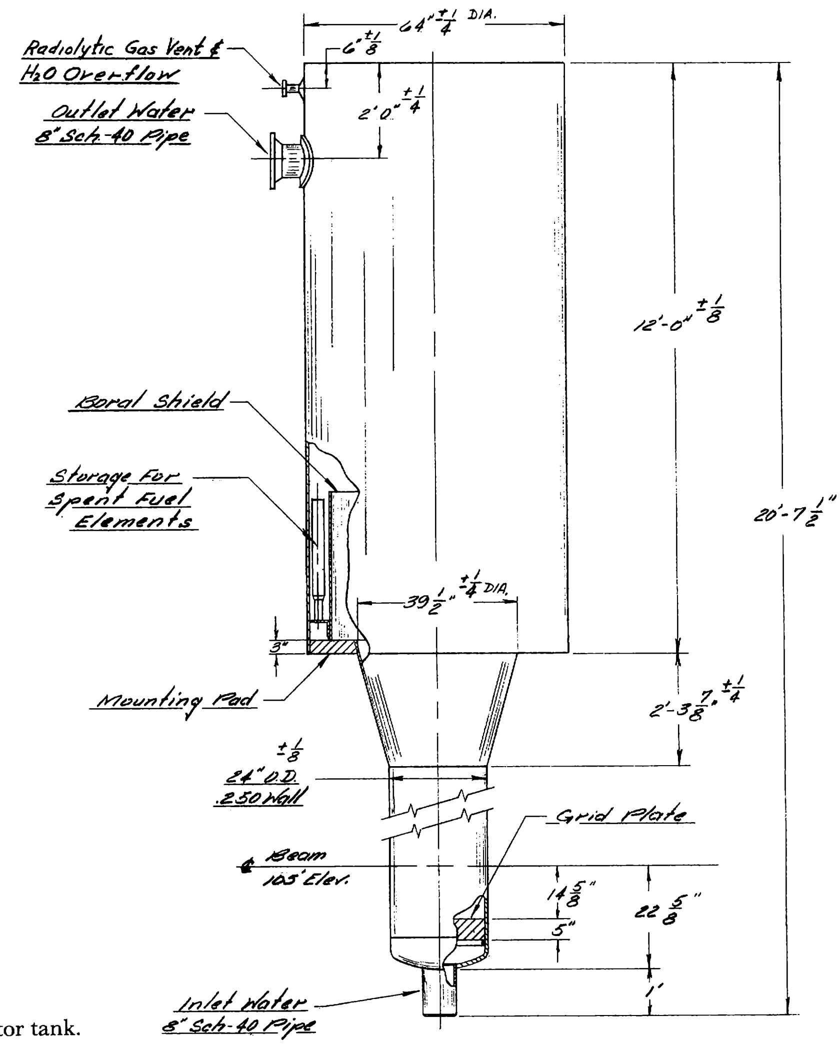


Figure 10. Reactor tank.

B. Design Conditions

1. Working pressure: 10 psi (the top of the vessel is open to the atmosphere).
2. Maximum temperature of coolant: 200°F.
3. Volume: 2079 gal H_2O (to overflow line).
   1837 gal H_2O (to centerline of discharge pipe).
4. Weight, unloaded: 2,150 lb.
   loaded: 19,800 lb.
5. Materials: 1100 and 3003 alloy aluminum body, 6061 nozzles and flanges.
6. Tolerances, welding code, and inspection are covered by specifications.[25]

C. General Description

Water enters from beneath the vessel through an 8-in. schedule 40 pipe welded to a standard A.S.M.E. dished tank bottom (see Figure 10). A 24-in.-o.d. cylindrical extension with a ¼-in. wall connects to a transition cone made of ½-in. plate, which in turn is welded to a 2½-in.-thick flange above. This thick plate serves as a mounting pad for the reactor tank and as the end plate for the enlarged portion of the vessel. The enlarged portion, 64-in.-o.d. with a ½-in. wall, serves as holdup or decay volume. The height of the tank is determined not only by the requirement for holdup volume, but also by the need for a minimum of 15 ft of water shielding above the active portion of the core.

The water is discharged through an 8-in. schedule 40 pipe nozzle located 2 ft from the top of the tank. A small line made of ¾-in. schedule 40 pipe and placed 1½ ft above the discharge water pipe serves as an overflow and as a vent to the exhaust air system. Since the exhaust air system is maintained at a negative pressure, any radioactive vapor leaving the surface of the water will be carried directly to the stack without contaminating the work area above the reactor.

A circular ring welded inside the dished head near the juncture of the 24-in.-diameter cylinder provides a shoulder for setting the grid plate. A lug on the grid plate mates with a groove in the ring for angular alignment of the core assembly.

D. Fabrication and Erection

Tolerances for the tank were established for several purposes. The vessel had to fit within a steel lined recess in the concrete shield without interference. In addition, the 2½-in.-thick mounting plate had to be square with the axis of the tank in order to maintain proper operating clearances in the control rod system. Finally, a ½-in. air cooling gap was needed between the graphite reflector and the 24-in. cylindrical portion of the tank.

Erection was not difficult, but interferences showed that all the tolerances had not been met. Shims of variable thicknesses, from ⅛ to ½ in., were distributed on the steel liner flange under the 2½-in.-thick plate of the reactor vessel. A layer of Embeco was troweled on the shelf between shims before the reactor tank was lowered into place. This technique assured squareness of the 24-in.-diameter portion through the graphite reflector but resulted in a slight interference of the 64-in.-diameter section of the tank with the steel liner, a small strip of which was removed.

E. Comments

In the light of this experience, it is suggested that the reactor tank and its mating liner might best be manufactured by the same fabricator. Tolerances between these components should then be easier to maintain, and inspection procedures would be simplified. Also, the vessel designer should keep in mind from the very outset the method and apparatus that will be used to check the accuracy of this large structure, so that inspection problems will become apparent in the drawing board stage.

3. GRID PLATE

A. General Description

The grid plate accurately locates and supports the core components and is situated 14⅝ in. below the centerline of the core (105-ft elevation). It is fabricated from a 5-in.-thick aluminum forging to an outside diameter of 23¼ in. A manufacturing drawing is shown in Figure 11.

Thirty-two jig bored holes locate fuel elements or fuel element-shaped graphite pieces to a tolerance of ±0.005 in. At the lower end of each hole the element is accurately positioned by a close fit, the diametral clearance being 0.003 in. The weight of each element rests on a 40° tapered shoulder near the top of the hole which mates with a similar taper on the fuel element nose. The nominal distance between hole centers is 3.189 in. in the north-south plane and 3.035 in. in the east-west direction.

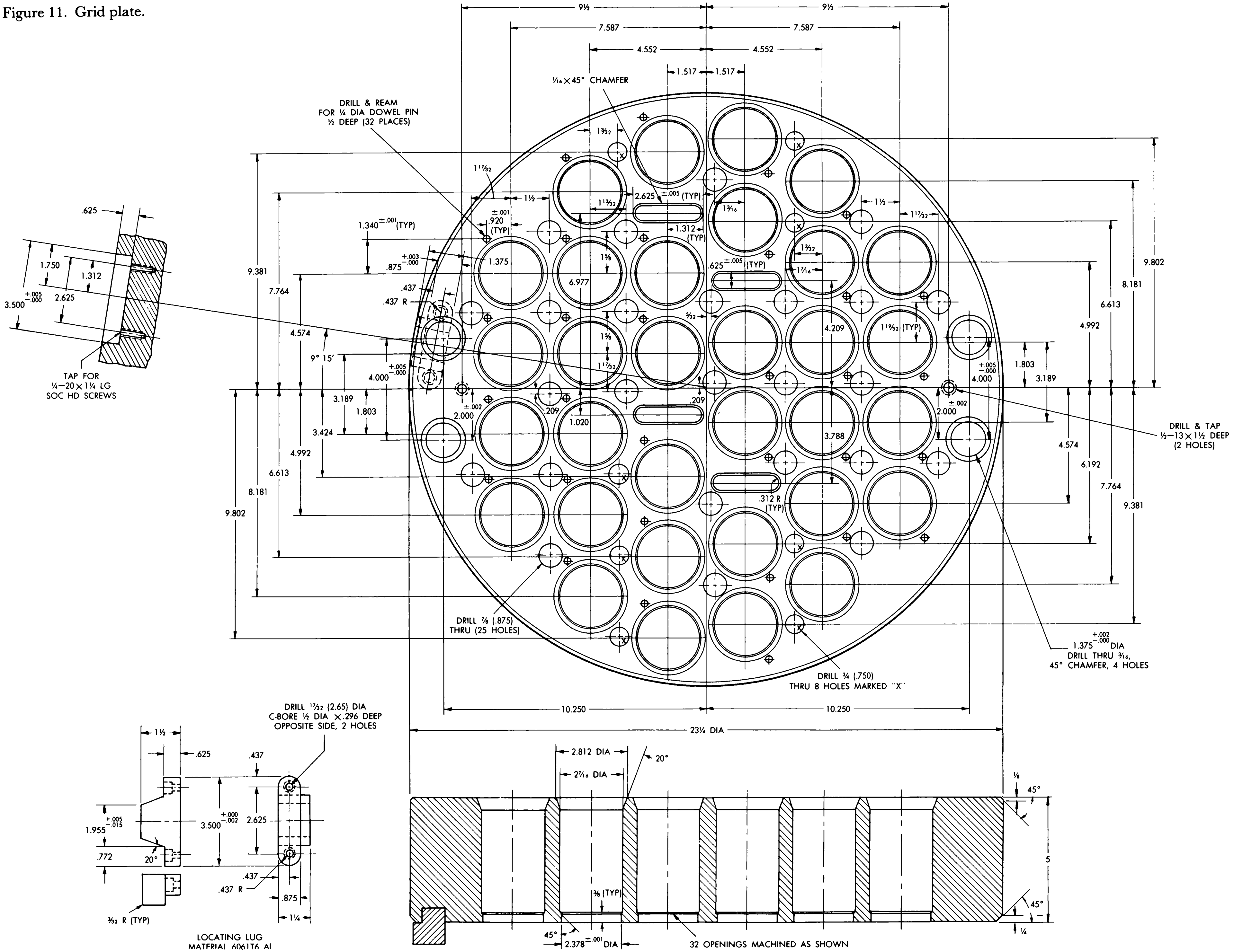


Figure 11. Grid plate.

Dowel pins of ¼-in.-diameter type 304 stainless steel are provided for each element position to insure proper alignment. Other openings in the grid plate include a set of small uniformly spaced holes for coolant flow, four accurately machined slots to receive the control rod sheaths, and four 1.375-in.-diameter holes for mounting the wide graphite pieces at the east and west extremities of the core (see Figure 9). The calculated weight of the grid plate is 112.9 lb.

B. Installation

A locating lug (see Figure 11) is fitted into a recess on the underside of the grid plate. The tapered sides of the lug match the groove provided in the mounting ring within the reactor tank as described in Section III. 2. C. above.

The grid plate, as initially installed, was not level because of the cant of the reactor tank or misalignment of the mounting ring; one end of the plate had to be raised almost 0.125 in. Checking the grid plate was difficult because of the cramped working space inside the 24-in.-diameter portion of the tank.

4. FUEL ELEMENTS

A. Design Conditions

1. Fuel alloy: 12 wt % of fully enriched U-Al mixture.
2. Weight of fissionable material: 140 g per element.
3. Weight of each element: 11.5 lb.
4. Water channel between plates: 0.112 in.
5. Coolant flow area per element: 5.292 in.^{2}.
6. Heat transfer area for one plate: 118.12 in.^{2}.
7. Heat transfer area for each element: 2126.2 in.^{2}.
8. Nonfissionable material: 1100 alloy aluminum.
9. Maximum fuel element temperature: 155°F at 1 Mw (calculated).

3. General Description

The fuel element used in the core of the MRR is based upon a Bulk Shielding Facility design because of its reliability and ease of fabrication. Each element consists of 18 parallel curved plates which fit into grooves in 3⁄16-in.-thick side plates, the whole

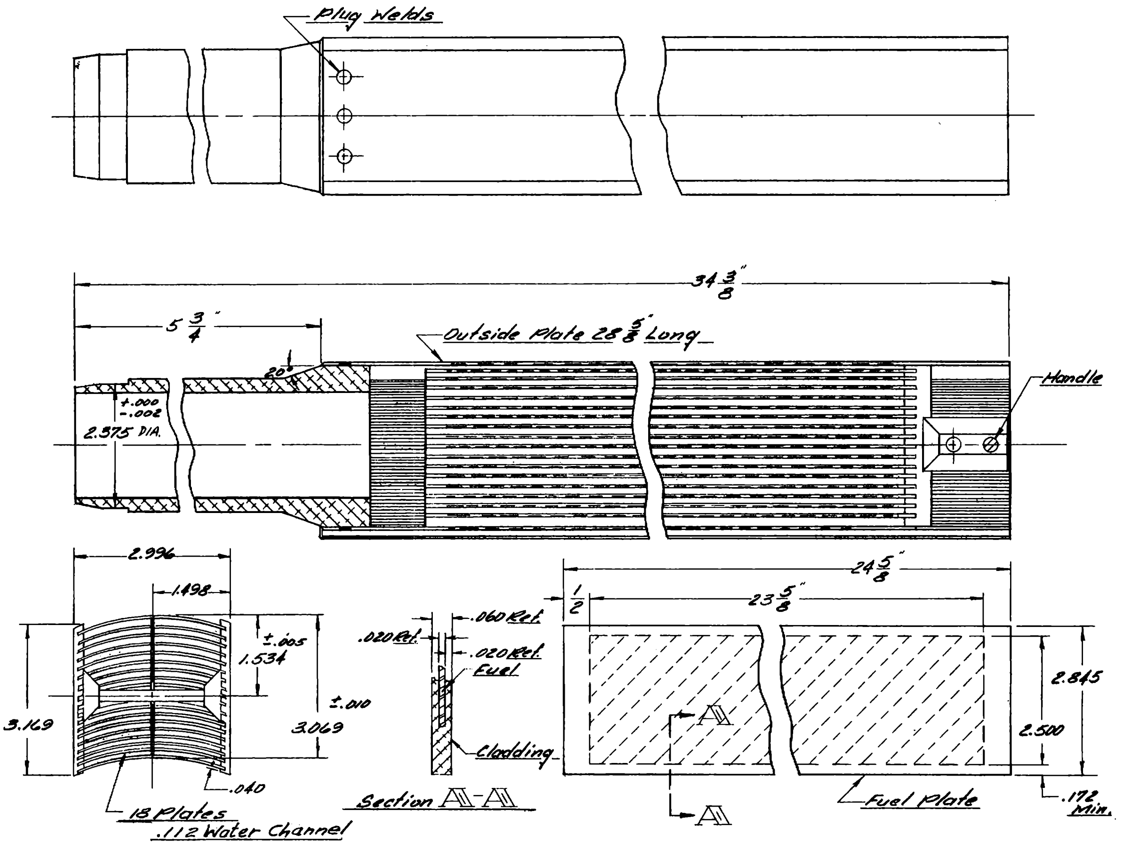


Figure 12. Fuel element.

structure being brazed to form a box of ≈3×3-in. cross section (see Figure 12). The length of the element including the nose piece is 34⅜ in.

The fuel plate is a hot-rolled sandwich of fully enriched U-Al alloy between two 0.020-in.-thick sheets of aluminum. The active portion of the plate is 23⅝ in. long, 2.500 in. wide, and 0.020 in. thick.

The lower end of the box structure is plug welded to a nose piece. An accurate diameter, taper, and dowel pin hole on the body of the nose piece mate with their counterparts in the grid plate. Cooling water flows through a 2-in.-diameter opening in the nose piece and upward between the fuel plates. At the top of the element, welded lugs reinforce a ¼-in.-diameter bale or handle (see Figure 13).

C. Fabrication

Each fuel plate was carefully inspected by the manufacturer for adherence to dimensional tolerances. In addition, plates were radiographed and examined by a BNL inspector for evidence of inclusions, surface pitting (limited to 0.005 in. maximum), or blisters.

A typical melt produced 41 plates, of which 8 were rejected because of inclusions. These carbon particles are thought to have originated in the graphite crucible. Of the 33 plates accepted, 29 had minute imperfections which were not considered to threaten the integrity of the aluminum cladding. Note the blemish in the left portion of a rejected plate shown in Figure 14.

The assembled fuel element, after a thorough cleaning and rinsing to remove residual brazing flux, was given a corrosion resistant coating of Alodine 1200. This was done in two steps, first a dip for 2 min at room temperature in a solution containing 1 to 1¼ oz/gal water, and, after rinsing in running water, a second dip for 10 sec at 110°F in a 0.05-oz/gal solution.

The specifications called for the longitudinal axis of the assembled element to be square with the locating surfaces on the nose piece and parallel to the side plates to within 0.005 in.

The fuel elements have been inserted and removed from the grid plate with ease. After almost one year of underwater service there are no apparent signs of corrosion, galling, or dimensional changes.

D. Fuel Handling

Although the reactor will operate in the 1 to 3-Mw range, the average power over an 8-hr day, 250-day year will be very low. Assuming a maximum burn-up of somewhat less than 15% it is estimated that fuel element replacement will be infrequent, about one element per year (based on a consumption of ≈1 g U^{235} for each Mw-day of reactor operation). Fuel burn-up may be calculated from flux plots and a record of the core position of each element.

A spent element is removed from the core by long handling rods and is raised several feet to the shelf within the reactor vessel where it is stored under water for several months. The decayed element is then raised to the reactor top and into a discharge pig with 8-in.-thick lead walls, weighing ≈5500 lb, in which it is transported to the canal facility of the BNL Graphite Research Reactor for storage.

5. CONTROL ROD SYSTEM

A. General Description

One regulating rod and three safety rods are used as control units for the MRR (Figure 15). Placement of the rods in spaces between fuel elements in the core permits the changing or discharging of fuel elements without disturbing the rod assemblies.

Each control rod assembly consists of a poison or absorber section, magnet, extension rod, guide tube, drive unit, position indicators, and snubber. The rods are driven by units located on a narrow stationary plug at the reactor top. The drive extension rod is connected to an electromagnet which holds the poison section until a scram signal interrupts the flow of current, whereupon the absorber falls into the core. The snubber cylinder is used to decelerate the rod during the last few inches of travel.

B. Design Conditions

	Safety Rod	Regulating Rod
Number required		1
Cross section, in.	¾×2	½×2½
Active length, in.	2	26
Material	B_4C, Cd line	SS
Travel, in.	2	26
Traverse time, sec	18	20
Weight (inc. armature), lb	19.	20
Total drop time, msec	60	375
Rod worth ($\Delta k/k$)	4.2%, 2.6%, 2.6	0.3%

Figures 16 and 17 are rod calibration curves.

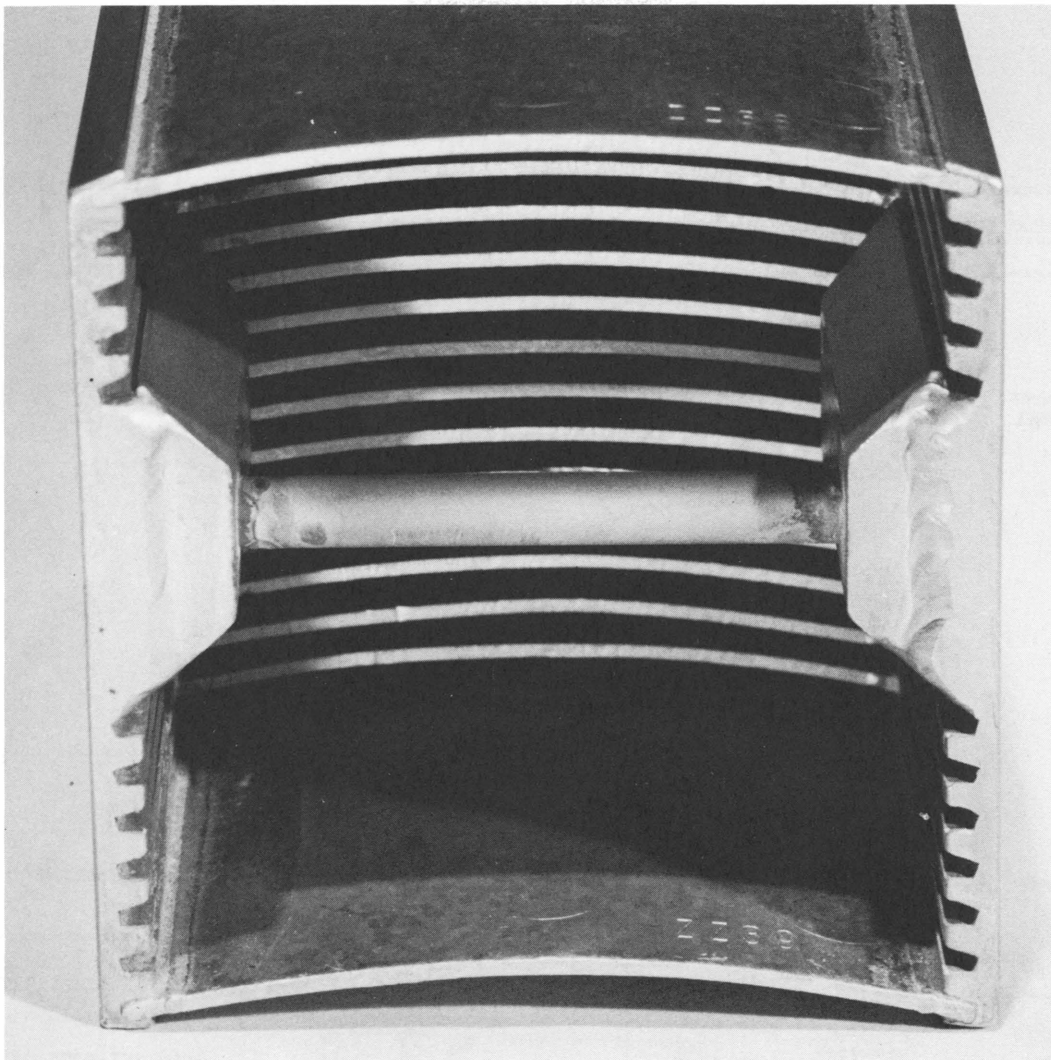


Figure 13. End view of fuel element.

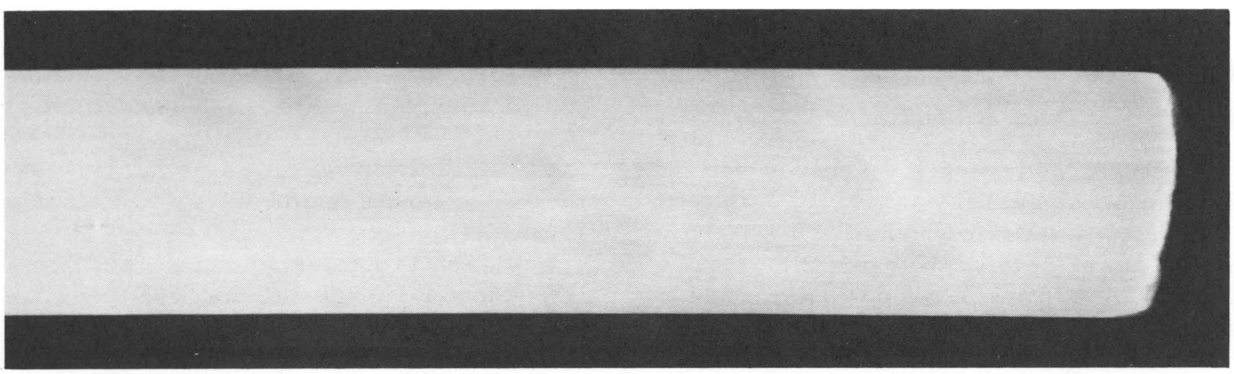
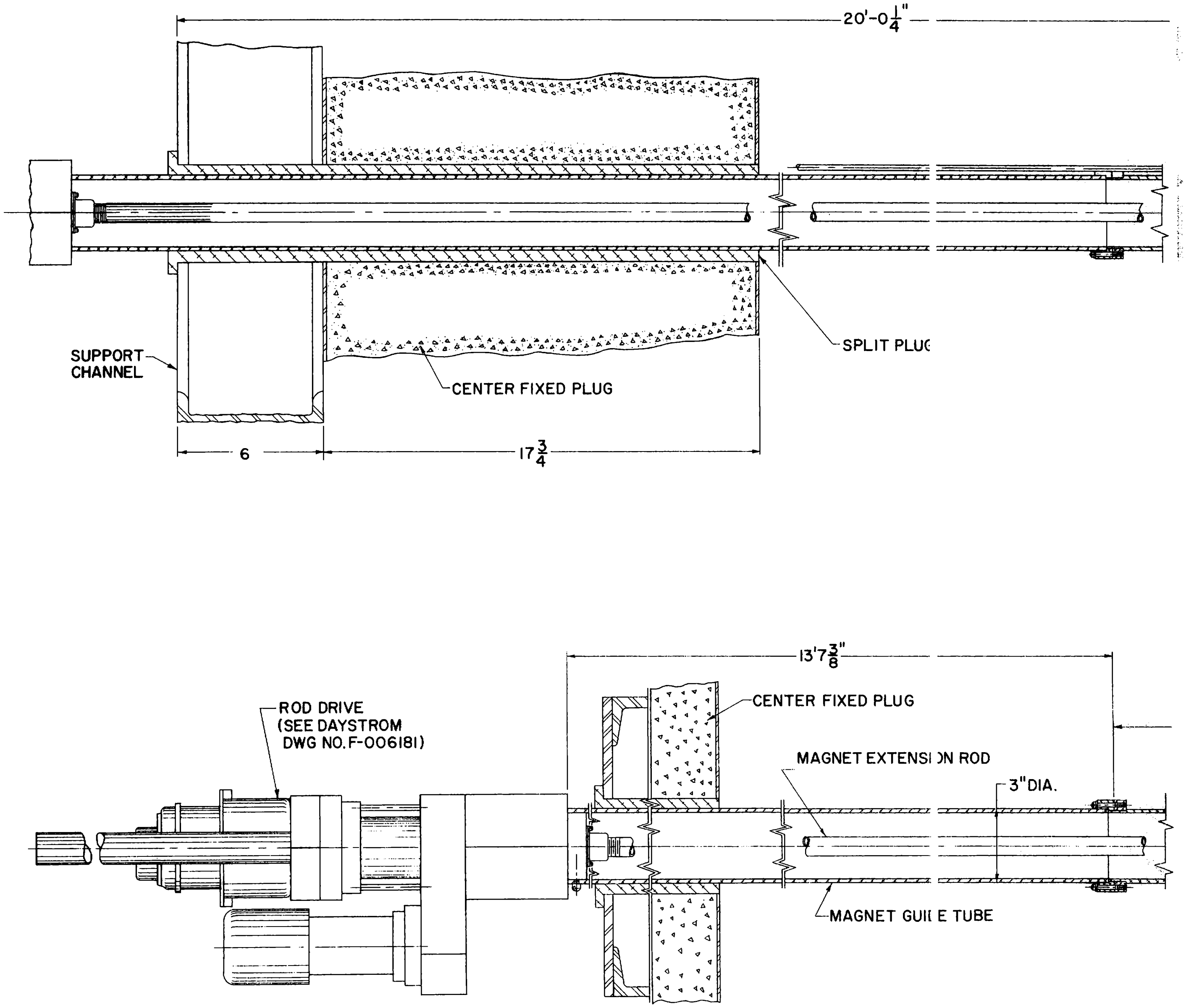


Figure 14. Radiograph of fuel plate.



EAST-WEST

C. Functions

(Taken from *Design Specifications for MRR,*[25] p. 70.)

The control rod system is designed to meet the following requirements:

1. Permit operator to withdraw or insert (one at a time) any of the three safety rods or the regulating rod, for purposes of starting up the reactor or regulating its power.
2. Permit operator to insert all three safety rods driven simultaneously at normal speeds preparatory to start-up.
3. Permit operator to transfer the regulating rod to automatic control for holding constant power.
4. Indicate to operator, on a graphic indicator, the position of each control rod (if it is attached to its magnet).
5. Indicate to operator, by means of pilot lights, when the rods are fully inserted. This indication operates throughout a failure of commercial power.
6. Provide an interlock between the rod control circuit and the Counting Rate Recorder to prevent all rod motion unless the latter instrument is

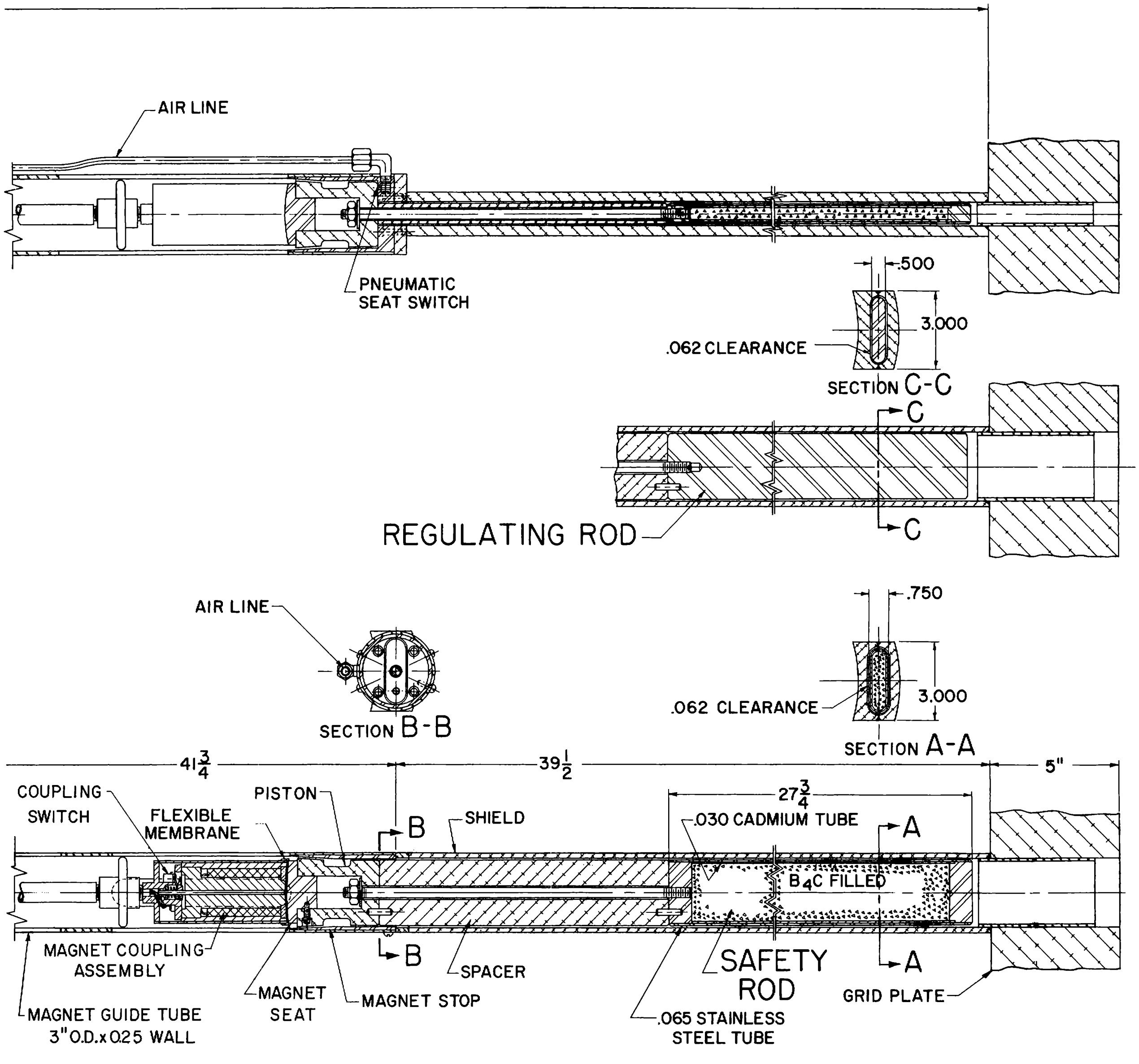


Figure 15. Safety and regulating rod assemblies.

within its operating range, except in the case of "scram" or "setback" action.

7. When two out of three of the safety amplifiers trip their setback relays (at the lower trip point), these relays cause a "setback," i.e., a simultaneous insertion of all three safety rods at their normal speed. No means are provided for disabling this action.

8. When two out of three of the safety amplifiers trip their scram relays (at the upper trip point), these relays cause a scram. No means are provided for disabling this action.

9. When any one of the six pushbuttons in as many locations is pressed, a "scram" is initiated. No means are provided for disabling this action.

10. When a lock-type switch is turned to its open position, the magnets cannot be energized and therefore the rods cannot be withdrawn to start up the reactor. No means are provided for disabling this action.

D. Safety Rods

The safety rod shown at the lower right and in section A-A in Figure 15 is a stainless steel can, 2½

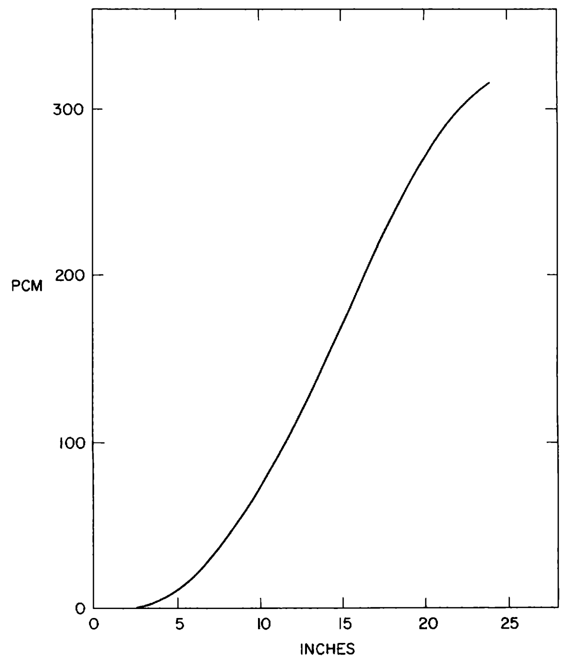


Figure 16. Calibration of regulating rod No. 1 (rod No. 4 at $11\frac{1}{2}$ in.; 1 inhour =2.33 pcm).

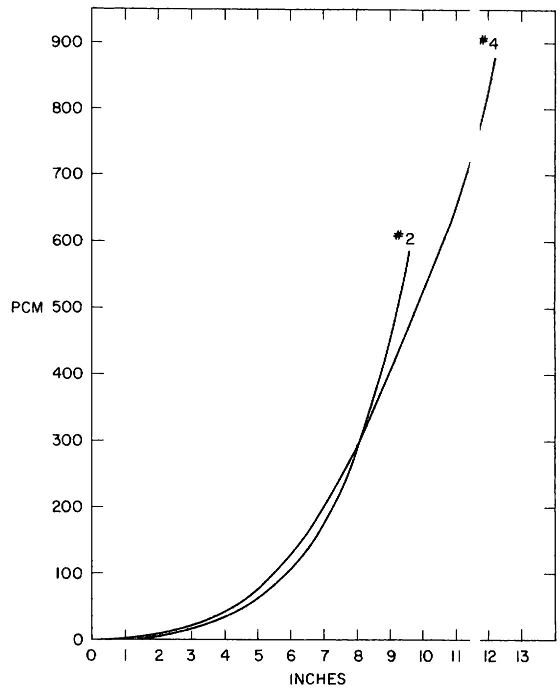


Figure 17. Calibration of safety rods No. 2 and 4 simultaneously (rod No. 1 at 24 in.; 1 inhour =2.33 pcm).

$\times\ \frac{3}{4}$ in. in cross section with a 16 gauge (0.065-in.) wall. The can is lined with a 0.030-in.-thick cadmium tube before filling with boron carbide crystals, the active length being 26 in. It is then tamped, capped, outgassed, sealed, and helium leak tested. An $11\frac{13}{32}$-in.-long, 2017 aluminum alloy spacer, similar in shape to the boron carbide filled can, is fastened above. The extension of this rectangular cross section permits vertical clearance for removal of adjacent fuel elements. Above the spacer is affixed a $3\frac{5}{16}$-in.-long cylindrical aluminum member which serves both as a mount for a nickel-plated soft iron magnet seat and as a decelerating piston or snubber by virtue of the controlled clearance between its tapered sides and that of a snubber cylinder. These components comprise the unit which falls freely after a scram signal.

The safety rod operates within a rod guide fabricated from two 1100 alloy aluminum extrusions welded together to form a sheath. The inside of the guide provides a 0.062-in. clearance around the rod, and the outside has concave and convex faces to match the curved shapes of neighboring fuel elements. The rod guide is stepped at its bottom, fitting into slots provided in the grid plate. At the top a flange is provided for fastening to the magnet guide tube.

The slotted magnet guide tube, made of 1100 alloy aluminum, has a 3-in. o.d. and is 42 in. long. At the rod sheath end is mounted a $1\frac{1}{16}$-in.-long stainless steel cylindrical insert which serves as a snubber cylinder – its tapered inner bore acts as a dashpot to slow and stop a scrammed control rod. At the upper end, the magnet guide tube is flanged to a 13 ft, $7\frac{3}{8}$-in.-long extension tube of the same diameter suspended from the drive housing at the reactor top.

A $\frac{1}{4}$-in.-o.d. stainless steel tube introduces air to a pneumatic seat switch located in the snubber cylinder. This is clearly shown in the north-south elevation in Figure 15. In the "fully inserted" position, the snubber piston restricts the constant air flow and results in a pilot light indication to the operator.

E. Safety Rod Drive

The safety rod drives, a proprietary item of the reactor contractor, are mounted on the stationary plug within a sheet metal box. A motor (Diehl SS-FPF-49-9) drives a hollow shaft through a gear train. The shaft in turn rotates a roller nut which is spline connected to the shaft. A rotary-to-linear translation is accomplished through the captive nut to a lead screw. After driving to the full "down" position the lead screw is prevented from rotating, and the roller nut then "advances" along the fixed screw – this movement is made possible by the aforementioned spline. This action causes a limit switch to shut off the motor. The upper travel is limited by a cam on the lead screw actuating a switch. A travel distance of 26 in. is traversed up or down in 3 min.

A Ford Instrument Synchro-Generator (Cat. No. 5HG), coupled to the lead screw for position indication, rotates 7.05 revolutions for the 26-in. travel of the rod. Position indicators in the control room trace the linear movement of the rods at nearly full scale.

F. Magnet Coupling Assembly

The control rod drive is fastened to a 1-in.-diameter extension rod, which in turn is coupled to a stainless steel watertight cylinder containing the magnet coil and yoke and having a flexible diaphragm end. The deflection of this membrane when the magnet is in contact with the soft iron seat (which is part of the free-fall unit) results in the movement of a small rod which actuates a miniature switch, both rod and switch being located within the cylinder. In this way, lights in the control room can indicate whether or not the rod drives are coupled. Electrical leads to the magnet and switch are carried within the hollow magnet extension rod.

Tests were made of the magnets in the control rod system. Typical results, compiled by the Instrument Group,[44] are as follows:

Minimum holding current	39 ma
Pickup current	42 ma
Operating current	58 ma

This test was conducted under 17 ft of water with a safety rod weight of 11 lb and a magnet air gap of 0.010 in.

G. Regulating Rod and Drive

The single regulating rod (shown in Figure 15) is used for fine reactivity adjustments. It is made from a solid stainless steel bar, ½×2½ in. in cross section and 26 in. long. The construction of the rod guide, magnet, and snubber is similar to that of the safety rod, as is the 0.060-in. operating clearance.

The drive is identical to the safety rod drive with two exceptions: (1) greater speed – 26 in. travel in 20 sec in either direction; (2) the addition of a helipot geared to the lead screw to relay rod traverse information to the power level controller.

H. Comments

Several problems were encountered both before and after the initial start-up. Leakage into the stainless steel magnet can through the pipe joint or soft soldered seal caused several shutdowns. Joints have been eliminated or redesigned, and spare units are kept on hand.

Poor contact between the magnet and the soft iron seat has resulted in excessive magnet currents. This has been largely corrected by strengthening the magnet extension rod (the rod formerly used, a ¾-in.-o.d. tube, deflected enough to open the gap).

On another occasion, the failure of a spring in the low travel limit switch of a drive unit resulted in overtravel and jamming of the mechanism.

6. GRAPHITE CORE PIECES

A. General Description

Within the core, graphite core pieces occupy the volume not filled by the fuel elements, control rods, and source and fission chambers. Displacing the water with this low capture cross section moderator increases the probability of a neutron reaching the treatment port.

As seen in Figure 9, eight graphite core pieces are similar to the fuel elements in shape so that the core geometry can be shifted to suit particular experiments. Eight additional graphite core pieces, irregular in shape, are used to complete the 23¼-in.-diameter core boundary. Aluminum nose pieces, identical to those found on the fuel elements, are used to mount the core pieces in holes provided in the grid plate.

B. Fabrication and Installation

The original specifications called for the graphite (type AGOT) to be canned in 0.060-in.-thick aluminum envelopes, sealed, and tested for leak tightness. This was accomplished after considerable difficulty. Soon after operation began, swelling of the cans was observed and remedial action became necessary. Although the exact cause is uncertain, it is thought that manufacturing or thermal stresses resulted in leaks, and a water-aluminum reaction generated gases which swelled the cans.

Tests conducted by R.W. Powell indicated that replacement of the aluminum envelope by a silicon carbide coating, 0.010 to 0.030 in. thick, deposited upon the graphite might offer a solution to this problem. This coating, called Alsicoat, is a recent development of American Lava, a division of Minnesota Mining and Manufacturing Company. The length of the piece to be clad is limited by manufacturing restrictions to 10 in. The graphite core pieces, as redesigned to conform to this limitation, have a solid anodized nose and a ½-in.-diameter tie rod running through nested sections of graphite. The assembly is held in place by a combination nut and handle bar.

7. FISSION CHAMBER

A. General Description

The fission chamber senses neutron flux by means of the highly ionizing fission fragments from a thin layer of U^{235}. Since the chamber responds to low intensity neutron fluxes, it is used at very low power levels. It operates within a graphite core piece (see Figure 9) which, unlike those described in the preceding section, is clad in aluminum and welded leak-tight.

In the upper portion of the graphite core piece, a slotted tube forms a guide for the 25½-in. motion of the fission chamber. The tube (2.875-in.-o.d. with a 0.203-in. wall) is fabricated from 1100 aluminum alloy and extends 32 in. above the top of the fuel elements.

The fission chamber resides in a thin-walled, 2¼-in.-o.d., 1100 alloy aluminum case seal welded at the bottom and having a quad ring gasketed head screwed to its top. A ¾-in. square aluminum extrusion with ⅛-in. walls is welded to the head and serves both as the conduit for the chamber leads and the connecting rod to the fission chamber drive.

B. Fission Chamber Drive

The 6063-T4 aluminum alloy square extrusion is made in two pieces. The upper part, 60⅝ in. long, has gear teeth machined on one face starting 2 in. from the top. The 24-DP rack extends for 34 in. A Bodine N-12R motor located on the fixed center plug at the reactor top drives a 24-tooth, 24-DP pinion gear to move the rack. A ball-bearing back-up roller (P.I.C. No. EI-9) on the opposite face of the rack bears the thrust load.

Two switches, ACRO No. MWLB-232, mounted on a support frame above the drive, limit the travel. Projections on the rack trip the switches at the ends of the 25½-in. stroke. Traverse time is 20 sec in either direction.

8. SOURCE

The source in the MRR is of antimony-beryllium and provides neutrons through a (γ,n) reaction to start the chain reaction. These neutrons are observed by the start-up range detecting instruments. The source is expected to emanate a total of 10^7 neutrons/sec and is activated to $\approx$5 curies.

The source is placed within an 1[illegible]¾-in.-long, 1100 alloy aluminum tube, 1⅝-in.-o.d. with a 3/32-in. wall, and sealed with a 1¼-in. pipe plug equipped with a grappling eye. This unit is housed in a recess within an aluminum clad graphite core piece provided with a nose piece for grid plate mounting. See Figure 9 for location within the core.

IV. Primary Coolant System

1. GENERAL DESCRIPTION

The core of the MRR is cooled by the forced circulation of water. High purity water is pumped through a closed circuit at $\approx$600 gpm (for 1-Mw operation) as shown in Figure 18. The coolant rises upward through the core, pauses in the decay portion of the vessel, and continues downward to the pumps and heat exchanger before returning to the reactor tank. The total system volume is 2350 gal with $\approx$ 2000 gal in the reactor vessel, 150 gal in the heat exchanger, and 200 gal in the piping. The system is monitored for flow rate, temperature, and pressure as indicated in Figure 18 and explained in Table 5. A water activity instrument and alarm are placed on the vessel discharge line, and water quality (conductivity) instruments are placed up- and down-stream of the water treatment units. Pressure drop through the system is shown in Figure 19.

The primary system is constructed of aluminum except for the stainless steel pumps and nickel-iron valves. Rubber full-face gaskets are used on flanges between components of dissimilar materials to prevent corrosion. All pipes are fabricated from schedule 40, 3003 alloy aluminum. Fittings, including welding neck flanges, are of forged aluminum 6061 ST, schedule 40 and butt welded. Valves and fittings are rated at 125 lb or better, while the flanges conform to a 150-lb ASA specification. An inert gas shielded arc welding process was used in accordance with ASME Code Specifications. The field weld joining the inlet water

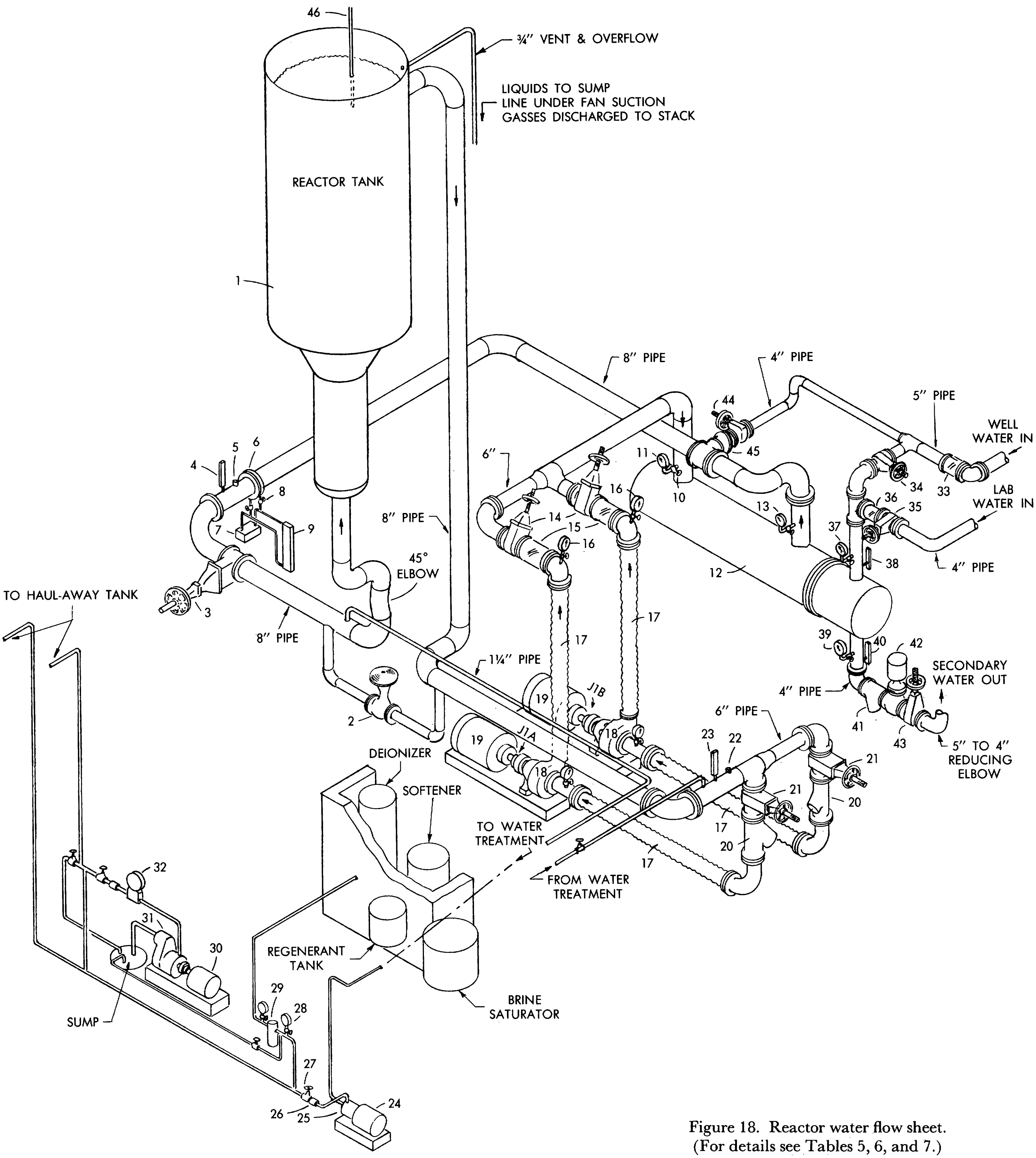


Figure 18. Reactor water flow sheet.
(For details see Tables 5, 6, and 7.)

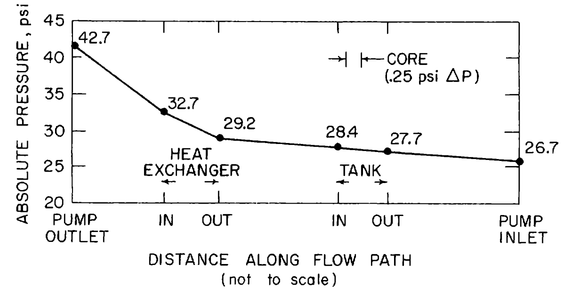


Figure 19. Pressure drop in primary coolant system at 600-gpm flow.

pipe to a 12-in.-long stub at the bottom of the reactor vessel was radiographed. Piping is sized for 5-Mw operation, and permission has recently been given to raise the power level from 1 to 3 Mw.

The original design called for a tank in which to dump the primary system water, but this was omitted because in normal operation the reactor vessel will rarely be emptied. When necessary, "clean" water can be discharged to the diffusion well and active water evacuated, in steps, to a 600-gal haul-away tank.

2. EMERGENCY COOLING

In the event of a power failure the pumps could not circulate the water through the cooler to dissipate the ≈ 100 kw of afterheat. A 4-in. pipe connects the tank inlet to the discharge line. A valve on this line, held closed by air pressure, opens upon the interruption of power and short-circuits the line to the pump and heat exchanger. Convective currents then circulate the cooler water from the upper portion of the tank through the core. The decision in favor of up-flow through the core was based, in part, on these emergency cooling conditions.

Upward flow raises the question of whether the fuel element can be lifted from its position in the grid by the action of the water. Calculations indicate that the upward force due to the frictional drag on the fuel element surfaces is ≈ 0.58 lb. This lifting force, added to the 1-lb force due to the pressure drop across the core, comes well below the 11.5-lb weight of the element. The calculations are based upon the following:

Flow rate, gpm	600
Average velocity through core, ft/sec	2.06
ΔP across core, psi	0.26
Reynolds number	4300

3. PUMPS

The 8-in. reactor tank discharge pipe divides into two 6-in. lines, each equipped with a pump and valves. The pumps in this parallel system are sized so that, for 1-Mw operation, one pump is capable of handling the full load. Valves on the suction and discharge sides of the pump serve to isolate the unit for servicing or for throttling. The pumps take suction on the reactor tank and discharge to the heat exchanger.

Each pump has a 600-gpm capacity at a total dynamic head of 60 ft, discharge head of 87 ft, and a net positive suction head normally at 55 ft.

The centrifugal pumps, manufactured by the Byron Jackson Company, are horizontal with vertically split cases and are specified as Figure 1025. They are constructed of stainless steel with an 11 to 13% chromium content, and the cases are rated at 125 psi. The pumps are driven by 15-hp, 3-phase, 60-cycle, 440-volt induction motors.

4. HEAT EXCHANGER

The horizontal heat exchanger has reactor water on the one-pass shell side and secondary water on the two-pass tube side. A higher pressure is maintained on the tube side so that, should a leak occur, flow would be from the secondary to the primary side. The tube side was chosen for the secondary system because it can better withstand the greater pressure and is easier to clean. Tubes are fabricated of 6061 aluminum alloy and the shell from a 3003 alloy.

Heat exchanger design data are listed in Table 4.

Table 4

Heat Exchanger Design Data

	Tube side	Shell side
Design pressure, psi	25	125
Test pressure, psi	88	188
Pressure drop (calc.), psi	3	3
Inlet and outlet sizes, in.	5	8
Max. working temperature, °F	50	150
Inlet H_2O (1 Mw) temperature, °F	52	85
Outlet H_2O (1 Mw) temperature, °F	68	76

Estimated weights, lb:	Dry	1280
	Flooded	2500
	Bundle	420

Table 5

Component Description – Primary Coolant System
(Item numbers refer to Figure 18)

Item	Description	Manufacturer	Mfr. Part No.	BNL Part No.	Comments or Use
1	Reactor tank	Aluminum Company of America			See Section II.
2	4-in. Valve, air operated, N.O.*	McAlear Mfg. Co.	Type 110		By-pass valve.
3	8-in. Gate valve, nickel-iron	Walworth Co.	200 WOG		Used to isolate pumps and HX** without draining vessel.
4	Thermometer, 0° to 160°F	Weksler Instr. Corp.			Inlet water temperature.
5	Thermocouple well	(thermocouple to Control Rm.)		MU-5	Inlet water temperature to Control Rm.
6	Orifice plate			MU-1	150 lb, 0 to 1200 gpm.
7	Flow transmitter	Minneapolis-Honeywell, Brown Instr. Div.	914808	MU-3	Transmits H_2O flow (gpm) to Control Rm.
8	½-in. Gate valve, aluminum	Wm. Powell Co.			Isolate items 7 and 9.
9	Manometer, 120 in. H_2O	Meriam Instr. Co.	Type W, 30EB25	MU-2	Flow indicator.
10	½-in. Gate valve, aluminum	Wm. Powell Co.			Isolate pressure gauges.
11	Pressure gauge, 0 to 100 psi	Weksler Instr. Corp.			HX primary inlet pressure.
12	Heat exchanger, type CSA	Griscom-Russell Co.	17-5K2-95		
13	Pressure gauge, 0 to 100 psi	Weksler Instr. Corp.		MU-14	HX primary outlet pressure.
14	6-in. Gate valve, nickel-iron	Walworth Co.	200 WOG		Throttle or isolate pump.
15	6-in. Check valve	Chapman Valve Mfg. Co.			Prevent reverse circulation.
16	Pressure gauge, 0 to 100 psi	Weksler Instr. Corp.		MU-12 & 13	Pump outlet pressure.
17	Vibration isolator, 6 in.				
18	Pump, centrifugal	Byron-Jackson Pumps Inc.	332786	J1A, J1B	600-gpm, 27-ft suction positive head, 87-ft total dynamic head.
19	Motor, induction	Continental Electric Co.	NZ 326		15-hp, 1750-rpm, 3-phase.
20	6-in. Strainer	Cooper Alloy Foundry	6-160		"Y" pattern.
21	6-in. Gate valve, nickel-iron	Walworth Co.			Isolate pump.
22	Thermocouple well	(thermocouple to Control Rm.)		MU-4	Reactor outlet temperature.
23	Thermometer, 0° to 160°F	Weksler Instr. Corp.			Reactor outlet temperature.
†					
46	Level indicator and alarm	Uehling Instr. Co.	Type 5, #19967 Model 20R2	MP-44	High and low level alarm to Control Rm.
47	Pressure gauge, 0 to 100 psi	Weksler Instr. Corp.		MU-10 & 11	Pump suction pressure.

*N.O.=normally open.
**HX=heat exchanger.
†Items 24 to 32 covered under "Water Treatment Equipment," Section IV.6.; items 33 to 45 covered under "Secondary Coolant System," Section V.3.

Table 6

Component Description – Water Treatment Equipment
(Item numbers refer to Figure 18)

Item	Description	Manufacturer	Mfr. Part No.	BNL Part No.	Comments or Use
	Deionizer tank	Elgin Softener Corp.			14 in. dia. × 72 in. high.
	Regenerant tank	Elgin Softener Corp.			14 in. dia. × 15 in. high.
	Softener tank	Elgin Softener Corp.			16 in. dia. × 54 in. high.
	Brine saturator	Elgin Softener Corp.			23 in. dia. × 36 in. high.
24	Motor, 3 hp	U.S. Motor Co.	2433876		3600-rpm, 3-phase, 220/440-volt.
25	Water treatment pump	Byron-Jackson Pumps Inc.	1¼ TLM, 33218 Bilton type	J-2	Inlet: reactor water; outlet: water treatment unit.
26	1¼-in. Check valve				Aluminum.
27	1¼-in. Gate valve	Wm. Powell Co.	Teflon packing		Cut off side stream.
28	Pressure gauge, 0 to 100 lb			MU-15 & 16	Check ΔP across filter.
29	Filter	Micro Metallic Corp.	G pore size		Sintered stainless steel.
30	Motor, 1 hp	General Electric Co.	5K182HG593		1730-rpm, 3-phase, 220/440-volt.
31	Waste pump, 15 gpm	Worthington Pump Co.	1CNGK62	J-3	Inlet: from sump; outlet: haul-away tank.
32	Flowmeter (with alarm)			MU-58	Indicates gallons in haul-away tank.
	Haul-away tank (not shown)	Brooks Equipment & Mfg. Co.	Model EX		Stainless steel.
	Quality indicators (not shown)	Industrial Instruments Inc.	Conductivity cell Type CEL-L	MU-32 & 33	Located on line before and after H_2O treatment facility.
			Indicator Solu Bridge RE-189	MU-18 & 19	

5. COMPONENT DESCRIPTION

For a description of the components of the primary coolant system, see Table 5, which is keyed to Figure 18.

6. WATER TREATMENT EQUIPMENT

A 10-gpm sidestream is bled from the primary water system in a 1¼-in. pipe placed upstream of the reactor tank. This stream, as well as raw make-up water, is filtered, softened, and deionized before being returned to the primary system at the tank discharge line (see Figure 18). The effluent contains <0.5 ppm total ionized solids and has a specific resistance $>1\times10^6$ ohms/cc.

The sintered metal filter has a stainless steel element with a 10-micron pore size. It is used primarily to filter out particulate matter during initial filling or for make-up water. A cross-over line permits backwashing the filter, with the residue going to a sump.

The monobed ion exchange column is in continuous service and will remove in a single pass any corrosion or fission products. A specific activity appearing in the primary water is Na^{24} produced by an (n,p) reaction with Al^{27}. Rezex-5H is used in the cation portion and Rezex-42 in the anion portion of the bed. This rubber-lined vessel is constructed of steel and conforms to the ASTM A283 specification. The softener tank, made of the same material, has as its bed 4.5 ft^3 of Elgin Rezone-20, 38.5 in. deep.

The life of the bed is $\approx$12,000 gal water, after which the resin is exhausted. Regeneration of the beds results in $\approx$240 gal liquid waste solution. This empties by gravity into a 50-gal stainless steel sump tank sunk flush in the basement floor and equipped with a high level alarm and a float switch which operates a sump pump. The contents are drawn through a 1½-in. stainless steel pipe to a 600-gal haul-away tank made of 18-8 stainless steel and located in a shielded emplacement outside the reactor building. This tank provides temporary storage for waste liquids. When full, it is transported to a central waste treatment area of the Laboratory.

The components of the water treatment equipment are described in Table 6, which is keyed to Figure 18.

V. Secondary Coolant System

1. GENERAL DESCRIPTION

The primary water gives up its heat to the secondary cooling system in the exchanger. A flow of 520 gpm of 52°F well water through the two-pass tube side of the exchanger is used for 1-Mw operation. Well water supplies the needs of coolers and air conditioners in the Medical Research Center complex before entering the basement of the MRR. The well water passes through the exchanger and flows out of the building, returning to the ground via diffusion wells.

Table 7

Component Description – Secondary Coolant System
(Item numbers refer to Figure 18)

Item	Description	Manufacturer	Mfr. Part No.	BNL Part No.	Comments or Use
33	5-in. Check valve	Chapman Valve Mfg. Co.	CL-50		Stops back flow of lab. water.
34	5-in. Gate valve, N.O.*	Crane Co.			Well water inlet to HX.
35	4-in. Gate valve, N.C.*	Crane Co.			Lab. water inlet to HX.
36	4-in. Check valve	Chapman Valve Mfg. Co.	CL-50		Stops back flow of well water to lab. water.
37	Pressure gauge, 0 to 100 lb	Weksler Instr. Corp.		MU-22	Secondary water inlet pressure.
38	Thermometer, 0° to 160°F	Weksler Instr. Corp.		MU-20	Secondary water inlet temperature.
39	Pressure gauge, 0 to 100 lb	Weksler Instr. Corp.		MU-23	Secondary water outlet pressure.
40	Thermometer, 0° to 160°F	Weksler Instr. Corp.		MU-21	Secondary water outlet temperature.
41	4-in. Strainer	Crane Co.	41943		125-lb service.
42	4-in. Valve, pneumatic	Minneapolis-Honeywell	64128-1		Back-pressure valve.
	Valve positioner	Moore Prod. Co.	721P315		Receives signal from controller.
	Pressure controller	Minneapolis-Honeywell	704P251-91		Pre-set for back pressure.
43	4-in. Gate valve, N.O.	Crane Co.			Isolate diffusion well line from the system.
44	4-in. Gate valve, N.C.	Walworth Co.	725FS		For emergency filling of reactor tank.
45	4-in. Check valve	Chapman Valve Mfg. Co.	CL-50		Stops back flow of primary water to emergency fill line.

*N.O. = normally open; N.C. = normally closed.

A 4-in. by-pass line is shown in Figure 18 which ties the well water inlet to the primary water circuit. This is an emergency source of water for the primary system which, except in case of a catastrophic leak, can maintain the water level in the reactor vessel. For normal operation, a 1-in. make-up line introduces well water to the primary system through water treatment equipment.

Pressure in the secondary system is greater than in the primary to insure that a leak in the heat exchanger will be inward with respect to the primary circuit. Should a leak occur, the additional volume in the reactor tank would result in a high water level alarm. Pressure is maintained by use of a pneumatically operated valve located on the discharge side of the heat exchanger. The valve receives a signal from a pressure controller which is pre-set for the desired back pressure. At 500 gpm, the service water inlet pressure is 48 psi, and the pressure drop across the exchanger is 4 psi. As previously noted, the primary water inlet pressure is 18 psi with a 3.5-psi pressure drop. Instrumentation for the secondary circuit includes thermometers and pressure gauges at the exchanger inlet and discharge.

In addition to the well water, a 4-in. laboratory service line connects to the cooling water supply to the heat exchanger. This line is intended as a supplementary source of water should the well water line, with its many upstream components, be blocked. With this coolant available, the reactor would not be forced to shut down.

The piping arrangement is such that circulation of well water through the exchanger must be continuous whether or not the reactor is operating. To slow the build-up of iron deposits within the tubes, it may be judicious to install a system that would by-pass the exchanger.

2. SERVICE PROBLEMS

Fouling of the secondary water (tube side) of the heat exchanger occurred after four to five months of service, due chiefly to a Laboratory-wide problem of high iron content in the water. Analyses showed an increase from 0.56 ppm in July 1959 to 1.20 ppm in November 1959. The average concentration in the Laboratory's domestic system is 0.03 ppm.

The aluminum heat exchanger tubes were cleaned in July 1959 with a steel tube brush, followed by clean water rinsing. No chemical cleansing was permitted. The cooler has been operating efficiently since that time.

The Plant Maintenance Group has tried to remedy this problem by applications of Actophos, a Betz Chemical Company product, to the well water to keep the iron in suspension. The value of these treatments is as yet undetermined.

3. COMPONENT DESCRIPTION

The components of the secondary coolant system are described in Table 7, which is keyed to Figure 18.

VI. Reflector

1. GENERAL DESCRIPTION

The MRR has a dry graphite reflector surrounding the reactor vessel in the core area. Graphite was chosen instead of other reflector materials such as D_2O or beryllium because of its lower initial cost and ease of handling. Another factor in the decision was the availability of surplus graphite from the Brookhaven Graphite Research Reactor. The reflector is composed of a 17-layer array of graphite blocks, each with a cross section varying from 4×4 in. to 4×12 in. The over-all dimensions of the assembly are 68 in. high, 101¼ in. north to south, and 63¼ in. east to west. In all, 724 blocks with a total weight of 10 tons are used in the structure.

The 50 to 100 kw of gamma heat generated in the reflector is carried away by filtered cooling air which rises upward around the graphite structure and is sucked down through many cooling holes closely arrayed near the core. Holes spaced around the reflector perimeter help cool the graphite adjacent to the neutron shield. The annulus between the reactor tank and the reflector also is air cooled. A variable orifice is provided to control the pressure drop.

The assembled reflector is shown in Figures 20 and 21. It rests upon shims fastened to 4-in. I-beams. The 5-in. space beneath the reactor serves as an exit air plenum. The east and west sides of the reflector are opposite the treatment ports and are recessed to receive the bismuth blocks described below in Section X. The Broad Beam Facility with its supplementary thickness of graphite is on the south, and the north face is equipped with three 4×4-in. experimental openings and six ion chamber holes.

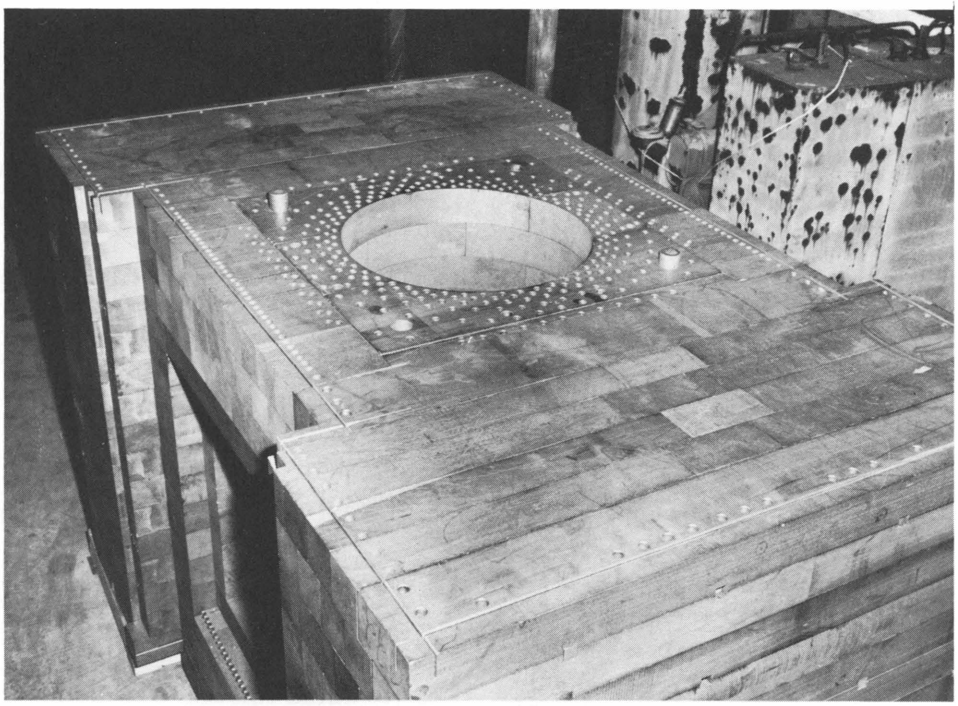


Figure 20. Top view of reflector showing cooling holes.

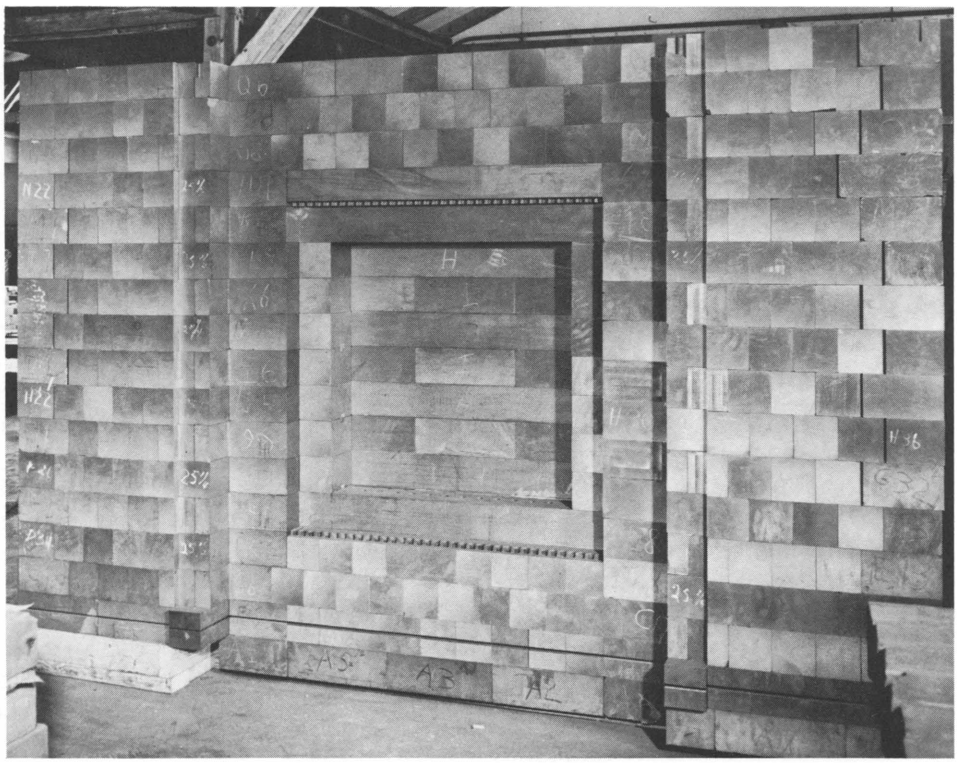


Figure 21. Side view of reflector.

One experimental hole, oriented radially with respect to the core, is vertically centered with respect to the active portion of the fuel (105-ft elevation). Two other ports, one 8 in. above and the other 8 in. below the central hole, have axes tangent to the core. Measurements have not yet been made, but less streaming of core gammas is expected through these tangential holes. Located 14 in. above the upper tangential hole are six 3¾-in.-diameter by 12-in.-deep ion chamber holes which were drilled during construction for proper alignment with liners cast in the concrete biological shield.

The surplus graphite stock was of the following grades:

Type	Density, g/cm³	Diffusion length, cm
AGHT	1.63	49.09
AGOT (AA)	1.70	51.64

2. MEMBRANE

To prevent "short circuiting" of the cooling air through graphite layer interfaces, an aluminum skin or membrane was used to cover the outer vertical surfaces of the reflector. The ⅛-in.-thick membrane is fabricated of an 1100 alloy and is fastened at its bottom to the inlet air duct. The membrane top is curved over to fit into a groove machined in the uppermost graphite layer.

The membrane has two openings or windows opposite the treatment ports where the aluminum is replaced by 0.090-in.-thick magnesium over an area $\approx 32 \times 32$ in. The AZ31 alloy, with an absorption cross section $< \frac{1}{3}$ that of aluminum, was used to conserve the neutron beam.

The membrane serves another purpose: pockets, ⅜ in. or 1⅛ in. wide, between the vertical aluminum membrane and the graphite, are convenient spaces to rest the neutron curtain consisting of ¼-in.-thick boral sheets or 1-in.-thick B_4C-filled cans, discussed below in Section VIII.

3. FABRICATION AND ERECTION

The design and arrangement of the blocks were determined partly by the dimensions of the surplus graphite. The bottom layer, composed of the wider blocks (4×12 in.), extends the full 63¼-in. east to west width. Subsequent tiers are arranged so that the longest and widest blocks are used for the outermost north and south walls. The long axis of almost every block is along an east-west line. One-inch square graphite keys running north and south effectively tie adjacent layers together, a technique successfully used on the Brookhaven Graphite Reactor. Perimeter blocks have from one to four keys, depending upon their length. Successive layers are displaced a half block width as in a brick wall.

A ⅛-in. gap at the north and south ends, between inside and edge blocks, is provided for graphite growth or thermal expansion without affecting the outside dimensions of the reflector. This space (see Figure 21) is in a plane perpendicular to the axis of extrusion of the blocks.

The reflector structure is designed with a 36-in. hollow square in its center. Fitting closely within but not keyed to the reflector is an independent subassembly of 4×12-in. graphite blocks, each layer doweled to the adjacent layers. Higher heat generation in the core area may cause this subassembly to expand independently of the reflector. The 24-in.-diameter reactor vessel fits into a 25-in.-diameter hole in this central reflector area, leaving a ½-in. gap for cooling air. This separate core block arrangement was used initially in the critical experiment.

Three hundred and twenty 1¹⁄₁₆-in.-diameter cooling holes are drilled in the 36-in. square core blocks. Perimeter holes, numbering 158, of the same diameter are distributed in the remaining structure near the outer edge of the reflector. The machining of these holes was complicated by the fact that they were drilled 10° from the normal, the zigzag path through the layers providing a longer flow path. Also, experimental holes and ion chamber holes penetrating the reflector necessitated detours for some cooling holes.

The length, width, and depth of each block was machined to within ± 0.005 in. Clearance between the key and keyway varies between 0.003 and 0.006 in. The 0.005-in. clearance between the aluminum membrane and its groove was inadequate and had to be opened to 0.015 in. The cost of machining the graphite for the reflector was $\approx$ \$0.25/lb.

VII. Cooling Air System

1. GENERAL DESCRIPTION

Air enters the reactor building through a 30-in.-diameter pipe and butterfly valve at the bottom of

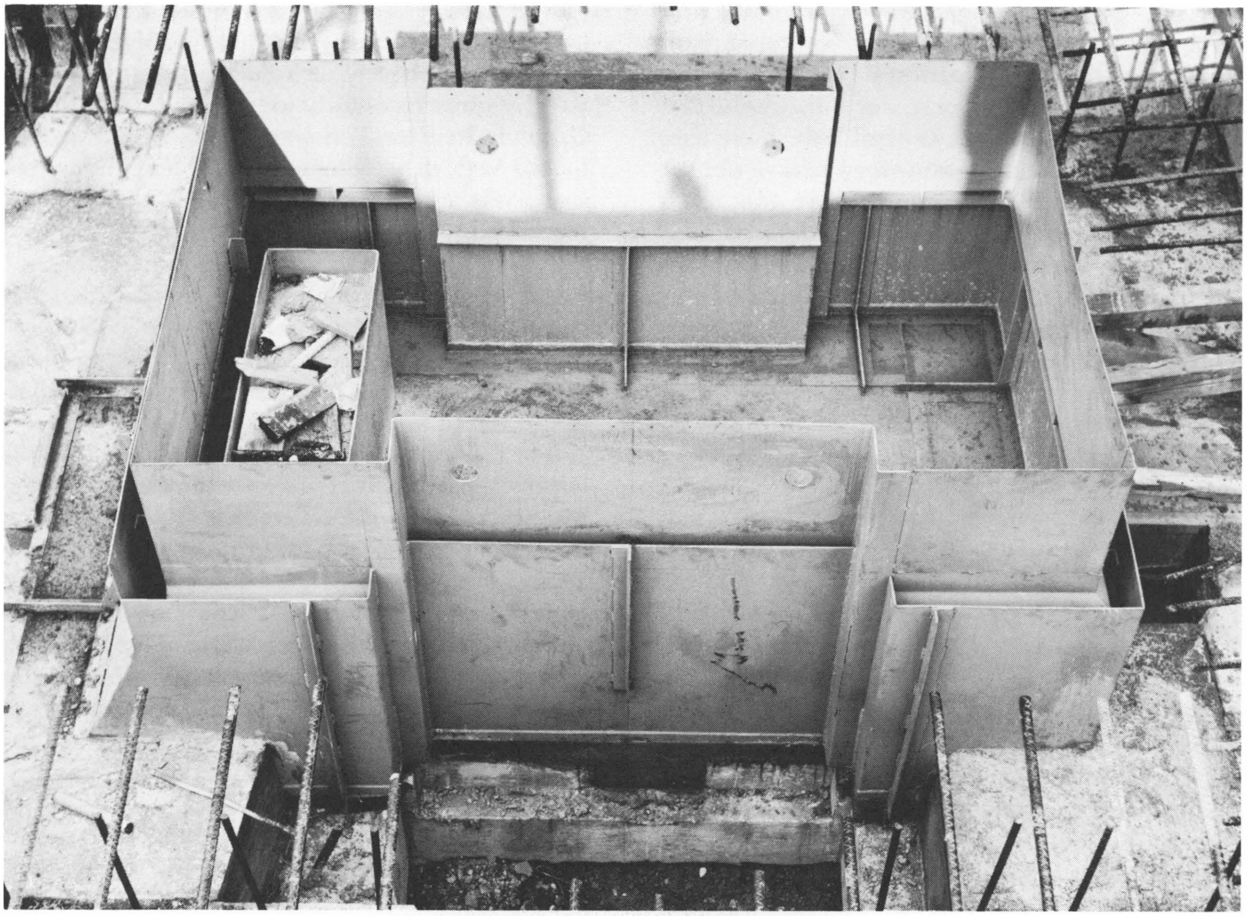


Figure 22. Cooling air duct.

a fresh air shaft located in Mechanical Room No. 5 (north wing basement). An air conditioning unit processes the air before discharge to the main and upper levels of the building. The air returns to the basement via open stairwells and may take two paths: (1) through a filter, blower, and 16-in. pipe which leads to the 150-ft stack; (2) through inlet filters, ducts, and channels where the air cools the thermal shield and graphite reflector before discharging, ultimately, to the stack.

The air following the first path carries away the motor heat in the equipment room and is pulled through an absolute filter by a centrifugal fan. The 16-in.-diameter Transite exhaust pipe runs under the basement floor to the east wing basement where it rises to meet an air-operated butterfly valve before joining the stack exhaust line. A schematic view of the reflector cooling system may be seen in Figure 38 (Section XII). Air following the second path is described below.

2. REFLECTOR CIRCUIT

An air flow of 4100 cfm at 80°F enters the system through two 12×16-in. inlet ducts in the basement. Each inlet is equipped with a deep-bed pocket-type filter using AAF No. 100 F.G. media. The pressure drop through each filter is rated at 0.26 in. H_2O at 20 fpm velocity. The air feeds into a hollow rectangular duct and upward through 2-in.-wide risers on the perimeter. Figure 22 shows this duct during construction.

The air continues its upward path in a channel between the aluminum membrane and the steel thermal shield and cools these members. Its temperature as it enters the 4¼-in.-high inlet air plenum is $\approx$ 90°F. There it is joined by an additional 1000 cfm of building air drawn from each of the shutter shaftways. Thus, a total of 6100 cfm or 27,000 lb/hr air is pulled through the reflector cooling holes. The graphite temperature rise varies between 40°F near the core to <10°F outside the 36×36-in. core block area. The calculated pressure drop through the graphite and channel is 11.38 in. H_2O.

To cool the ½-in. gap between the reactor tank and the reflector ≈600 cfm air is needed. Regulating orifices at the reflector top provide the necessary pressure drop to insure proper air distribution. Two slotted concentric sheet metal collars, one fixed and the other rotatable, open or close thirty ½-in.-diameter holes to maintain an estimated pressure drop of 8 in. H_2O. The openings can be adjusted, if necessary, by means of a rod operated from outside the shield.

The heated air collects in a 5-in.-high discharge plenum immediately below the reflector and is drawn into an exit air duct having a 14½×36½-in. opening. The duct extends downward through the concrete shield, changing in shape to a 24-in.-diameter pipe, to a point 3 ft below the basement floor, where it elbows and continues its run to the east wing basement (Mechanical Room No. 6). The emerging 24-in. pipe flanges into an air operated butterfly valve (with a manual over-ride) and continues to a filter bed. Air is exhausted from the system by one of two damper equipped centrifugal blowers and is discharged to the base of the stack. The blowers, each rated at 6200 cfm, provide the necessary negative pressure to insure the inward flow of active gases and their eventual path through filters to the stack. These cooling fans are interlocked with the reactor control system so that the control rod magnets are de-energized unless a blower is in operation.

The filter bed is a sheet metal enclosure containing silver plated copper mesh batts 4 in. thick, 11⅝ in. wide, and 68¾ in. high. Six units stacked side by side form a 71¹⁄₁₆-in.-wide array. Each module is in a galvanized metal frame equipped with ½-in. hardware cloth faces. The copper wool is compressed to a density of 20 lb/ft^3. Following this, and located in the same enclosure, is a bank of absolute filters capable of screening 99.95% of 0.3-micron particles. The medium, glass fiber paper, gives a static pressure drop of 1 in. H_2O.

The air cooling system was originally designed to include a caustic scrubber by-pass to "clean" the air chemically in the event of a fission gas release. After "cleaning," the air was to be returned to the line and pass through the absolute filters before discharging to the stack. Removal of ≈99% of the iodine is possible by this method. Silver plated

Table 8

Component Description – Cooling Air System
(Item numbers refer to Figure 38)

Item	Description	Manufacturer	Mfr. Part No.	Comments or Use
1	Inlet air filter	American Air Filter Co. Inc.	Model A	Deep pocket bed.
2	By-pass filter	American Air Filter Co. Inc.		Read in cfm.
3	Draft gauge	Ellison Draft Gage Co.		Inclined type.
4	24-in. By-pass damper	Duro-Dyne Corp.		
5	Flow element	Taylor Instrument Co.	88S78 and 79	Pitot-Venturi type.
6	Outlet air thermocouple			To Sim-ply-trol pyrometer in Control Rm.
7	24-in. Butterfly valve (air operated)	Morgan Smith, Div. of Allis-Chalmers Mfg. Co.	63066, R.S. type	Uses ½-in. Hanna solenoid air valve and 14 MCC air cylinder.
8	24-in. Butterfly valve (hand operated)	Morgan Smith	R.S. type	For former scrubber system.
9	Copper mesh filter	Metal Textile Corp.		Silver plated.
10	Absolute filter	Flanders Mill, Inc.	"Air-Pure" No. 2, H-92	
11	Exhaust fan	Bayley Blower Co.	EX-330	Equipped with Westinghouse 25-hp motor, 1725-rpm, 3240 frame.
12	Outlet damper	Bayley Blower Co.	56824	
13	Draft gauge	Uehling Instr. Co.	Type B	Reads pressure in reactor bldg. to aid in adjusting outlet dampers.
14	Exhaust fan, 2630 cfm	Trane Co.	Type B1, Model 22	For north wing basement.
15	16-in. Butterfly valve	Morgan Smith	R.S. type	Air operated.
16	Inlet air thermocouple			To Sim-ply-trol pyrometer in Control Rm.

copper wool filters were substituted in the actual system because they are more compact and easily serviced and their efficiency in trapping iodine is at least as good. Also, their use eliminates the possible difficulties of putting the scrubber into operation after an emergency.

The cooling system will respond to an emergency air contaminating event in the following way: within 2 sec after a trip signal the 30-in. fresh air line valve as well as the 16-in. building exhaust valve will be closed. The only remaining route for the radioactive air will be through the iodine trap, absolute filters, and finally the 150-ft-high stack. The automatic 24-in. valve upstream of the copper wool is throttled to one-third flow for optimum filter efficiency.

Instrumentation includes an air flow element in the 24-in. line downstream of the reflector and temperature scanning for reflector inlet and exhaust air as well as several graphite thermocouples. A Jordan Remote Area Monitor System (RAMS 2), connected to the control room, monitors the following:

	Alarm Point, mr/hr
Exhaust filter air	50
Reactor top	50
Opposite experimental hole	10
Opposite Broad Beam Facility	10
Patient and Animal Facilities	1000

Another feature of the circuit is a by-pass that connects to the 24-in. pipe downstream of the reflector. A riser on the Transite pipe emerges from the basement floor and connects to a damper and deep-bed pocket-type filter. When air flow through the reflector is not desired, basement air can be short circuited through this leg.

3. COMPONENT DESCRIPTION

For a description of the components of the cooling air system, see Table 8, which is keyed to Figure 38 (Section XII).

VIII. Thermal and Neutron Shield

1. GENERAL DESCRIPTION

In order to protect the dense concrete shield from dehydration and the effects of thermal stress, a steel thermal shield is placed between the core and the biological shield. Core gamma leakage is thus reduced to tolerable heat generation rates in the concrete. In addition, a neutron curtain composed of boron carbide and boral fits between the graphite reflector and the thermal shield. Neutrons captured in this curtain are prevented from entering the thermal shield where they would induce secondary radiations. Heat generated in the neutron and thermal shield can be conveniently dissipated by the cooling air system. About 0.15% of total reactor heat is generated in the thermal shield and 0.75% in the neutron curtain, i.e., almost 1% of the total reactor heat is generated in this area.

Bismuth blocks used as an extension of the thermal shield opposite the treatment ports serve to filter the gamma radiation from the emerging beam. (These are discussed in Section X below.) The boron curtain has openings at the treatment ports, Broad Beam Facility, and experimental holes.

2. THERMAL SHIELD

The thermal shield of laminated steel construction surrounds most of the reflector (see Figures 23 and 29). Assuming a reactor power of 1000 kw and a gamma flux at the surface of the graphite of 7×10^{10} Mev/cm^2-sec, calculations[20] show the heat release in the steel plates to be 35.56 Btu/ft^2-hr. (The conversion factor is 1 Mev/cm^2-sec $= 5.08 \times 10^{-10}$ Btu/ft^2-hr.) Since 80°F cooling air sweeps by more than one face of the steel panels (because of ½-in. gaps between plates), the temperature rise in the side plates will be small, an average of 5°F. The horizontal plates above and below the reflector are subjected to a greater temperature rise because of contact with a boral layer and because the ambient air temperature is higher. The bottom plates, swept by the warmed air, are subjected to a temperature gradient ranging from 200°F near the reactor centerline to 100°F 4 ft away. Expansion joints in this area are necessary.

The bottom plates, 3 in. thick, have their major axis running east to west. A clearance of ½ in. around each of the four plates is maintained. These members rest on a dense concrete base and are prohibited from "walking" by two 1-in.-diameter dowels accurately cast in the concrete. Mating holes in the plates are drilled 1/16 in. larger for linear thermal expansion.

I-beam segments, 4 in. at 7.7 lb, are welded to the bottom plates and are equipped with 1-in.-thick spacers and shims. The reflector is set upon

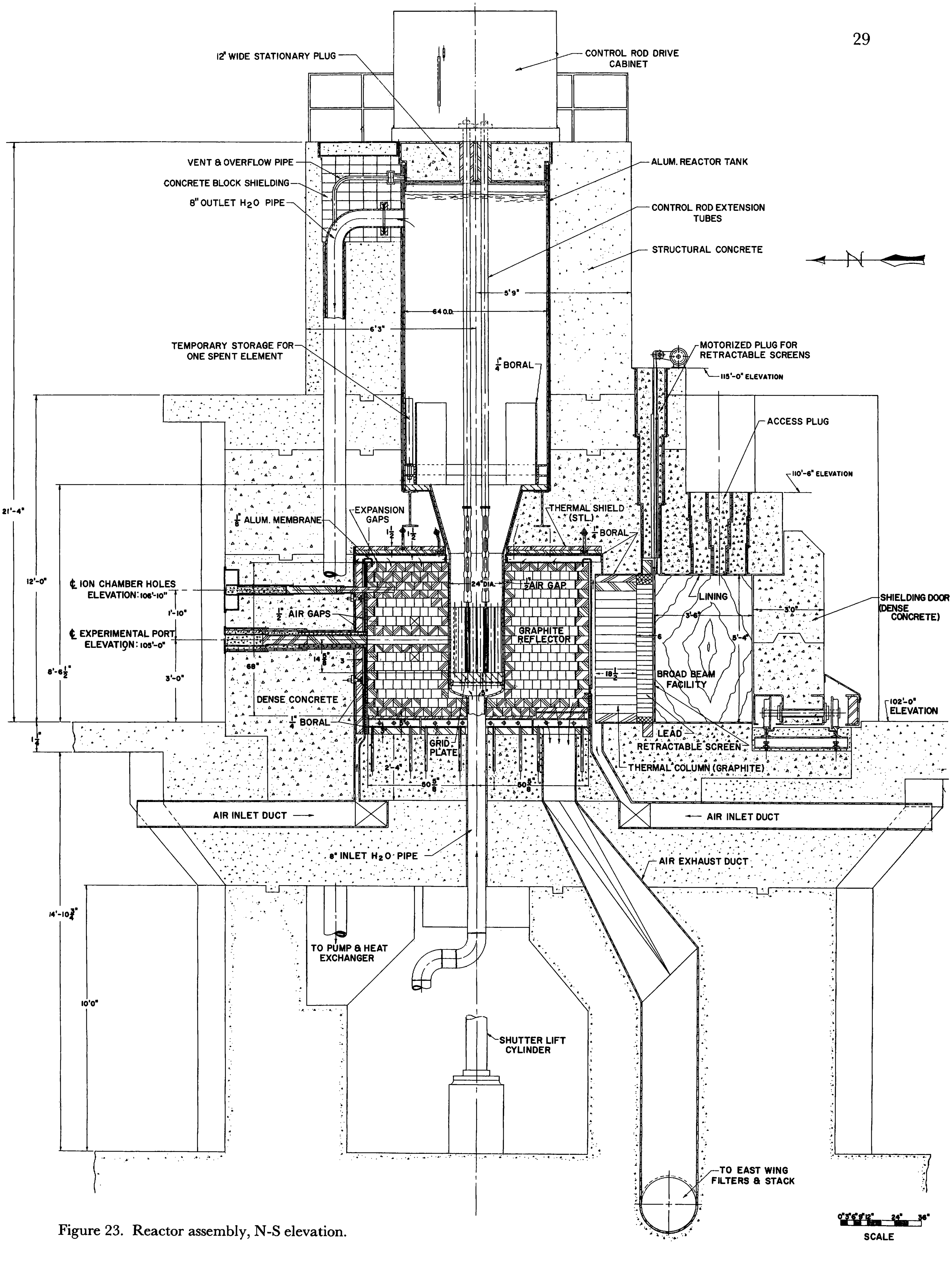


Figure 23. Reactor assembly, N-S elevation.

these segments, and the 5-in. space between the graphite and the thermal shield serves as an exit air plenum. A 3-in.-thick steel plate, resting on the 4-in. I-beams above the exit air duct opening, reduces radiation streaming into the duct below. This plate, as well as all others in the thermal shield, is a mild steel bed plate, mill sheared to final size.

The side plates are identical on the east and west faces and are assembled to leave a framed opening ≈4×4 ft opposite each shutter. The vertical plates are laminated of a 3-in. inner plate and two 2-in. plates, with ½-in. cooling air gaps on each side of the 3-in. plate. The lintel and base plate of the framed opening are 4 in. thick.

The side plates are mounted by a free-floating technique. Wedge type anchors cast into the concrete walls receive 1-in.-diameter bolts. The bolts are drawn up tightly to bear against tubular spacers which fit into clearance holes in the plates. Stand-offs, ½ in. thick, maintain the gap between the 3-in. and 2-in. plates. The dead weight of the 3 in. members is not taken by these fasteners; welded angle clips support these side plates.

The top plates are made of two 1½-in. thicknesses, the layer nearest the concrete oriented east and west and the other north and south. Each plate is fastened to studs imbedded in the concrete in much the same way as the side plates. It was convenient for the building contractor to use the top plates as the concrete form, and care had to be taken to insure that no concrete found its way between the ½-in. expansion joints. This was done by filling the gap with oakum and providing sheet metal covers. The filler was later removed when the joint was inspected.

The thermal shield on the north wall consists of three 3-in.-thick vertical plates set side by side with a ½-in. expansion joint between them. In addition, ½-in. cooling air gaps are maintained on each vertical face. Cut-outs for experimental and ion chamber holes are made in appropriate locations. These plates are mounted by the free-floating method.

3. NEUTRON SHIELD

The boral and boron carbide linings are placed between the reflector and the steel thermal shield. On the east and west faces, 1-in.-thick cans filled with boron carbide capture thermal neutrons and contribute to the attenuation of lower energy epithermal neutrons. Boral plate, ¼ in. thick, is used on less critical faces.

Assuming a core neutron leakage of 10^{13} neutrons/cm^2-sec (at 1 Mw) and a surface density of 2.92×10^{21} B^{10} atoms/cm^2 of boral plate, it can be shown that the lifetime of this shield is 10 years, based on 8-hr/day, 250-day/year full power operation and 85% burn-up in the boron. The heat release, primarily the result of neutron capture, is calculated at 117 Btu/ft^2-hr. The boral and boron carbide cans will run 20°F hotter than the cooling air.

The boron carbide cans of 6061 aluminum alloy are rectangular and constructed of extruded channel frames covered with a 0.063-in.-thick skin. The size of the cans varies from 21½×31 in. down to 8^{11}⁄$_{16}$×3^{15}⁄$_{16}$ in.; all are 1 in. thick. Larger cans have internal tie rods to prevent spreading. Many of these containers reside in the space between the membrane and the reflector, their edges resting on the membrane lip. Other cans located outside the membrane are bolted to the steel thermal shield through spacer tubes welded to the skin.

The containers are filled with B_4C sold by the Norton Company under the name Norbide and specified as technical grade 4F, a run of mill grade having a grain size of 8 mesh and finer and a specific gravity of 2.51 g/cc; 400 lb were used. After the cans were filled, recessed cover plates were welded on, each cover having a ⅛-in.-diameter hole covered with fine mesh screen for outgassing helium generated during irradiation.

Boral plates, ¼ in. thick, are screwed directly to the top and bottom horizontal steel plates and around the perimeter of the inlet air plenum. On the north face the boral is housed between the graphite and the membrane. Boral is a sandwich-type plate having a 0.168-in.-thick core consisting of a mixture of 35 wt % B_4C and aluminum, clad on both sides with pure aluminum. Sheets were purchased sheared to size at the mill. Mounting holes were punched, and larger openings were drilled (with a carbide tipped tool) or sawn on site. The band saw blade life is extremely short 18 to 22 in. of cut.

IX. Biological Shield

1. GENERAL DESCRIPTION

A dense concrete biological shield surrounds the core and graphite reflector to reduce gamma and neutron leakage to a tolerable level. In less critical areas, standard structural concrete is used to complete the shield structure.

The biological shield has several openings, the largest being two vertical shaftways, semicircular in cross section, on the east and west sides of the reactor, where shutters control the radiations to the treatment ports. Three stepped, cylindrical thimbles and six ion chamber holes pass horizontally through the north side of the shield; these are fitted with plugs to preserve the integrity of the shield. To the south, a rolling dense concrete door can be opened to provide access to the Broad Beam Facility during shutdown, and completes the biological shield when closed (described in Section X. 2. B.).

The critical experiment demonstrated that with the proposed treatment port geometry a thermal neutron flux of at least 10^{10} neutrons/cm^2-sec at the point of target penetration could be achieved with a 25½-in.-thick dense concrete shield (see Figure 5). This distance had to be kept to a minimum because of the rapid deterioration in flux as a function of distance from the core. The east and west reactor walls were kept to this minimum thickness for >6 ft on either side of the emerging beam to provide maximum maneuverability for treatment or experimental setups. Shielding walls and ceilings 2 ft thick surround the portal area to form rooms 21 ft long by 11 ft wide (see Section X).

A dense concrete slab almost 3 ft thick extends outward from under the reactor to form the floor of the Broad Beam Facility and also reaches into the treatment rooms for more than 2 ft (see Figures 23, 24, and 29). A similar slab, 3½ ft thick, above the reflector has approximately the same geometry. The north wall is >4 ft, 7 in. thick; the east and west walls are 25½ in. thick and are backed by 2-ft-thick outer walls; and, as mentioned above, the south portion is a 3-ft-thick shielding door. In all, nearly 125 cubic yards of dense concrete were used.

Within the reactor vessel the water shielding above the core is >15 ft deep. The fuel element storage rack located on the ledge above has ≈8 ft of covering water. A spent element in this rack rests close to the vessel wall, so that radiation streams upward through the tank clearance annulus, necessitating an overlapping plug over the reactor vessel top. This plug, 18 in. thick and filled with 300-lb/ft^3 concrete, is an effective shield and reduces the general radiation level on the reactor top to ≈40 mr/hr.

The area immediately beneath the reactor in the basement is inaccessible while the reactor is in operation; readings as high as 20 r/hr have been monitored here. A cement block wall (shown in Figure 38) surrounding this area reduces the radiation in the general basement area to levels ranging from 150 mr/hr near the pumps and exchangers to <30 mr/hr near the basement perimeter. After shutdown, the shutter hydraulic cylinders and primary water equipment in the cubicle under the reactor are completely accessible.

2. DENSE CONCRETE

Because of the stringent space limitations at the treatment ports, limonite and steel punchings were chosen as the heavy aggregate, the higher cost being justified by the need for 285-lb/ft^3 concrete in this area and by the fact that there has been considerable experience with this type of concrete at Brookhaven.

A. Properties

(Taken from *Tests on BNL Shield Concrete.*[33])

Specific gravity, g/cc	4.58
Specific heat, cal/g-°C	0.164
Thermal conductivity, cal/sec-cm^2-°C	0.0085
Coefficient of thermal expansion, in./in.-°C	
Limonite ore	13.7×10^{-6}
Limonite mortar	16.2×10^{-6}
Heavy grout	12.2×10^{-6}
Modulus of elasticity, lb/in.^{2}	3.5×10^{6}

B. Mixing, Placing, and Testing

Each batch was mixed in a small 2-yard portable mixer. Careful weighing and control of water volume were necessary to keep within the 1½-in. maximum slump specification. The mix, in lb/cubic yard, was as follows:

iron punchings	4960
limonite	1790
Portland cement	690
Plastiment	15
water	360

Elephant trunk hoppers were used to keep the free fall during placement to <2 ft. The mixture was then lightly vibrated for even distribution. The finished wall was tested by means of a small source and counter. Some evidence of moderate segregation, revealed in an initial test, was remedied by close control and supervision.

The 2-ft-thick walls of the treatment rooms are constructed of dense concrete for the most part

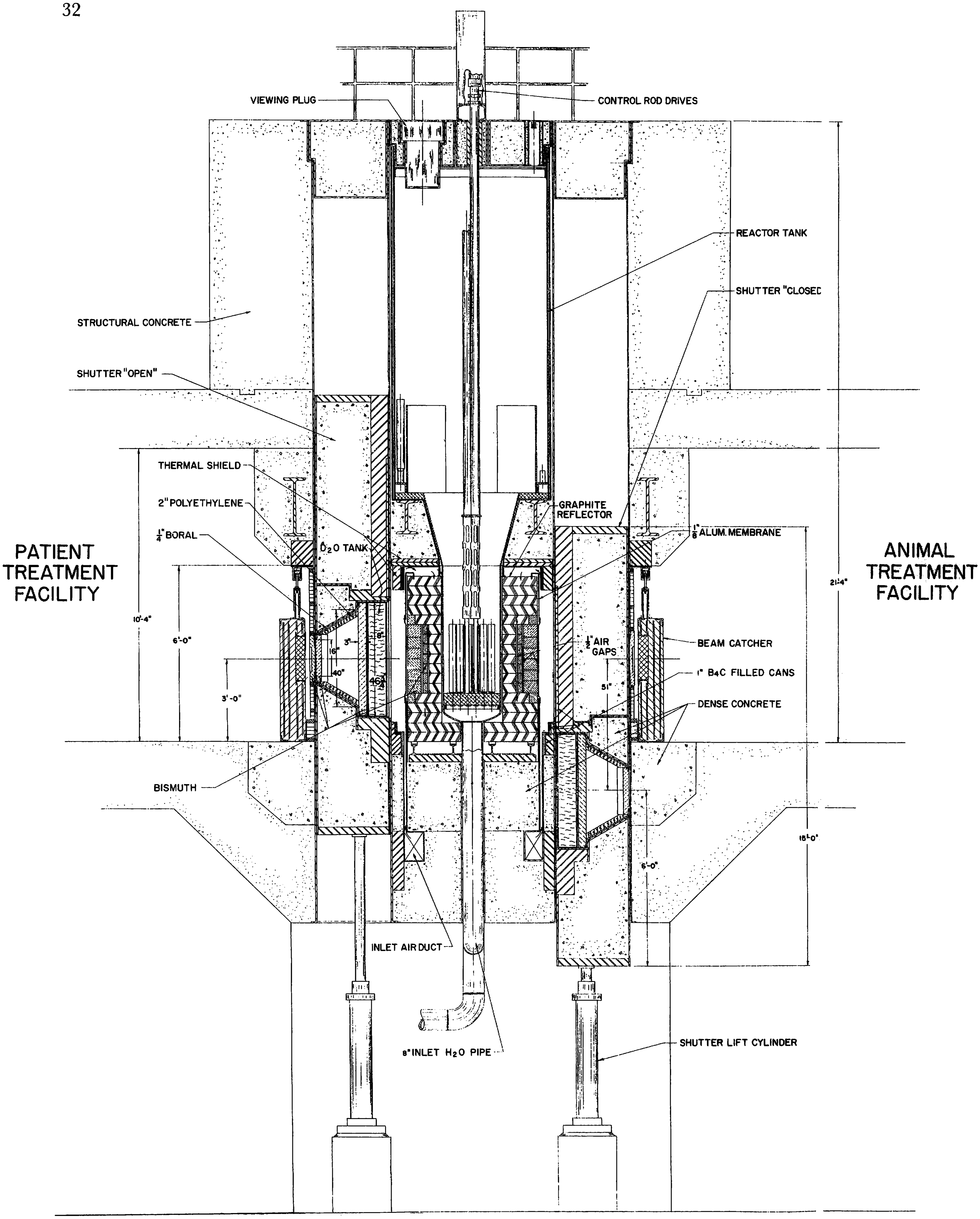


Figure 24. Reactor assembly, E-W elevation.

(see Figure 29). At the extremities, and well out of line with the treatment port, light concrete was substituted to reduce the cost of the shield. This saving was not realized because above tolerance γ-ray leakage in this area necessitated the installation of a 3-in.-thick lead wall in front of the light concrete portion of the shield.

3. TOP PLUGS

Three shielding plugs fit over the reactor tank, providing a flush working surface at the reactor top (see Figures 23, 24, and 40). A narrow stationary plug, 12 in. wide by 78 in. long by 17¾ in. deep, spans the center of the circular opening. Control rods are mounted on this plug, which is accurately aligned with the reactor structure by two locating dowels. It is of welded construction, fabricated from ½-in.-thick 6061 alloy aluminum, and filled with dense concrete; it weighs $\approx$2850 lb.

Semicircular stepped plugs fit into the openings left by the center plug. These too are 17¾ in. deep, concrete filled, and constructed of the same alloy. A ½-in. clearance is provided between these plugs and their seats for ease in removal. The west plug is equipped with a transparent water-filled insert to permit viewing of the core for fuel handling operations. A small access hole in the east plug, used for handling tools, is located in line with a spent fuel station in the storage rack below. A shielding pig will be placed above this hole for fuel discharge.

The shutters for the treatment facilities are removed upward through shaftways in the shield. Stepped plugs, 32 in. deep, fit flush into recesses at the tops of the shaftways. These plugs are of steel shell construction filled with light concrete and weigh $\approx$3500 lb.

4. SHUTTER ASSEMBLY

A. General Description

The shutter assembly forms such an integral part of the biological shield that its description belongs in this section. The treatment port geometry is described in Section X.

The 21-ton shutters are of ¾-in.-thick steel shell construction, filled with dense concrete. They are split so as not to exceed the capacity of the 12-ton crane. A treatment "window" in the lower portion permits a controlled leakage of neutrons for experimental purposes.

When the shutter port is opposite the core (the "open" position) it is supported by an extended hydraulic cylinder in the basement below. A failure in the hydraulic system would result in the shutter falling closed. The normal stroke is 51 in. with a 10 to 11-sec traverse time.

The shutter is raised and lowered inside a vertical cavity in the reactor shield lined with ¾-in.-thick steel plate. The casing is 27 ft, 4 in. long and has a semicircular cross section with an inside radius of 24¼ in. Two machined ways run the length of the casing and serve as guides for the shutter bearing blocks. Opposite the core, the beam emerges through a 48-in. square opening in the flat back plate and a 16-in.-wide by 36-in.-high hole in the curved portion of the casing. These coincide with the shutter port while in the open position. The casing is of welded construction and is cast into the concrete. Anchors are welded to the outside surface of the casing to prevent shifting. The installed casing is square to within $\pm$⅛ in. over-all (see Figure 25).

Heat generated in the shutter[20] amounting to $\approx$1100 Btu/hr is dissipated by cooling air drawn into the ¼-in. clearance openings between the shutter and casing. The air is exhausted to the reflector cooling system through ten 1¼-in.-diameter holes in the casing which are located opposite the inlet air plenum above the graphite reflector. The calculated air flow past each shutter is 1000 cfm, and the temperature gradient across the shutter ranges from 100°F on the flat plate nearest the core to 80°F at the front, upper, and lower extremities of the shutter.

The shutters and casings were assembled in the fabricator's plant to test mechanical clearances. Figure 26 shows the test setup with the shutters placed back to back. The 16$\times$36-in. opening in the casing can be seen.

B. Upper and Lower Subassemblies

The semicircular shutter is 15 ft long over-all, as shown in Figure 27. A stepped joint divides the upper and lower segments. Two 1½-in.-diameter bolts hold the halves together. The shutter is of steel shell construction consisting of a ¾-in.-thick curved plate joined to a 5¾-in.-thick flat back plate and capped with top and bottom plates, the inside being filled with BNL dense concrete. Both subassemblies are equipped with iron-oilite wear plates that align with the machined ways in the casing. There are eight of these friction reducing

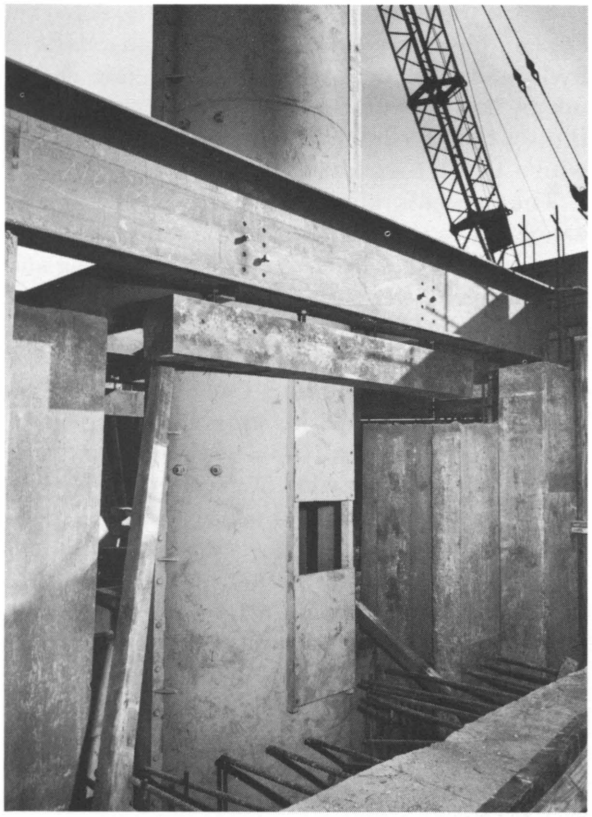


Figure 25. Shutter casing during construction.

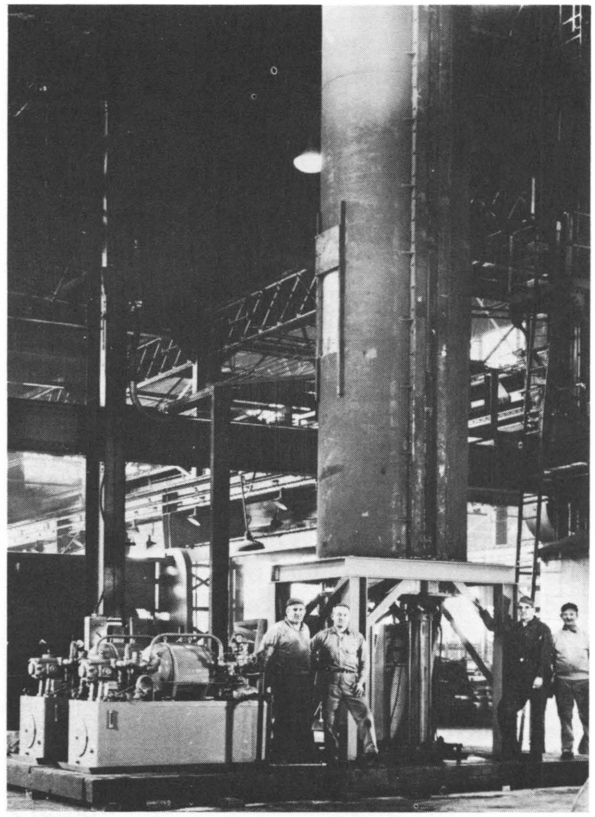


Figure 26. Shutter test.

plates, each screwed to a pad and located near the top and bottom of the shutter halves.

The upper subassembly weighs 18,900 lb and is 81½ in. high. Four 1-in.-thick boron carbide-filled aluminum cans are firmly held in place on the back of the shutter facing the core. Thus, with the shutter in the "closed" position, the continuity of the stationary shield is maintained by the combination of B_4C, 5¾-in.-thick steel plate, and dense concrete. Two ½-in. stainless steel conduits are imbedded in the concrete for a future instrument or access line to the treatment cone in the lower half.

The lower half of the shutter is 103 in. long and weighs 16,000 lb, not including the contents of the treatment cone. The treatment port has the following geometry: on the core side of the shutter a rectangular recess 48 in. high, 46½ in. wide, and 12¾ in. deep is joined to the base of a truncated pyramid, 40-in. square at its base and diminishing to 22½ in. wide by 20⁹⁄₁₆ in. high where it intersects the semicircular plate. The maximum opening in the port facing the treatment room is 16-in. square.

A 4-in.-thick bottom plate is tapped for mounting the piston end of the hydraulic lift. The piston is located 13 in. from the flat back plate, under the center of gravity of the assembled shutter.

C. Shutter Elevator Equipment

Shutters are raised by means of 8-in.-bore hydraulic cylinders which rest upon reinforced concrete pedestals (see Figure 28). The piston rods, as mentioned above, are fastened to the bottom plates of the shutters. Hydraulic pressure for lifting is provided by a pump unit. The shutters are gravity lowered by draining hydraulic fluid through an orifice; should power or pressure fail, the shutter would lower and close the treatment port. The cylinder is provided with a cushioned blank end to reduce the impact of the lowered shutter. The installation of the cylinders is covered by specifications.[37]

Two hydraulic drive packages are provided, each having pumps, a motor, and controls. Each unit has the capacity to deliver pressure to both cylinders while the other unit stands by. The shut-

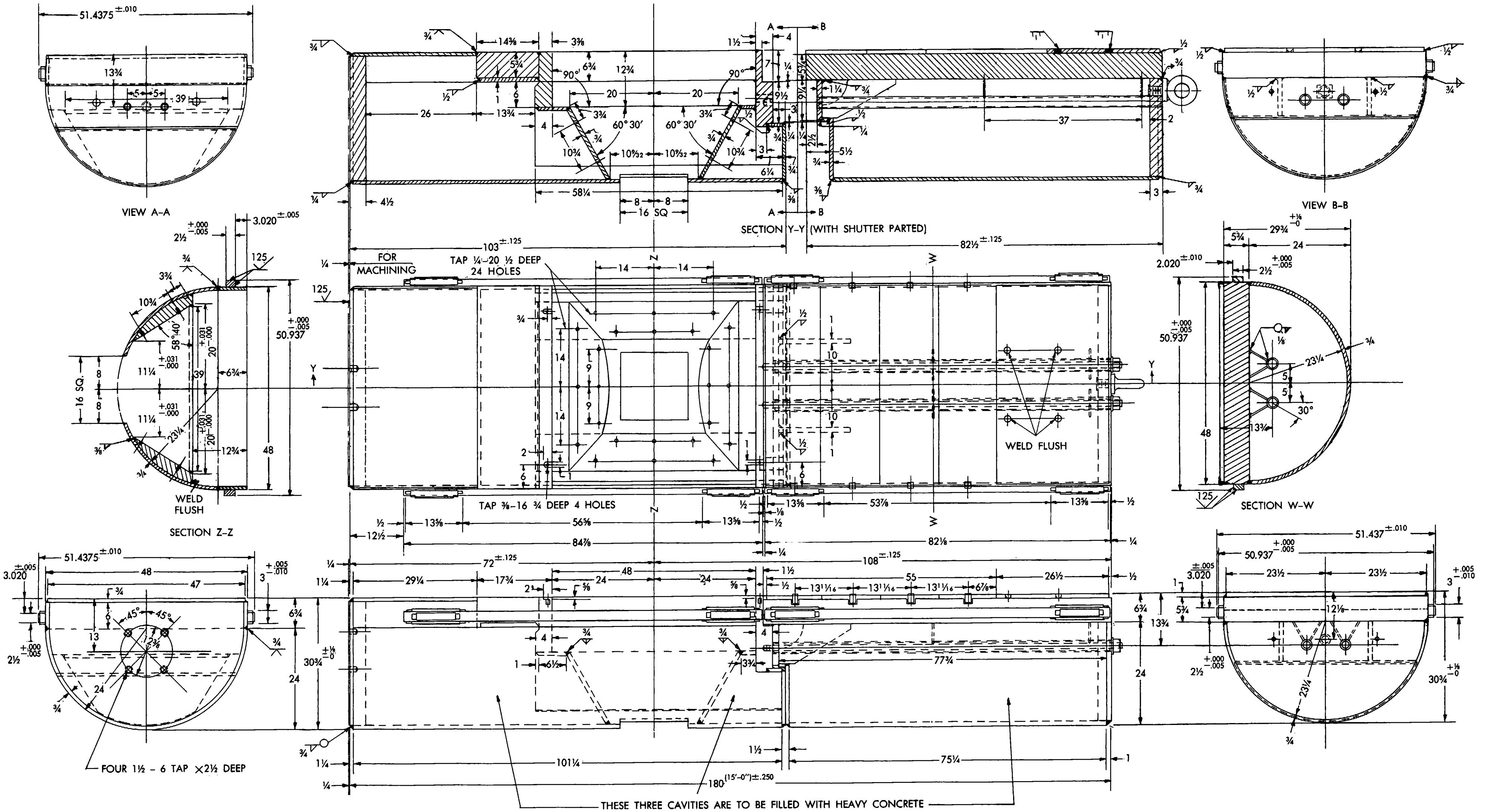


Figure 27. Shutter assembly.

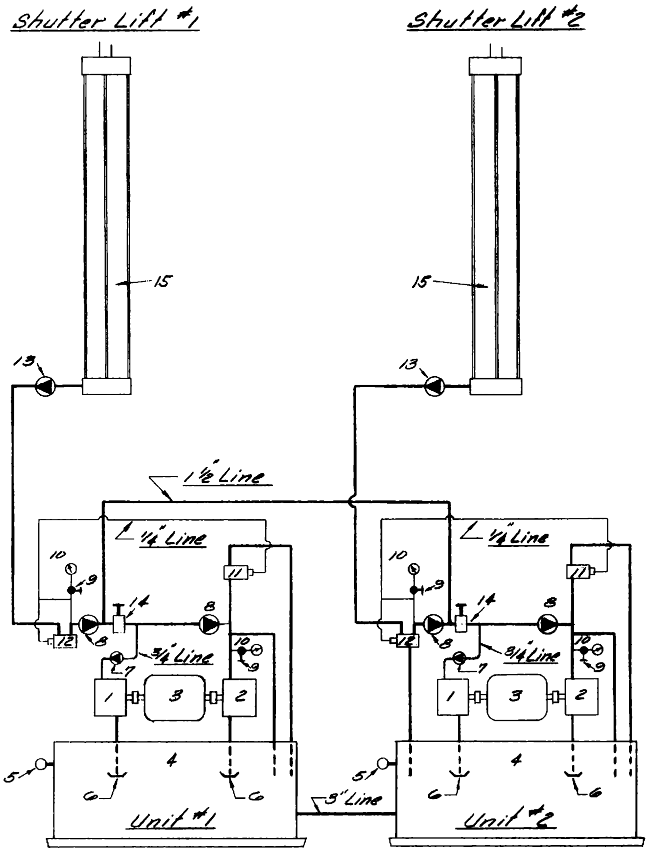


Figure 28. Schematic drawing of hydraulic system for shutter lift. (For details see Table 9.)

ter is driven upward by the use of a high and a low volume pump, each connected to a double-shaft, 50-hp electric motor. Two inches from the top of the stroke, a limit switch actuates a solenoid-operated two-way valve which by-passes the flow from the high volume pump to the sump. The low volume pump drives the shutter to the end of its stroke at a slower speed and maintains it in the open position. The shutter is closed by gravity and controlled by an orifice check valve. When the oil pressure is reduced, the cylinder fluid can bleed back to the reservoir. Lifting pressure is 1000 psi and holding pressure is maintained at 1200 psi.

Outside each treatment room, near the observation window, is a control station. The switches for pump selection, start, emergency stop, and shutter opening and closing are behind a locked panel. A pressure gauge, timer, and indicator lights complete the instrumentation.

An electrical interlock prevents both shutters from being raised (opened) simultaneously. However, with one shutter open, the other can be raised. As previously mentioned, any pump or power failure results in lowering of the shutter, which closes the treatment ports.

D. Component Description

For a description of the components of the shutter assembly, refer to Table 9, which is keyed to Figure 28.

X. Experimental Facilities

The first floor level plan (Figure 29) shows the layout of experimental facilities. Two shielded rooms, on the east and west sides of the reactor, will be used primarily for neutron capture therapy. Vertical shutters with special ports provide precise control of the neutron stream. The rooms are identical except in their location relative to the hospital area; together they provide means for a standardized therapy program. The Patient Treatment Facility is an extension of the hospital insofar as it is connected to the Operating Room Wing and is isolated from the work area and other experimental areas in the reactor building.

A Broad Beam Facility is located at the end of the thermal column on the reactor south face. Its many uses may include a wide variety of mammalian whole-body exposure studies. An animal as large as a burro can fit within the shield, or large numbers of mice can be irradiated simultaneously in a controlled environment. Another subject of continuing interest to the Medical Department is whole-body phantom experiments in which a tissue equivalent material, such as a sugar-urea-water mixture, is used to obtain valuable data on beam spectrum at various penetrations.

Three experimental thimbles or activation ports will have several uses. For investigations on diagnostic and therapeutic possibilities of radioactive isotopes of very short half-life, the convenient access to these ports (in which the isotopes are prepared) from the treatment room is important. The tubes are adaptable for collimated neutron beams, which are of value in determining the penetration and energy changes of neutrons passing through tissue equivalent materials. The study of radiation effects in biological samples is another field in which these facilities can be useful.

Neutron fluxes and gamma dosages in the various facilities are given in Table 10.

Table 9

Component Description – Shutter Assembly
(Item numbers refer to Figure 28)

Item	Description	Manufacturer	Mfr. Part No.	Comments or Use
1	Pump	Racine Hydraulics & Machy., Inc.	Model 2FA 21006	Variable volume vane, 12 gpm at 1200 rpm.
2	Pump	Racine	K-27	700 gpm at 1200 rpm.
3	Induction motor	Louis Chalmers	Type OGX 2315773	50-hp, 1200-rpm, 445-S frame, 2⅜-in. double end shaft.
4	Reservoir, 130 gal	Racine		Conforms to Joint Industrial Committee specifications.
5	Heat exchanger	Racine	Bul. 820	
6	Filter (suction)	Racine	Bul. 830	
7	¾-in. Check valve	Racine	Bul. 100	
8	1½-in. Check valve	Racine	Bul. 100	
9	¼-in. Globe valve	Racine	Bul. 320	
10	Pressure gauge	Racine	Bul. 800	(Marsh) 0 to 2000 psi.
11	1¼-in. 2-Way valve	Racine	Bul. 248	Solenoid controlled, pilot operated.
12	1½-in. 4-Way valve	Racine	Bul. 48	Solenoid controlled, pilot operated.
13	1½-in. Check valve	Racine	Bul. 100	With orifice.
14	1½-in. Gate valve	Crane Co.	Stl. 600	
15	Hydraulic cylinder	Tomkins-Johnson Co.	HH-4	8-in. bore, 4-in. piston rod, 52-in. stroke; cushioned blank end.

Table 10

Neutron Fluxes and Gamma Dosages at 1 Mw
(The values shown are approximate. Precise measurements have been made and will continue to be made.[45])

Facility	Neutron flux, n/cm²-sec		Gamma dosage, r/min	Distance from core center, in.
	Thermal	Fast		
Patient and Animal Ports	2×10^{10}	None >3 Mev; <1000 at 1.5 Mev	37	73½
Broad Beam Facility				100 (to center of room)
Cd screen up	1.5×10^{9}			
Cd screen down	4×10^{6}			
Tangential experimental tube				20⅝ (in-core)
	10^{8}			(pile face)
Radial experimental tube	10^{13}			12½ (in-core)
	10^{8}			101⅛ (pile face)

The contaminated air from the facilities is continuously sucked into the reactor through clearances in the experimental ports, drawn through the reflector cooling system, and discharged through filters to the stack.

1. PATIENT AND ANIMAL TREATMENT FACILITIES

A. General Description

Each of these shielded rooms has as its focal point a treatment port which is a complex of reflector, moderator, filter, and shield so placed as to provide a maximum thermal flux with the lowest possible fast neutron and gamma contamination. Although the initial geometry was determined in the critical experiment, provision was made for altering the components or their arrangement to optimize and refine the beam. A program of reorientation of parts has been completed under the direction of the Project Engineer.

The room is 11 ft, 2½ in. by 21 ft, 2 in. Placement of the treatment port 36 in. above the floor and almost centrally in the reactor wall provides clearance for a full range of treatment positions. Access to the room is through two shielding doors. From outside the room, full visibility of the reactor wall is possible through two observation windows. A television camera for close-up surveillance is also in use.

Cables and instrument wires can be snaked through an offset conduit in the 2-ft-thick shielding wall. The treatment rooms are air conditioned and contain water, drain, and power connections.

B. Treatment Port

The path of the emerging beam to its target at the apex of the pyramidal opening in the shutter may be seen in Figure 29. In the present arrangement, the core-born radiations penetrate 7½ in. of

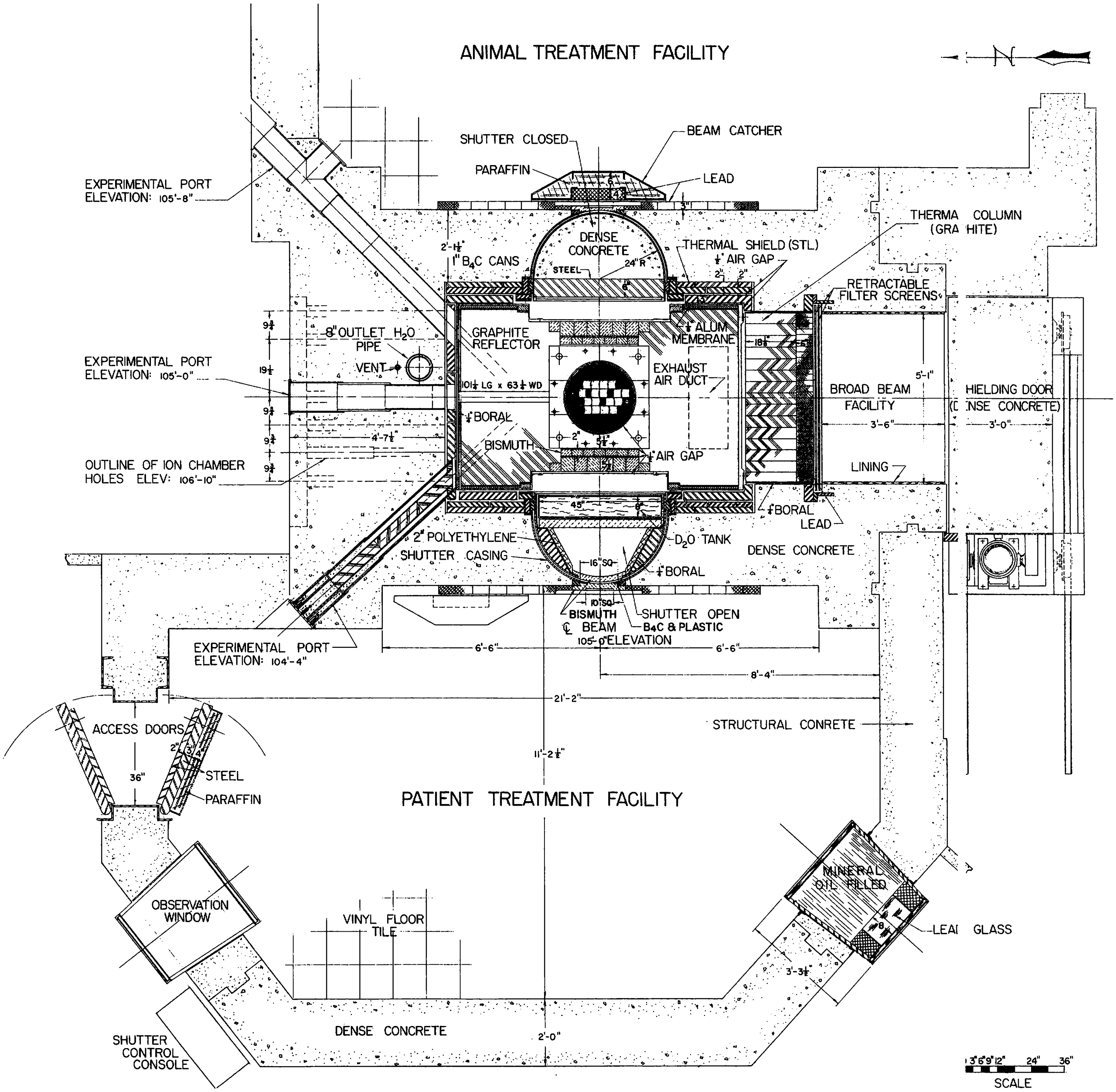


Figure 29. Reactor assembly, horizontal section.

bismuth and two 0.090-in. magnesium membranes before passing to the open shutter. The shutter port contains an 8-in.-thick D_2O tank followed by a 3-in. slab of bismuth. The walls of the pyramidal opening are lined with ¼-in. boral covered with 2-in. slabs of polyethylene to increase the axial leakage flux. A 2-in. thickness of bismuth is fastened inside the curved face of the shutter.

An additional curved bismuth block, 1 in. at its thinnest, is secured to the shutter casing. On the core side of this block a ⅜-in.-thick B_4C and resin shield frames the 10×10-in. treatment port and is, in effect, a continuation of the boral liner. On the front face of the bismuth block a recess is provided for a "head block," a special shield with a reduced aperture to fit a specific experiment. Up to 4-in. of lead can be mounted on the reactor shield face to cut down gross leakage through the shield next to the shutter.

a. Bismuth. Each port has two stationary bismuth block walls within the reflector which are continuously in the radiation stream. These are cooled by reflector air drawn downward in ½-in. channels on both faces of the innermost wall. The 2-in.-thick inner wall absorbs a large fraction of the core gammas and releases heat in the first 1 to 1½ in. at a calculated rate of 680 Btu/ft^2-hr. Block construction was chosen for ease of handling through the small 16×36-in. opening in the shutter casing in case a change of geometry is required.

High purity bismuth (99.999% analysis) was precision cast in graphite molds to a tolerance of ±1/32 in. Only one face of the block had to be machined, and this method of fabrication reduced surface imperfections to a minimum.[34] Attention to surface imperfections was important because of the method of containment. Polonium, formed from bismuth by neutron capture, was enveloped by a novel technique. A 0.030-in. coating of pure magnesium was built up on the blocks by metal spraying. Prior to spraying, the blocks were lightly sandblasted to clean the surfaces and insure a stronger magnesium-to-bismuth bond. Surface imperfections such as pit holes had to be enlarged and rounded so that the coating would not bridge the crevices instead of adhering to the surface. Blocks were handled with extreme care and measured before and after spraying. The coating thickness varied from 0.025 to 0.040 in. Several blocks removed after almost one year of service have shown no damage or appreciable alpha contamination.

A block of the same high purity bismuth was cast in a steel angle frame and fastened within the shutter. This block is 47 in. high, 42¾ in. wide, and 3 in. thick and weighs almost 2100 lb. A curved, stepped bismuth block, 2 in. thick and weighing 250 lb, conforms to the semicircular shutter face and fits within the 16×16-in. port opening. In the treatment room, a 270-lb bismuth shield is bolted to the shutter casing. This curved block is 20 in. high, 19½ in. wide, and a minimum of 1 in. thick. Since the bismuth in the shutter is under irradiation for very short periods, Glyptal coatings are considered adequate for containment. In all, the beam passes through 11½ in. of bismuth.

b. D_2O Tank. A tank filled with heavy water is located in each shutter to thermalize the neutron beam without parasitic capture. The tank is 46¾ in. high, 45 in. wide, and 8 3/16 in. thick. It is fabricated by heliarc welding of 0.090-in.-thick aluminum faces to a ¼-in.-thick frame and tested under a static water head of 6 ft; tubular tie rods within the tank prevent excessive bending. The tank is filled with 271 liters of D_2O through a ¾-in. pipe opening. Dissociation of the heavy water will be no problem because of the short time it is in the primary beam, therefore a helium sweep system was considered unnecessary.

Provision has been made to install a somewhat smaller D_2O tank on the core side of the shutter if necessary. This is a 6-in.-thick container made up of three 2-in. compartments; separate filling of one or more of these in-pile sections allows the selection of different neutron energy values. Filling is done by pressurizing a reservoir, located in the basement, with 9 psi of helium. Individual plug valves are opened to fill each compartment. The vent lines are left open to prevent pressurizing of the 3-part tank and to provide an overflow to a sight glass for "full" indication. The helium pressure is switched to the vent line for draining. A mercury trap sized to vent at 2.5 psi protects the tank from overpressure.

c. Viewing Windows, Access Door, and Beam Catcher. Two observation windows provide full visibility into each treatment room (see Figure 29). Their design is similar to that used in the Hot Analytical Facility at ORNL: each consists of a welded stainless steel tapered box with 1-in.-thick plate glass ends. The 3 ft, 3½-in.-long window was to be filled with a zinc bromide solution; however, for the present 8-in.-thick lead glass, which recently became available, has been installed behind the outer plate glass, and the remaining volume has been filled with mineral oil to form a satisfactory shield.

Access to each treatment room is through a pair of hand-operated steel shielding doors, each 42 in. wide, 84 in. high, and 5 in. thick, with a space between. The inner door has a 4-in.-thick layer of paraffin on the side facing the reactor. The doors weigh 5000 lb each and pivot on $1^{11}/_{16}$-in.-diameter steel pins rotating in Fafnir Ball Bearing Flange Cartridges, Type LCJO; the shock of closing is absorbed by tubular gaskets manufactured by the Bridgeport Fabrics Corp., Style HD-604N-1A. When open, the doors provide a full 36-in. access width.

When the shutter is closed, a beam catcher is placed in front of the treatment port to reduce the general background radiation levels (see Figure 29). The beam catcher consists of an $18 \times 18 \times 4$-in.-thick lead block facing the port, surrounded and backed by a minimum of 6 in. of chlorine-free paraffin, all within a 6061 aluminum alloy container suspended on rollers from a track above. The track, manufactured by the Richards-Wilcox Company (No. 233) is adjustable to clear from 1 to 4 in. of lead shielding on the reactor face.

2. BROAD BEAM FACILITY

A. General Description

The Broad Beam Facility is a small room surrounded by the biological shield on the top, bottom, and two sides (see Figure 30). It is open to the entire south face of the reflector. A 20-ton, dense concrete rolling door provides full access to the room when open and completes the shield when closed. The facility is 5 ft, 1 in. wide, 5 ft, 6 in. high, and 3 ft, 6 in. deep.

A beam emerging from the core travels through 38 in. of reflector graphite. It is further thermal-

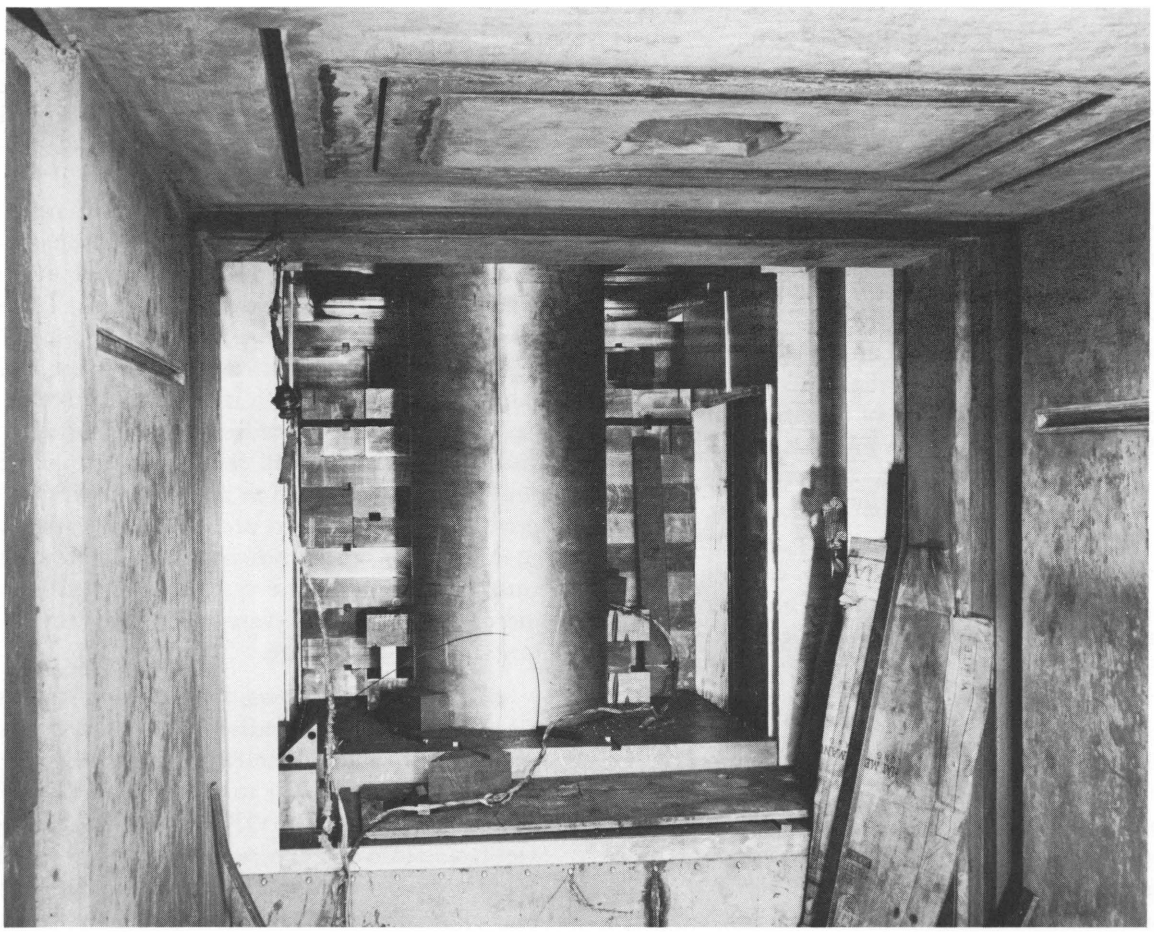


Figure 30. View through Broad Beam Facility (during erection of reflector).

ized by an 18⅛-in.-thick graphite wall cooled on the core side face by inlet cooling air. A 6-in.-thick lead wall abuts the graphite and serves as a gamma filter. Before diffusing into the room, neutrons pass through one or more retractable screens which extend over the entire face of the facility and can be used to alter the energy, spectrum, or constituents of the beam. At present a cadmium filter can be lowered to make the room a gamma facility. Future experiments may require a depleted uranium sheet interposed to give a fast neutron current.

The 18⅛-in.-thick graphite wall is fabricated from 4 × 4-in. blocks of AGHT and AGOT grades. The assembled structure is 65½ in. high and 60½ in. wide. Since this wall is kept stationary by the lead walls on one side and brackets on the other, keys and dowels were not needed in assembling the 232 blocks.

The lead gamma shield, also assembled from blocks, is 65½ in. high, 60½ in. wide, and 6 in. thick, and weighs 9800 lb. Preliminary testing was done on samples of various lead alloys, i.e., corroding, chemical, acid-copper, common-desilverized, and scrap lead of unknown analysis, by irradiation in the Graphite Research Reactor at a flux of 10^{10} neutrons/cm^2-sec either for several minutes or for several days. Specimens were counted over a period of several hours. Corroding lead conforming to ASTM Specification B29-55 was chosen as the shield material because it acquired less activity and decayed more quickly than the other lead alloys. Calculations[23] indicated that, of the thermal neutron flux incident on the shield, 50% would be scattered, 11% absorbed in the lead, and 39% transmitted to the Broad Beam Facility.

For access from the top, a 2×3×3-ft stepped plug of dense concrete is set in the ceiling of the facility. Within this plug, a small cylindrical plug permits the insertion of a periscope or other apparatus. With the addition of special shielding and a remote handling device, it may be possible to insert or discharge small specimens through this top plug while the reactor is operating. Instrument lines may be run into the facility via an offset trough.

Without protection the dense concrete walls would become active after a time; therefore, a nonactivating lining fabricated of a ⅜-in. thickness of B_4C sandwiched between layers of plywood is mounted on the exposed surfaces, anchored to uni-strut sections cast flush into the concrete at convenient locations.

B. Shielding Door

The shielding door of the Broad Beam Facility is moved horizontally by an electric motor. It is constructed of two sections so as not to exceed the crane capacity, each being a monolithic dense concrete block. The lower block is cast into a carriage that rolls along tracks; it contains 62.0 ft^3 concrete and weighs 20,000 lb including the 2150-lb carriage. The upper section contains 70.6 ft^3 concrete and also weighs 10 tons.

The assembled door is 3 ft thick, 7 ft high, and 7 ft wide and generously overlaps the cave opening on all four sides (see Figure 31). The ½-in. operating clearance between the vertical face of the reactor wall and the door is backed by a 3×6-in. steel plate shield.

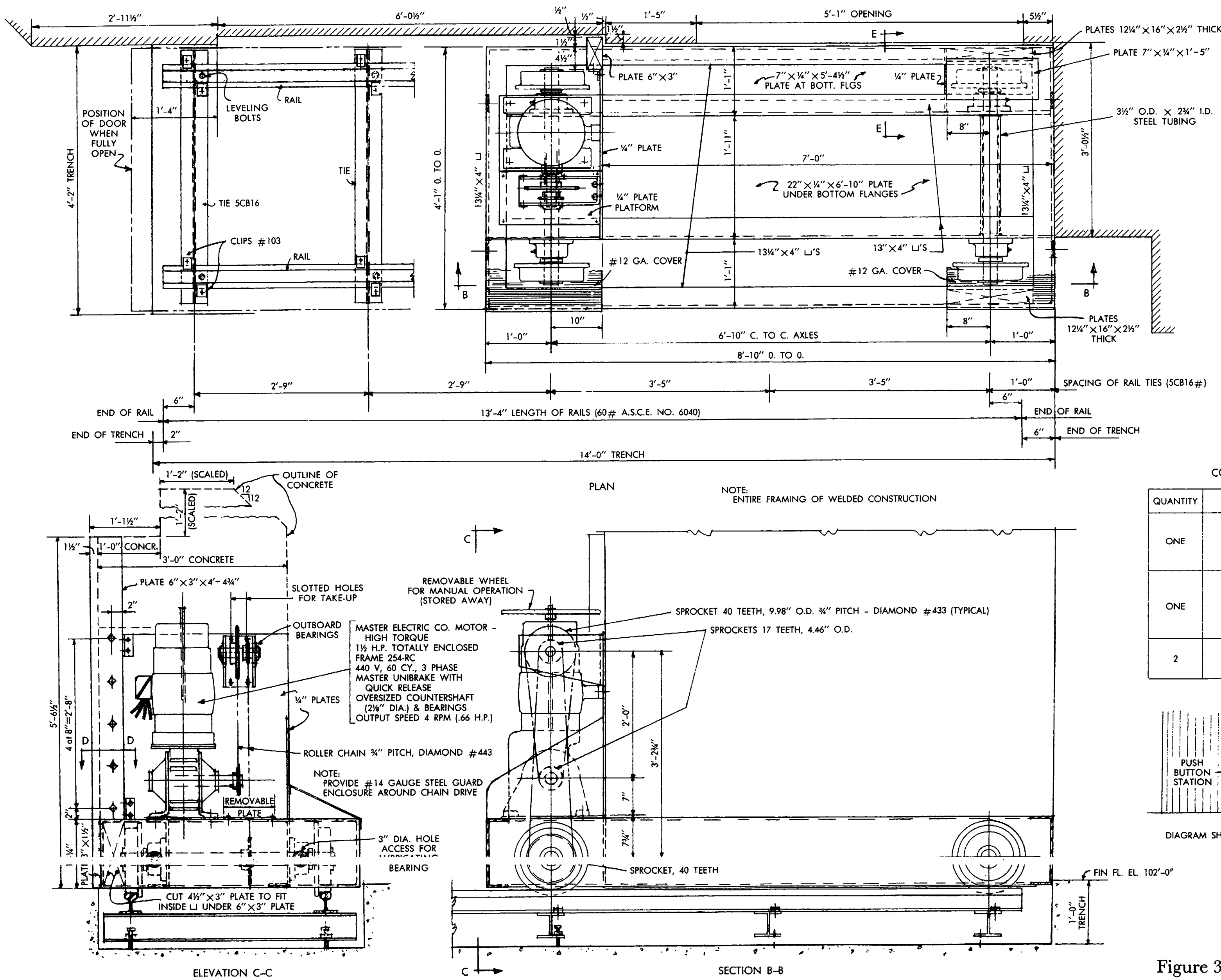
The reactor cannot be started with this door open, and its opening during operation would result in an emergency shutdown trip.

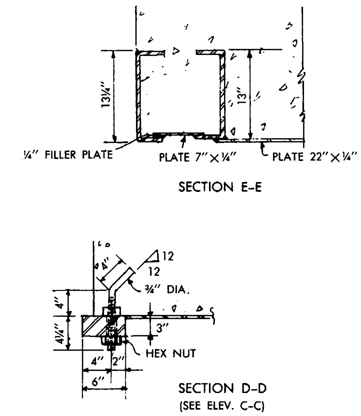
An electric gear motor drives the carriage through a roller chain transmission at the rate of 2 ft/min. Components are identified in Figure 31 except for the wheel bearings (Shafer Bearing Company, Model ZF-208), 12-in.-diameter wheels (Farrell-Check Steel Company, Pattern No. CW-232), and the 60-lb rails (ASCE No. 6040). The drive is equipped with an emergency manual over-ride for use in the event of a power failure.

3. EXPERIMENTAL THIMBLES

The three thimbles were reworked from surplus BNL Graphite Reactor experimental tubes. Each is a stepped steel cylinder 8½ in. i.d. at the small end, 10 in. i.d. in the second stage, and 10½ in. i.d. at the face of the biological shield. They are cast into the concrete biological shield in line with the 4×4-in. openings through the graphite reflector (see Figure 39). No shutters are provided for these facilities.

One thimble is at the 104 ft, 4-in. level, tangent to the core and passing 20⅝ in. from its center; it extends in a northwest direction and terminates in the Patient Treatment Room, 28 in. above the floor. The second is located at an elevation of 105 ft, 0 in. (see Figure 23), which is coincident with the center of the fuel; it extends radially from the edge of the core tank on a north-south line and is expected to have a higher ratio of epithermal neu-





ONE DOOR REQ'D.
AVERAGE SPEED 2 FPM

CONTROL EQUIPMENT (TO BE SHIPPED LOOSE)

QUANTITY	DESCRIPTION
ONE	A.C. REVERSING CIRCUIT BREAKER COMBINATION STARTER DUST TIGHT, 1½ H.P., 440 V, 3 PHASE, 60 CY., WITH CONTROL CIRCUIT TRANSFORMER, COILS 110 V, 60 CY. SQUARE-D #8739, TYPE CA2, FORM FT.
ONE	PUSH BUTTON STATION - HEAVY DUTY, DUST TIGHT MARKED "OPEN", "CLOSE", "STOP" MOMENTARY PRESSURE ON "OPEN" CONSTANT PRESSURE ON "CLOSE" SQUARE-D CLASS 9001 GD-33
2	LIMIT SWITCHES, DUST TIGHT, SINGLE ROLLER SQUARE-D CLASS 9007, TYPE M11A

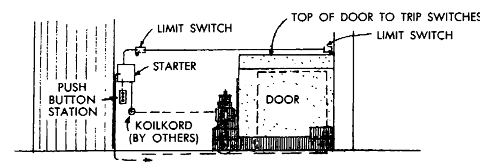


DIAGRAM SHOWING ARRANGEMENT OF CONTROL EQUIPMENT

Figure 31. Shield door, Broad Beam Facility.

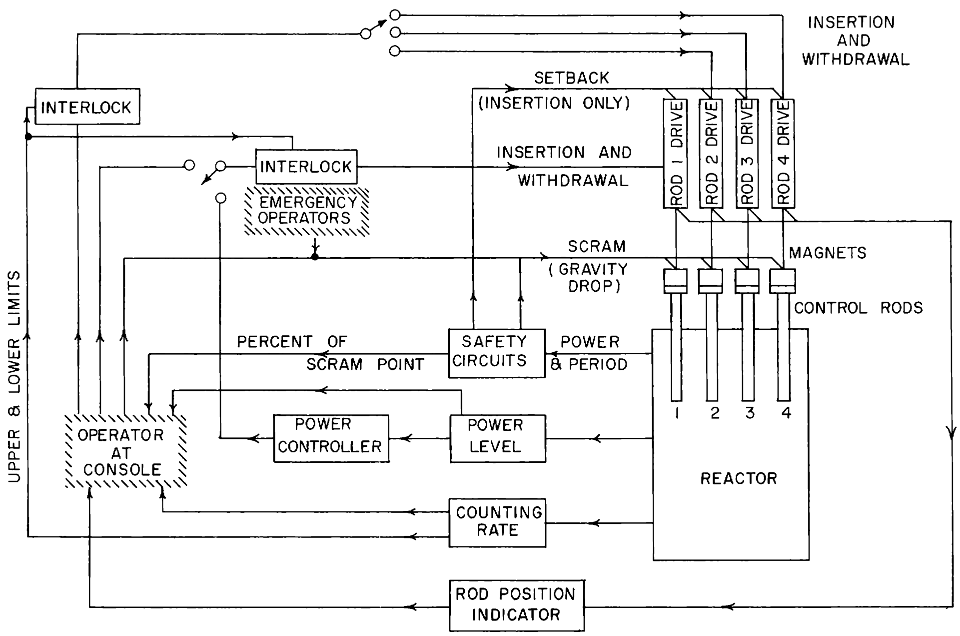


Figure 32. Nuclear instrumentation.

trons than the two tangential ones. The third thimble, elevation 105 ft, 8 in., passes tangent to the core and extends northeast to emerge 3 ft, 8 in. above the floor on the north face of the reactor. A 9-in.-i.d. spur intersecting the tube provides access from th Animal Treatment Room.

Dense concrete shield plugs are inserted in these holes at present, but special plugs will be designed for specific experiments as needed. Examples might include a loop for the production of short-lived isotopes in solid, liquid, or gaseous phases; a plug containing a circulating coolant such as deionized water, for use during irradiation of biological samples; or, if an external beam is required, plugs incorporating collimators, filters, or shutter devices.

XI. Instrumentation

1. GENERAL DESCRIPTION

The following systems (see Figure 32) comprise the nuclear instrumentation of the Medical Research Reactor: counting rate, power level, safety, control rod operation, and radiation monitoring (not shown).

In the reactor start-up or source range, the counting rate system provides a signal proportional to the reactor power. As the reactor becomes critical and for a short time thereafter, the period meter, a component of the safety system, is the instrument that signals the rate of change of the neutron level. As the power rises, this information is given by the power recorder, a part of the power level system which indicates, records, and controls the reactor power, except at the lowest levels.

The safety system, as its name implies, constantly guards against nuclear irregularities and is designed to scram or set back (automatically shut down) the reactor if the power level is too high or the period too short. The control rod operating system enables the operator to insert or withdraw the three safety rods or the regulating rod in order to meet the specific requirements of start-up, operation, or power regulating conditions. Gamma activities in working areas and process fluids are under continuous surveillance by the radiation monitoring system described in Section VII. 2. above.

2. COUNTING RATE SYSTEM

The antimony-beryllium source (see Section III. 8.), from its position in the core, initiates fission reactions, which are detected by a fission chamber also located in the core. The chamber is withdrawn from its start-up position opposite the center of the fuel by means of a motor drive controlled from the console (see Section III. 7. and Figure 9).

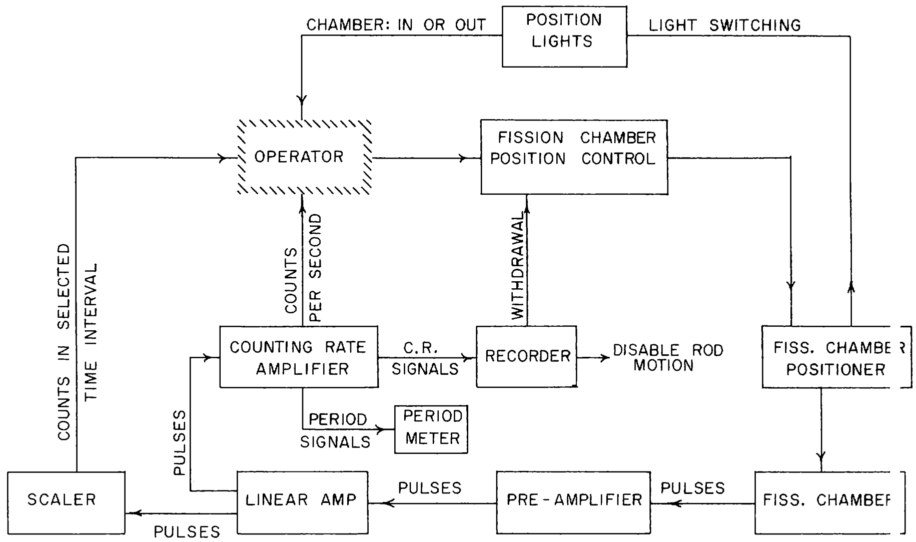


Figure 33. Counting rate system.

Low level pulses from the fission chamber are fed to a preamplifier at the reactor top and then to a linear amplifier in the Control Room (see Figure 33). A standard pulse from the linear amplifier is delivered to the counting rate amplifier which in turn sends a dc signal proportional to the log of the counting rate to the count rate recorder. This instrument indicates and records counting rate at low power levels and prevents rod withdrawal if the rate is <2 or $>10^4$ counts/sec. When the count rate exceeds 10^4, the recorder signals for withdrawal of the fission chamber.

A period meter accepts a signal from the counting rate amplifier to indicate low level reactor period. As an aid in determining criticality after a fuel reloading, a scaler is provided which receives a standard pulse from the linear amplifier and counts pulses in a selected time interval.

3. POWER LEVEL SYSTEM

Two ion chambers located in holes in the graphite reflector transmit a gamma-compensated signal through a calibration shunt and amplifier to a recorder where the power level is indicated and recorded in Mw, kw, or watts. The amplifier sends a portion of the signal (which is proportional to the reactor power) to a power level controller. The set point for power regulation is adjusted remotely by a set point control, which transmits a desired power signal to the power level controller. These signals, combined with a signal from the control rod position transmitter, result in a corrected signal which in turn is sent to an amplifier energizing the regulating rod drive motor. By use of a switch the operator can go from automatic control by the power level controller to manual regulation. Transfer from manual to automatic is possible only when the power level is near the set point. A schematic drawing is shown in Figure 34.

The power level system is a dependable source of information from lower intermediate to full power ($\approx$25 w to 5 Mw).

4. SAFETY SYSTEM

The safety circuit was developed by the BNL Instrumentation Division and has been described elsewhere.[22,40] The purpose of the safety system is continuously to survey the reactor operation and to initiate a scram or set-back if conditions become unsafe. The approach to safety and reliability is through a philosophy of redundancy-coincidence, which eliminates the need for disabling the circuit by automatic testing, fail-safe design, and monitoring of an integrated signal.

The safety system is composed of three identical channels, each providing similar information and almost independent of one another. Tripping the scram devices of two out of three channels will result in a reactor scram signal (see Figure 35). This method of control, called redundancy-co-

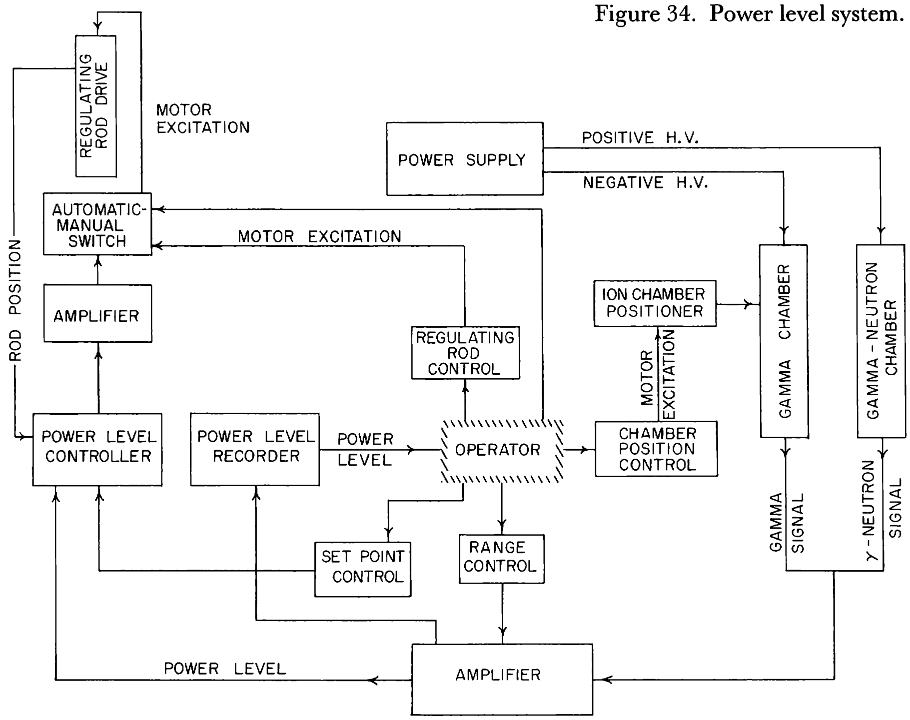


Figure 34. Power level system.

incidence, markedly reduces the probability of shutdowns due to nonnuclear failures in a single channel. Any one channel can be temporarily removed from service without affecting normal operation, which eliminates the need for lockouts or other disabling devices and allows continuous surveillance; it has the further advantage of making automatic testing possible. Testing is done by a monitoring circuit that switches a period and power recorder to each channel in sequence. Each channel undergoes a test in which simulated period and power signals result in a trip signal. The operator can thus cross-check the readings of each channel and test the power and period trip points. At present the period signal sets back at 12 sec and scrams at 6 sec, and the power signal sets back at 3.4 Mw and scrams at 3.6 Mw.

The trip signal in each safety channel is a combination of a signal proportional to reactor power and one proportional to the inverse period, so that trip period is lengthened with increasing power. The condition for a trip is

$$\frac{\tau'}{\tau}+\frac{P}{P'}=1$$

where τ' = trip period at $P=0$ and P' = trip power at $\tau=\infty$. Each safety amplifier contains a meter calibrated from 0 to 100% of trip point to show the operator how close a channel is to a scram point. By holding a constant reading on this meter the operator can start up and level off the reactor.

A fail-safe feature is provided by including a 1000-cycle, 20-v monitoring signal in addition to the 300 v dc in the circuit of each chamber which transmits the power-proportional trip signal. This 1000-cycle signal must be received at the safety amplifier to prevent a trip. Thus a channel will scram if there is an open circuit, defective chamber, ground, or power failure.

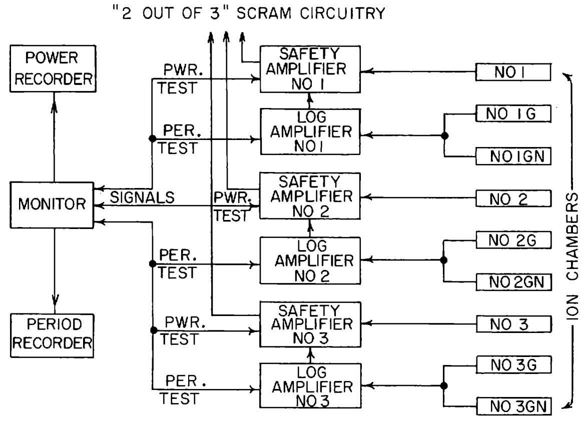


Figure 35. Safety system.

Figure 36. Console and instrument board.

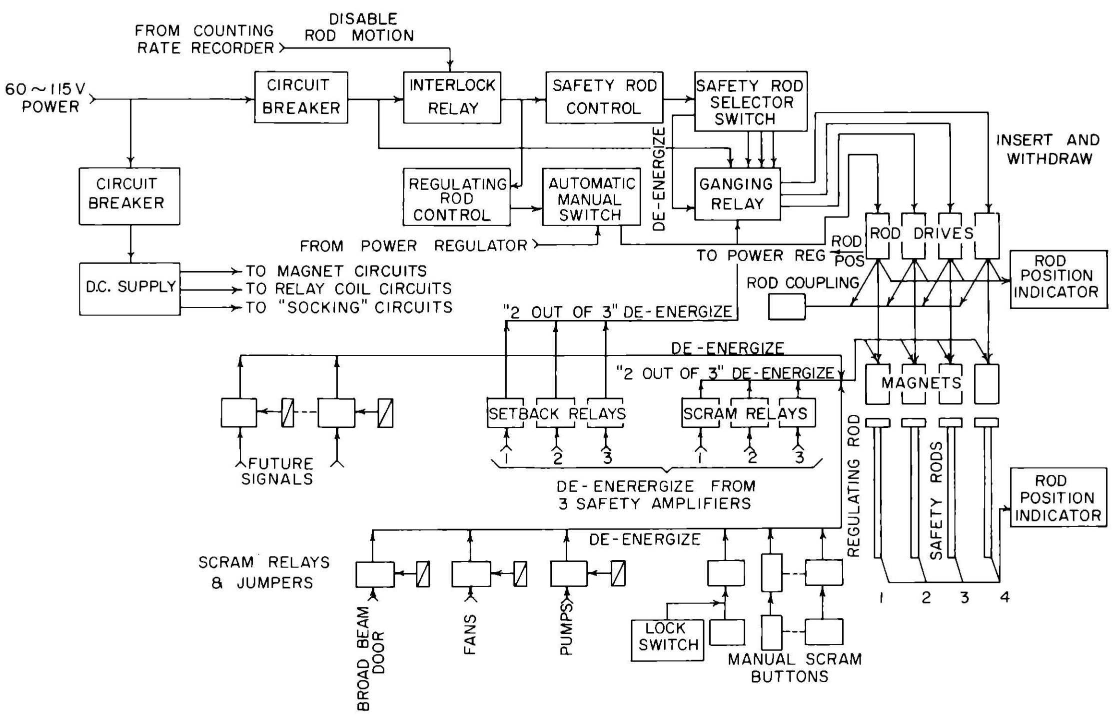


Figure 37. Control rod operating system.

Many chassis on the instrument board (see Figure 36) are designed as plug-in units so that spares can be readily inserted, and shutdown time can be eliminated while a unit is removed to the central instrument shop for servicing.

5. CONTROL ROD OPERATING SYSTEM

Many components of this system are described in Section III. 5. A schematic drawing is shown in Figure 37, and in Table 11 are listed the locations of the ion chambers and the trip point values for 3-Mw operation.

An interesting instrument developed at BNL is the rod position indicator shown at the center of the instrument board in Figure 36. Corresponding to each rod, this instrument contains a vertically mounted endless belt made of Cronar (a du Pont polyester film with high strength and dimensional stability), opaque over half its length and back illuminated. A signal from the position transmitter on each control rod drive is accepted by receiving synchros and rotates driving sprockets which move the belt, so that the position of the opaque part indicates the position of the control rod. The system has low inertia and can rapidly follow

Table 11

Safety Interlocks and Mechanisms (3-Mw Operation)

Variable	Detector location	Detector	Alarm point	Set-back point	Scram point
Neutron flux (power)	Reflector	Ion chamber #1		3.2 Mw*	3.4 Mw*
Neutron flux (power)	Reflector	Ion chamber #2		3.2 Mw*	3.4 Mw*
Neutron flux (power)	Reflector	Ion chamber #3		3.2 Mw*	3.4 Mw*
Neutron flux period	Reflector	Compensated ion chamber #1		6.5 sec*	6 sec*
Neutron flux period	Reflector	Compensated ion chamber #2		6.5 sec*	6 sec*
Neutron flux period	Reflector	Compensated ion chamber #3		12 sec*	6 sec*
Lockdown switch	On console	Key			Manual
Manual scram #1	On console	Pushbutton			"
" " #2	Reactor balcony	"			"
" " #3	Exit Patient Facility	"			"
" " #4	Exit Animal Facility	"			"
" " #5	Airlock #2 door	"			"
" " #6	Airlock #1 door	"			"
Local radiation #1	Patient Facility	Ion chamber	1000 mr/hr		
" " #2	Opp. exp. hole	" "	10 "		
" " #4	Animal Facility	" "	1000 "		
" " #5	Opp. Broad Beam Facility	" "	10 "		
" " #6	Reactor top	" "	50 "		
" " #7	" "	" "	10 r/hr for "incident" detection		
Primary water activity #8	Return pipe from reactor tank	" "	100 mr/hr**		
Secondary water activity #9	Return pipe from cooler	" "	50 mr/hr**		
Cooling air #10	Exhaust filter housing	" "	50 mr/hr		
Water level	Reactor tank	Gas tube	High: 4 in. below vent line Low: 2 in. above outlet pipe		
Water flow	Reactor inlet	Orifice plate			<200 gal/min
Water flow	Raw water inlet	Orifice plate	350 gal/min		
Water quality	Reactor inlet	Conductivity cell	0.5×10^6 ohms/cc		
Temperature	Outlet air	Thermocouple	150°F		
Position	Broad Beam Facility door	Switch device			Door not fully closed.
Pump operation	Pump motor starters	Contacts			No pumps in operation.
Fan operation	Fan motor starters	Contacts			No fans in operation.

*Two out of three trips required for a set-back or scram.
**High setting to compensate for background.

rod position changes without needing an amplifier.

XII. Reactor Building

1. GENERAL DESCRIPTION

The MRR is housed in an air-tight steel cylinder 60 ft in diameter and 54 ft high and having a slightly domical roof (see Figure 1). This shell joins the concrete foundation walls about 1 ft above grade, and two wings are connected to it through air locks. The north wing contains an Operating Room with supporting equipment and leads to the hospital area. In the basement of this wing are air conditioning and heating components. An east wing, equipped with a truck loading platform, serves as a storage and assembly area. Its lower level contains the equipment that discharges the reflector cooling and building air through a 28-in.-diameter pipe to the 150-ft-high stack.

The building is designed to withstand an internal overpressure of 2 psi. This is based upon a 1-psi rise in building pressure from a 144-Mw-sec energy release (Borax I experiment) plus a 1-psi maximum barometric differential. Wind and snow loading requires an external pressure rating of 40 psf.

The ventilation system, of the once-through type, provides a change of fresh air to the 2.5×10^5-ft^3 building every 40 min. The filtered inlet air is conditioned to 80°F dry bulb temperature and 50% relative humidity, and is delivered to diffusers throughout the building. The fan draws the room air into the reflector, picks up reflector heat, and exhausts to the stack.

Liquid effluents from the building are secondary cooling water, radioactive waste, and slightly active liquids. Secondary cooling water is normally discharged to diffusion wells via a 4-in. return pipe, but the flow can be valved off if an alarm is sounded by a remote gamma-monitoring unit (Jordan RAMS-II) to indicate that the water has become radioactive from a heat exchanger leak. Radioactive waste from the regenerated beds and reactor vessel overflow are discharged by gravity to a 50-gal sump tank in the basement and then pumped to a 600-gal haul-away tank in the reactor yard for removal to the central waste treatment area of the Laboratory. Basement floor drains empty into a sump where a 1¼-in. jet-type ejector pump,* using 60 psi steam, discharges the contents through a sampling tank to the sanitary sewer. Water from sink drains throughout the building also goes through the sampling tank, from which samples are periodically taken for monitoring. If necessary, the flow can be diverted to two 1000-gal underground holdup tanks.

Utility lines from the Medical Research Center, entering through the basement wall in the north wing, supply power, steam, vacuum, and compressed air to the reactor building.

(For detailed drawings of the reactor building, see Figures 42 to 44, near the end of this report.)

2. DESCRIPTION BY LEVELS

A. Basement (elevation 86 ft, 0 in.)

The 60-ft-diameter basement (Figure 38) houses the water cooling circuit, shutter elevator machinery, inlet ducts for reflector air, and waste sampling unit. The massive concrete columns supporting the reactor structure are used as a shielded room in the area below the reactor tank, but personnel are not allowed inside while the reactor is in operation.

Access to the basement is by two stairways and through a 4×7-ft stepped plug in the ceiling located within the range of a 12-ton crane on the floor above for lowering heavy equipment.

Doorways lead to Mechanical Room No. 5, which is under the north wing. Here, air enters the building through an automatic valve and is processed in air conditioning equipment which includes filters, a chilled water system, refrigeration plant, condenser, and well water supply. Ducts distribute most of the air to points around the building, but a small portion (heated by the equipment in the machinery room) is exhausted by a fan through absolute filters to the stack. Two air compressors are provided, one for air conditioning control instruments and one for all other instruments, each capable of delivering 100 psi of dry, filtered air.

The east wing basement, Mechanical Room No. 6 (elevation 91 ft, 0 in.) is not gas-tight, as are the other basement areas, and is accessible only via a stairway from the storage room above. It contains the exhaust air equipment that discharges reflector cooling and building air to the stack.

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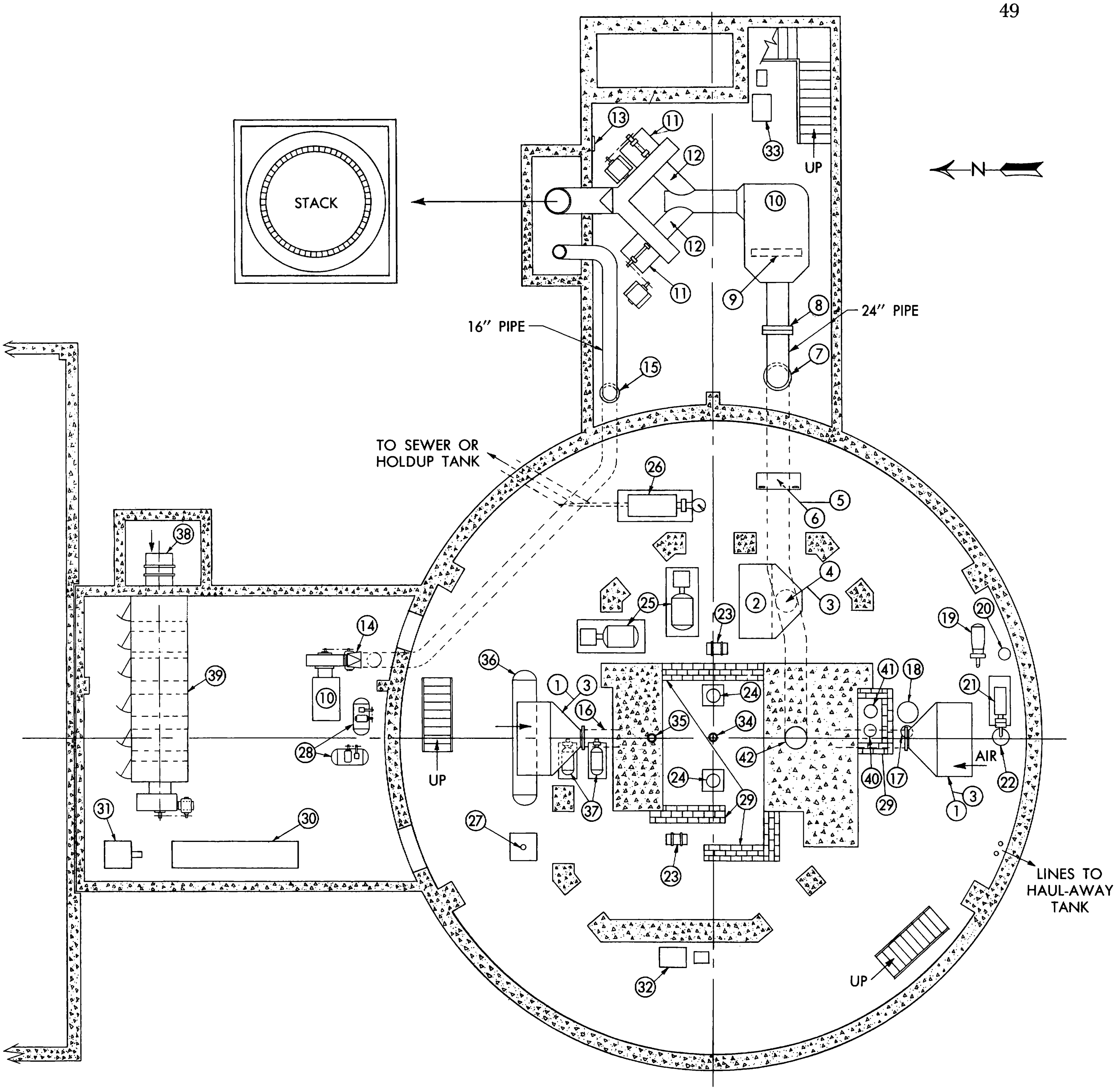
*Penberthy 4A, 26 gpm, 20-ft discharge head, [illegible]0-ft suction lift.



1 INLET AIR FILTER
2 BY-PASS FILTER
3 DRAFT GAUGE
4 24" BY-PASS DAMPER
5 FLOW ELEMENT
6 OUTLET AIR THERMOCOUPLE
7 24" BUTTERFLY VALVE (AUTOMATIC)
8 24" BUTTERFLY VALVE (HAND)
9 COPPER MESH FILTER
10 ABSOLUTE FILTER
11 EXHAUST FAN
12 OUTLET DAMPER
13 DRAFT GAUGE
14 EXHAUST FAN (BASEMENT AIR)
15 16" BUTTERFLY VALVE
16 INLET AIR THERMOCOUPLE
17 REGENERANT TANK
18 BRINE SATURATOR
19 WATER TREATMENT PUMP
20 FILTER (REACTOR WATER)
21 WASTE PUMP
22 SUMP
23 D_2O RESERVOIR
24 SHUTTER LIFT CYLINDERS
25 HYDRAULIC LIFT MOTOR & PUMP UNIT
26 WASTE SAMPLER & MONITOR
27 FLOOR SUMP & STEAM EJECTOR
28 AIR COMPRESSOR
29 SHIELD WALL
30 CHILLER
31 CONDENSATION PUMP
32 BUILDING AIR DUST MONITOR
33 EXHAUST AIR DUST MONITOR
34 INLET PRIMARY WATER PIPE
35 OUTLET PRIMARY WATER PIPE
36 HEAT EXCHANGER
37 PUMPS, PRIMARY WATER
38 FRESH AIR INLET & DAMPER
39 AIR CONDITIONING UNIT
40 DEIONIZER
41 SOFTENER
42 REFLECTOR AIR OUTLET

Figure 38. Reactor basement, process equipment layout.
(For details see Table 8.)

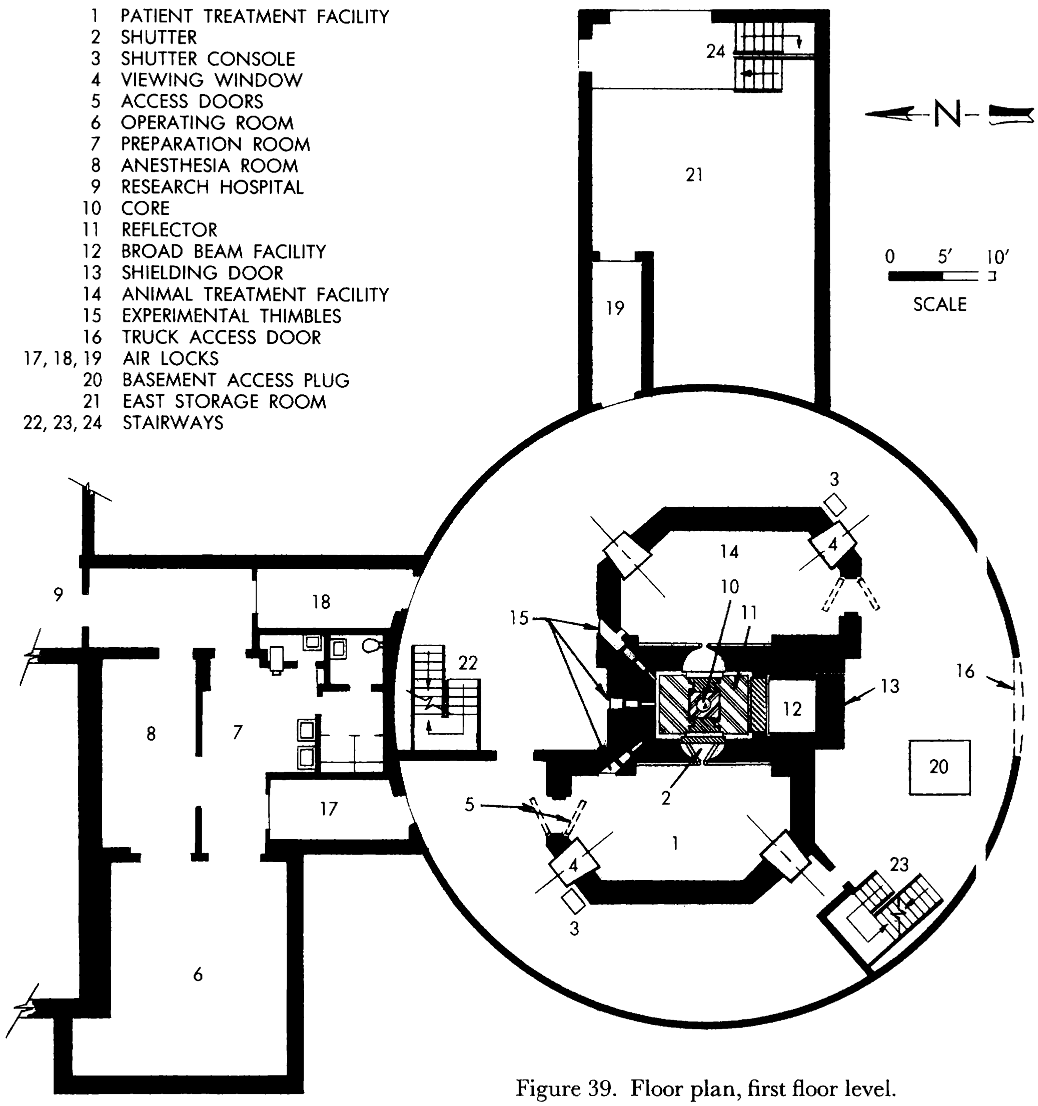


Figure 39. Floor plan, first floor level.

B. Main Floor (elevation 102 ft, 0 in.)

The main floor houses all the experimental facilities described in Section X and shown in Figure 39. Partitions around the Patient Treatment Facility separate it from the work and operational areas.

Three personnel air locks are needed. In the north wing one connects to the Operating Room and another to a by-pass corridor leading to the Medical Research Center. The third provides access to the east wing. In addition, a 10×16-ft gas-tight truck access door on the south side of the building can be opened when the reactor is not operating so that trucks can enter the building for unloading by the 12-ton crane. The 4×7-ft floor plug to the basement is located conveniently near the truck access door.

The concrete floor is capable of supporting the following live loads (given in lb/ft^2):

Patient and Animal Facilities	1000
Under Broad Beam Facility door	2000
Air locks, storage, receiving	500
Other main floor areas	500

C. Balcony (elevation 114 ft, 0 in.) and Reactor Top (elevation 123 ft, 4 in.)

Stairways from the main floor lead to the balcony covering the treatment rooms and extending to the building wall in the northwest quadrant. On the balcony is the Control Room (seen in Figure 40) with its console and instrument panels,

Figure 40. View from reactor top.

nuclear and process instrumentation, and an intercom system. A small office and instrument maintenance space are adjacent.

The balcony floor is designed for the following loads (in lb/ft^2):

Under crane	500
Control Room	125

The reactor top, reached by a stairway from the balcony, is a 12×18-ft platform containing flush plugs spanning the reactor tank, shutter shaftways, and the discharge water pipe recess. It is used as an operations area for shifting or discharging fuel, removing shutters, and servicing control rod assemblies. The entire reactor top is accessible to the building crane.

3. CONTAINMENT SHELL

The cylindrical shell of the reactor building is constructed of ⅜-in.-thick steel plates, reinforced at door openings to 1 in., which conform to ASTM Specification A-283 and are fully butt-welded for air tightness. Horizontal hoops formed from steel angles, spaced 36 in. vertically on center, are welded to the exterior surface of the shell; these are connected at intervals by channeled vertical spacers. The roof is butt-welded of plates shaped to form concentric circular bands when assembled.

A flange at the bottom of the cylinder fits into a recess at the perimeter of the foundation wall and is fastened to ¾-in.-diameter anchor bolts capable

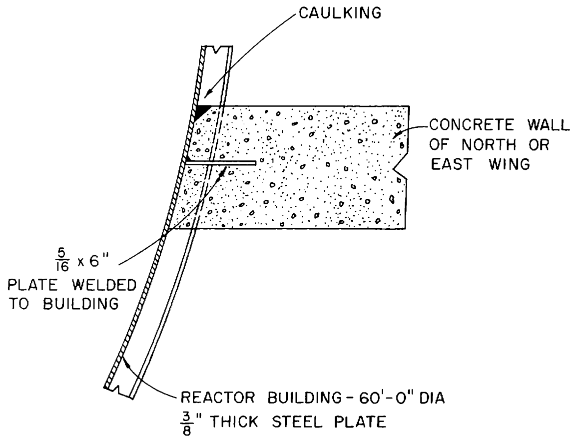


Figure 41. Leak-tight joint.

of withstanding the 150-ton upward thrust due to a 2-psi overpressure within. The recess was carefully filled with Embaco grout, and the air-tight seal was made with a continuous flexible caulking bead inside the building, between the concrete and the steel wall.

Where the walls and roof slabs of the wings meet the steel reactor container, leak-tight joints were achieved by use of thin steel plate edge welded to the tank (see Figure 41). This continuous plate, 6 in. wide, is cast into the concrete and more than doubles the surface area of the joint. Copper strips were embedded in the east wing air lock and soldered to the door frames to prevent leakage around the gas-tight doors. In the north wing, doors in each air lock are mounted within a steel corridor-like structure welded to one end of the reactor shell.

The containment shell is insulated with Foamglas blocks, 2 in. thick, mounted on the outer sidewall between the hoops. Corrugated aluminum siding panels, 0.024 in. thick, are fastened to the steel framework with stainless steel neoprene-backed fasteners. The roof is also insulated with Foamglas blocks, held in place with straps; over these is a built-up asphalt felt and fabric covering finished with a layer of marble chips. The inside of the domed roof is lined with acoustic tile.

The building was pressurized after its completion and tested for gross leaks in the welded structure by a portable weld leak tester[24] comprising a transparent box and a vacuum pump. The box consists of a 12×24-in. piece of 1-in.-thick Lucite with a continuous frame of resilient rubber, and has handles, a vacuum connection, and a vent valve. It is placed over the weld to be tested after the latter is swabbed with soap solution. Leaks were located and repaired while the welders were available and scaffolding was still in place.

The domed roof is structurally adequate but was difficult to erect. Steel roof plates, unless very accurately cut and assembled, may form flat surfaces or ripples when butt-welded and thus diminish the strength of the arch. A smaller dish radius or lap-welded construction might well be considered in future designs.

A. Gas-Tight Doors

There are four points of entry into the cylindrical building (see Figure 39), three of them air locks each containing two gas-tight doors, and the fourth a truck hatch that can be opened only when the reactor is not operating. Doors open inwards so that accidental overpressure would force them against their stops.

The two pairs of north wing doors are of special BNL design and meet the requirements of a flush sill (so that litters can be wheeled in), light weight, and quick operation. The doors are fabricated from 6061 aluminum alloy and weigh 160 lb each. They are 6 ft, 10½ in. high, 3 ft, 7½ in. wide, and 2¾ in. thick, of hollow construction, and each has a ⅛-in.-thick panel welded to the reactor side and a similar panel bolted to the other side. A pneumatically operated, edge mounted, inflatable gasket (Continental Rubber Works No. 3243) expands to seal against the stainless steel facing of the door frame. The structural steel frame is continuously welded to the building shell. Each door is equipped with a push-button control station (GE Type CR-2940), and the two doors to each air lock are controlled so that only one may be opened at a time. Operation of the button control at a door causes gasket air to be vented through a solenoid operated valve (¾-in. Ross, 4-way), which leaves the door free to open. At the same time, a pressure switch (Minneapolis-Honeywell No. L-404-B) opens and inactivates the air dump circuit on the opposite door of the air lock. When a door is closed, a switch (Micro BZE-7RQ?) is energized which causes the gasket to be reinflated, the pressure switch closes, and the dump circuit of the opposite door is restored. A regulating valve (Moore No. 4250-30) is used to reduce line pressure to the 10 to 15-psi optimum gasket pressure. Gasket dump time is reduced by a ½-in. check valve in parallel with the regulator.

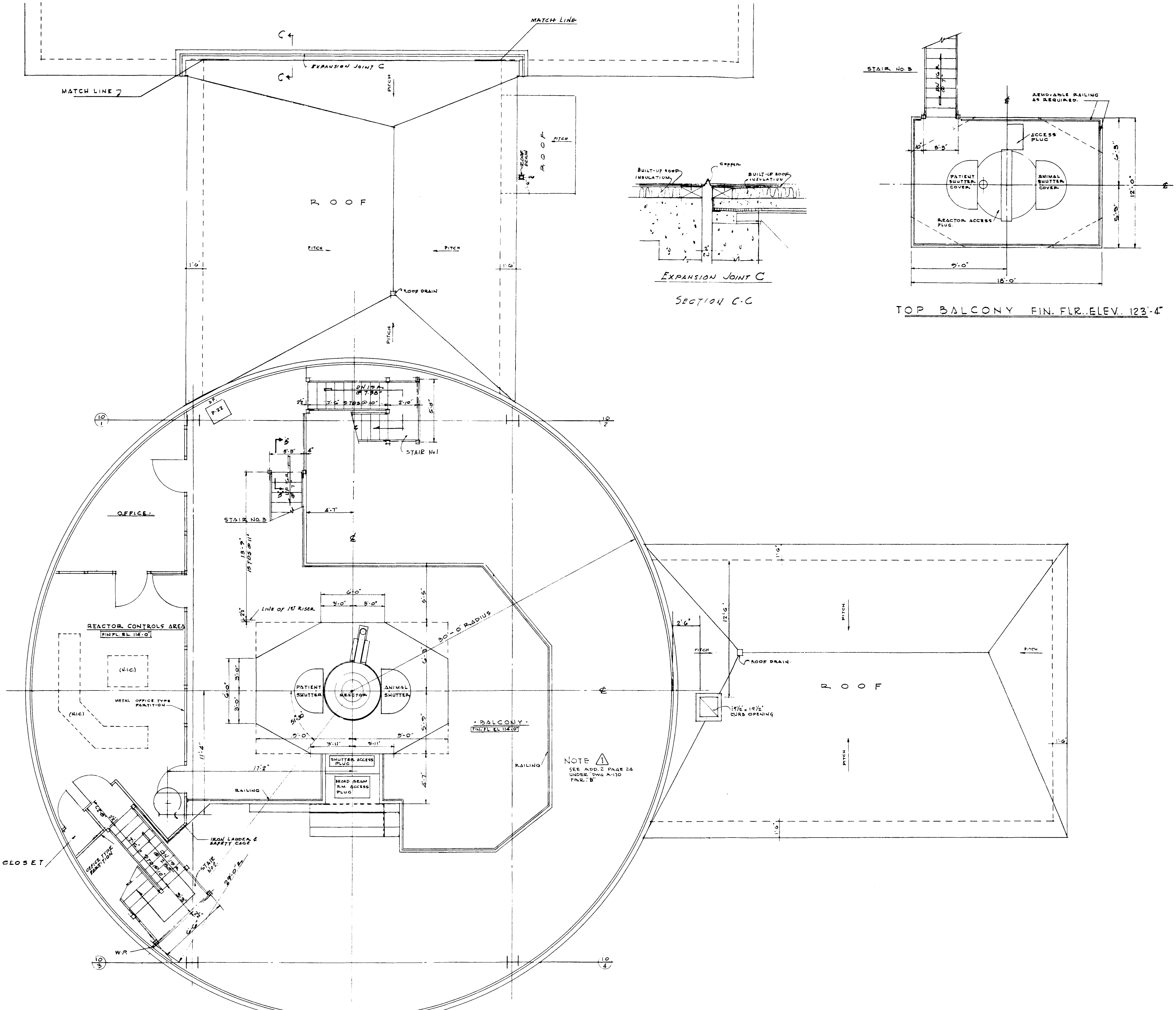


Figure 42. Plan of balcony. (This drawing does not show operating room extension; see Figure 39.)

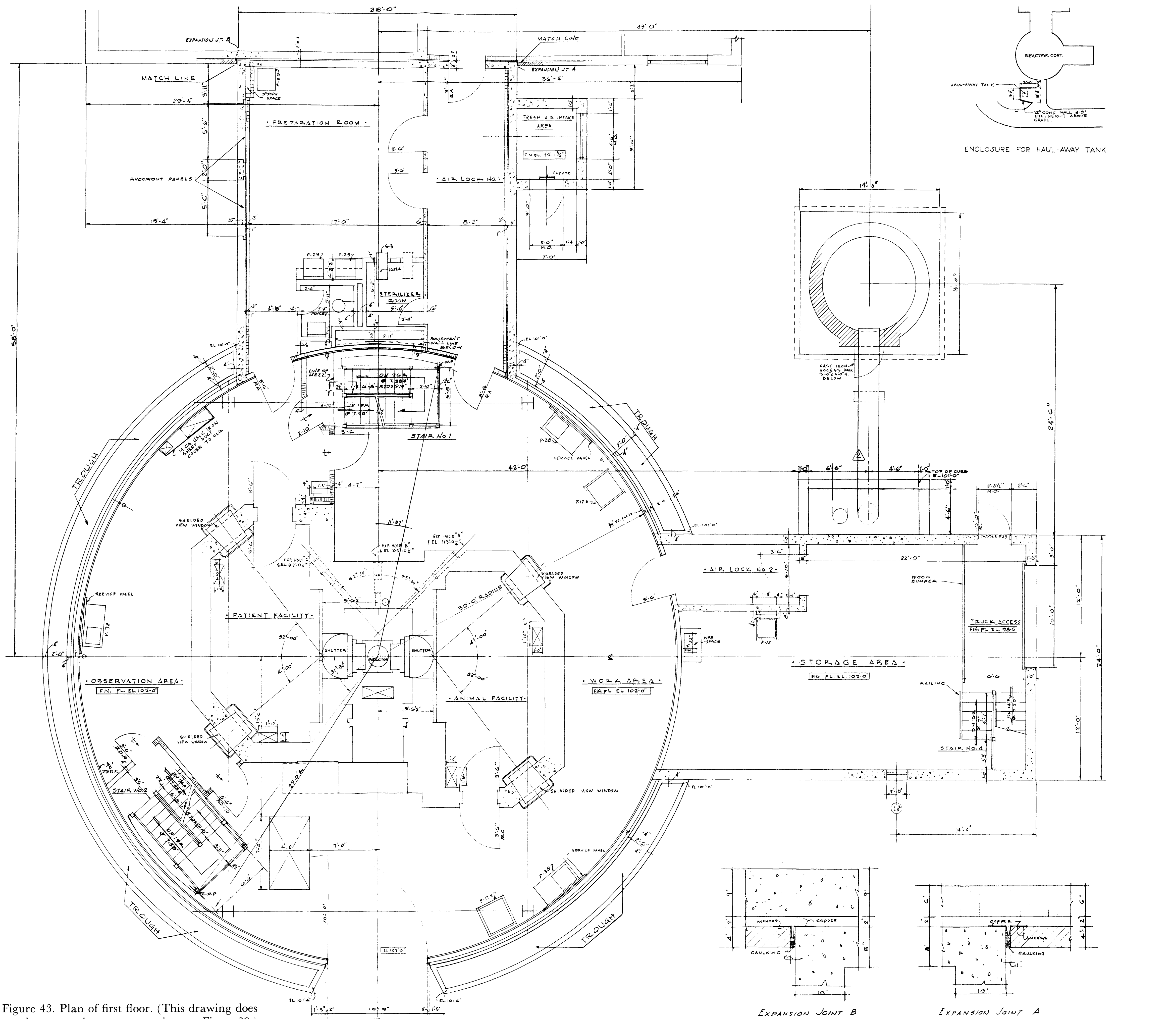


Figure 43. Plan of first floor. (This drawing does not show operating room extension; see Figure 39.)

The east wing air lock, an integral concrete structure, is equipped with two steel doors manufactured by the Jamison Cold Storage Door Company. A spring latch pulls the door against a seat on the frame and compresses a solid rubber gasket fastened to the door face. This sealing arrangement requires a 1-in.-high floor sill, which is permissible here. Clearance through an open door is 6 ft, 9 in. high by 3 ft, 1½ in. wide. A mechanical interlock prevents both doors from being opened at the same time.

The gas-tight truck access has a 10-ft-wide by 16-ft-high bulkhead door, also manufactured by Jamison, with a solid rubber gasket held against the door frame by five cam levers or dogs. It is of one-piece hollow steel construction and can be opened only from inside the building.

B. Service Penetrations

All service lines entering the reactor building or breaching a contained area pass through pipe sleeves cast into the concrete and equipped with welded rings embedded in the wall. The space between the entering service pipe or conduit and the sleeve is filled with oakum and pressure packed from each end with oakum–lead wool caulking.

For electrical lines, integrity between the conduit and the wires within was attained by leading the wires into a box and looping them in a trap-like configuration before continuing the run. The box was filled with a potting compound after a short length of each wire in the box was bared to permit sealing between the conductor and insulation.

C. Building Relief Valves

Three water-sealed vents are provided to prevent damage to the reactor building in the event of either accidental overpressure or excessive vacuum. A 5 ft, 9-in.-long, 8-in. standpipe rises from a water-filled tank, 24 in. o.d. by 16 in. high, made of 3003 aluminum alloy. The volume of the water in the system is such that at a building pressure slightly greater than 2 psi, the liquid rises in the standpipe and air can bubble through the water trap. Excessive pressure could cause a slug of water to be ejected from the building. Conversely, a high vacuum drawn on the reactor container by an exhaust fan lowers the water level in the standpipe and permits outside air to bubble into the system. The reservoir level is checked periodically; make-up water is added through a filler plug.

4. BUILDING CRANE

A 12-ton traveling crane services the main floor area, balcony, and reactor top, and can lower equipment through the floor hatch to the basement. Its coverage is ≈23 ft, 6 in. east to west and 45 ft, 0 in. north to south. The reactor is centrally located beneath the crane structure, the main rails of which are at the 142 ft, 7-in. level.

The crane was manufactured by the Conco Engineering Works (Type "CRM"). Motors, equipped with brakes, drive the bridge and trolley through fluid couplings for smooth, stepless acceleration to full speed. The hoist is driven by a motor and brake through a locking worm-wheel drive. The hoist has a 60-ft lift and is equipped with upper and lower limit switches to prevent overtravel. The crane is controlled from a push-button station suspended from the hoist by an adjustable ratchet cable reel. Crane speeds are as follows:

	FPM	HP, SINGLE SPEED
Bridge	40	1½
Trolley	40	1
Hoist	9	10

Heavy loads in the treatment rooms, east wing, and other main-floor areas not under the crane are moved by an electric fork-lift truck.

5. EXHAUST STACK

A circular brick chimney 150 ft high, located just north of the east wing, discharges the building air to the atmosphere. It rests on a 6-ft-deep reinforced concrete pad. The stack is 9 ft, 3 in. i.d. at its base and 2 ft, 0 in. i.d. at the top.

The height of the stack was determined by several factors, including the rate of Ar^{41} discharge (calculated at 0.73 C/hr at 1 Mw) and the maximum permissible radiation limit of 5×10^{-8} C/m³* in the air at the point of exposure over a 24-hr period. This problem is covered in detail in the *MRR Hazards Report.*[26]

*This limit was set by the Health Physics and Meteorology groups at BNL and represented a safety factor of 10 over the *Handbook 52*[46] figure of 5×10^{-7} C/m³. The National Commission for Radiation Protection has since published a new value[47] of 2×10^{-6} C/m³.

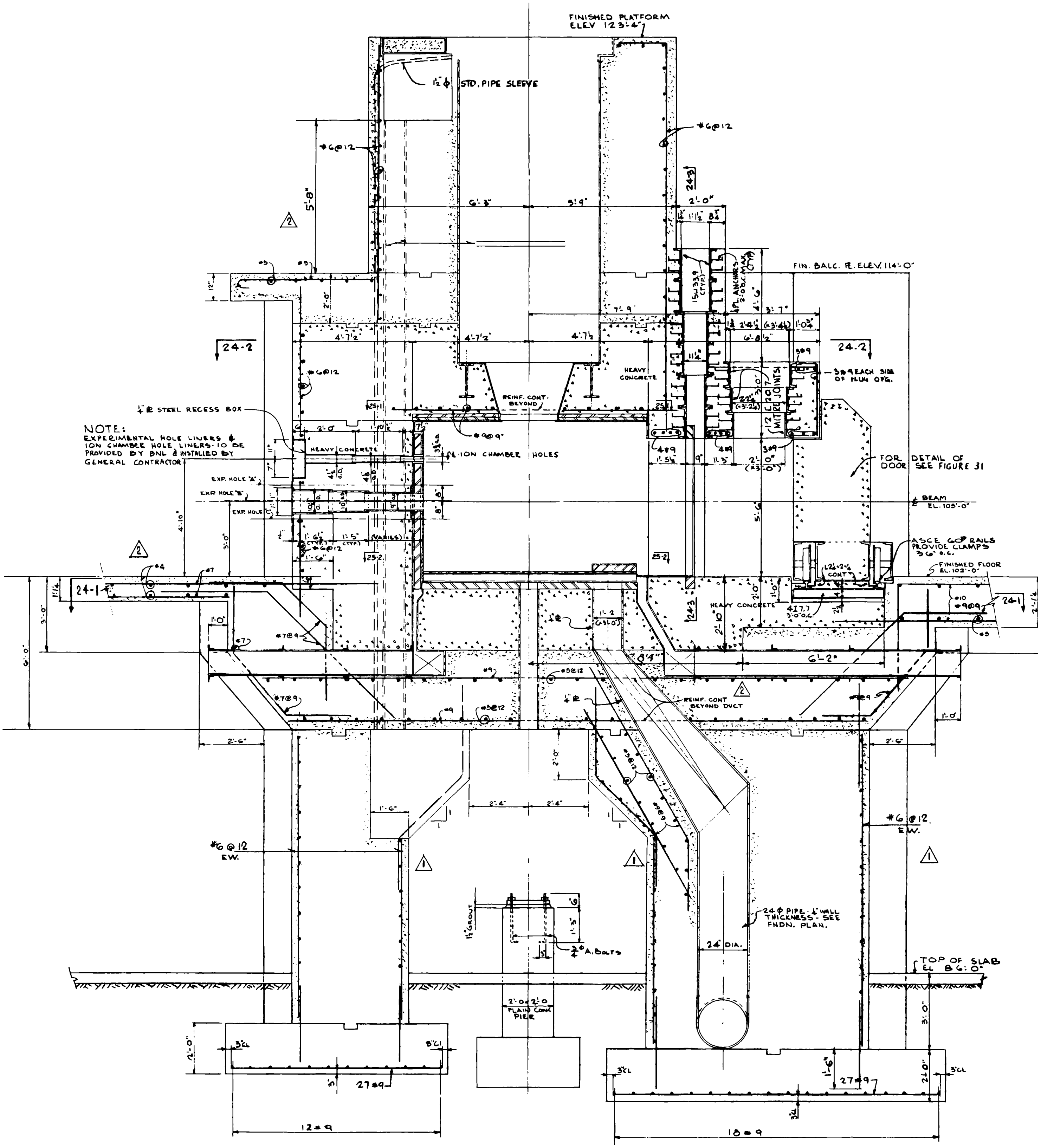


Figure 44.*A*: N-S section.

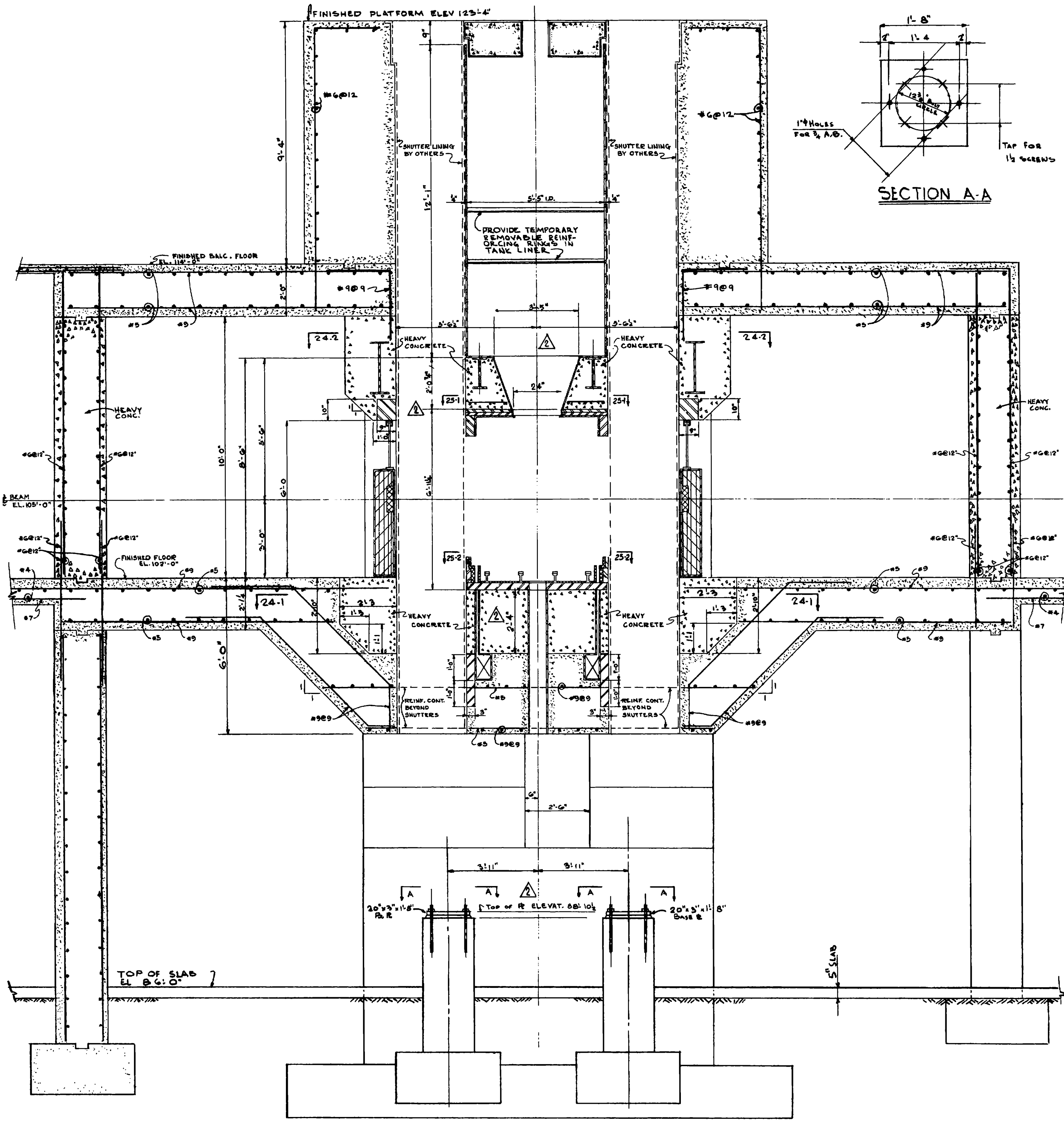


Figure 44.*B*: E-W section.

Appendix A
Summary of Reactor Data

TYPE: Tank type, thermal, heterogeneous, light water moderated and cooled, graphite reflected.

OWNER: Atomic Energy Commission.

OPERATED BY: Brookhaven National Laboratory.

POWER: 1 to 3 Mw.

FUEL ELEMENTS: 18-plate MTR type, 140 g U^{235}, U-Al alloy fuel, >90% enrichment. Plates: 0.060 in. thick (0.020 in. fuel, clad in 0.020-in.-thick 1100 aluminum). Spacing between plates: 0.112 in. Active length of element: 23⅝ in. Spacing between elements: 0.120 in. N-S; 0.038 in. E-W.

CORE: Critical mass (minimum): 2.24 kg U^{235}. Average specific power in fuel: 1340 kw/kg (at 3 Mw). Average power density: 50 kw/liter (at 3 Mw). Channel velocity of coolant: 2.16 ft/sec. Subassemblies: 17 fuel elements, 8 element-shaped graphite core pieces, 1 source chamber graphite core piece, 1 fission chamber graphite core piece, 5 graphite odd-shaped core pieces (to fill out cylinder).

CONTROL: Three safety rods, B_4C with 0.030-in. Cd lining, clad in stainless steel jacket, ¾×2½×26 in. One regulating rod, stainless steel, ½×2½×26 in.

TANK: Diameter: 24 in. at core, 64 in. at top. Length: 20 ft, 7½ in. Capacity: ≈2000 gal.

COOLING SYSTEM: Primary: 600 gpm low-conductivity water. Secondary: 520 gpm well water. Water treatment: 10 gpm sidestream, presoftened before entering a standard monobed ion exchange column.

REFLECTOR: Graphite, AGOT and AGHT grades. 5 ft, 8 in. high, 5 ft, 5 in. wide, 8 ft, 3 in. long. Cooled by 6100 cfm dry, filtered air which is discharged through an iodine trap and absolute filters to the 150-ft stack.

SHIELD: Dense concrete: Limonite and steel punchings (285 lb/ft^3). Thermal shield: 3 to 7 in. steel (air cooled). Neutron: 1-in.-thick B_4C filled cans or ¼ in. boral. Special: Up to 11½ in. bismuth in each treatment port; up to 4 in. Pb in wall in treatment room; 15 ft H_2O over top of fuel in core.

OPERATING TEMPERATURES (AT 1 Mw): Primary H_2O, reactor inlet: 75°F; outlet: 86°F. Secondary H_2O, heat exchanger inlet: 52°F; outlet: 68°F. Reflector air, inlet: 81°F; outlet: 92°F.

EXPERIMENTAL FACILITIES: Patient Treatment Facility: 11×21-ft shielded room with port on reactor face equipped with a 20-ton vertical shutter. Flux: 2.03×10^{10} n/cm^2-sec (thermal) and 37 r/min (gamma). Animal Treatment Facility: Same as above. Broad Beam Facility: Shielded cave (5-ft cube) open to face of thermal column. Beam varied by use of retractable filters. Rolling dense concrete door provides access during shutdown. Flux: 1.5×10^9 n/cm^2-sec (thermal) with screen up. Two tangential tubes: Horizontal, 4×4-in. opening in graphite. One radial tube: Same as above.

HISTORY: Construction start: September 1956. Reactor critical: March 1959. Full power: April 1959.

Appendix B
Cost Breakdown (in Dollars)

1. Reactor Assembly

Reactor tank, grid plate, and top plug	15,000
Control rods and drives	21,000
Console, instrument board, and wiring	52,000
Fuel elements and graphite core pieces	14,000
Tools and miscellaneous	6,600
Total	108,600

2. Cooling Water System

Heat exchanger	8,600
Pumps	5,400
Valves, piping, and instrumentation	26,900
Water treatment	6,500
Sump and haul-away tank	2,500
Total	49,900

3. Special Materials

Graphite (machining and erection)	6,100
Bismuth	45,430
Boral and boron carbide	6,200
D_2O system (exclusive of D_2O)	4,500
Lead (Broad Beam Facility)	1,700
Polyethylene	910
Fabrication costs	3,800
Total	68,640

4. Reflector Cooling System

Ducts	16,300
Fans	3,000
Filters	2,300
Valves and piping	9,500
Copper filters	980
Stack	19,230
Total	51,310

5. Steel Work

Thermal shield	11,300
Structural and miscellaneous	12,300
Total	23,600

6. Reactor Building

Excavation and backfill	4,650
Concrete: Dense	41,400
Structural	67,380
Steel container	60,000
Siding, roofing, and insulation	21,000
Gas-tight doors	16,000
Wings, partitions, finish, and miscellaneous	74,400
Crane (including steel work)	19,230
Erection of steel, reactor components, etc.	23,440
Total	327,500

7. Services

Heating, ventilation, and air conditioning	99,330
Plumbing	26,470
Supply and diffusion wells	38,540
Electrical	68,440
Total	232,780

8. Experimental Facility Details

Shutters, including dense concrete	73,940
Installation of shutters, thermal shield, and tank	7,000
Observation windows and lead glass	8,400
Steel doors	8,200
Broad Beam Facility door	9,300
Beam catcher	1,970
Miscellaneous	1,500
Total	110,310

9. Miscellaneous

Development costs including critical experiments, design studies, and instruments	13,500
Salaries, wages, insurance, and travel	38,440
Miscellaneous labor and machine costs	15,900
Architect-Engineer (portion applied to MRR)	51,780
Total	119,620

Grand total 1,092,260

Appendix C
Organizational Chart for Medical Research Reactor

DESIGN COMMITTEE

GERALD F. TAPE – *Director's Office*
R.W. POWELL – *Project Engineer*
T.V. SHEEHAN – *Mechanical Engineering*
H.J.C. KOUTS – *Reactor Physics*
E.E. STICKLEY – *Medical Physics*
J.E. BINNS – *Instrumentation*
J.G. PETER – *Architecture*

DESIGN STAFF

R.W. POWELL – *Project Engineer*

Operations

J. SEARS – *Supervisor*
D. OLDHAM

Instrumentation

J. BINNS – *Group Leader*
D.G. PITCHER – *Supervisor*

Design

J.B. GODEL – *Supervisor*

CRITICAL EXPERIMENT AND REACTOR PHYSICS GROUP

H. KOUTS – *Group Leader*

G.A. PRICE
K.W. DOWNES
H.P. SLEEPER, JR.

MR. A. RAND and MR. E. BARNETT were members of the Project Engineer's staff during the early stages of the design.

Appendix D
Acknowledgments

The author wishes to express his appreciation to Mr. Robert W. Powell, under whose direction the Medical Reactor was designed, constructed, and brought into operation. His encouragement and cooperation made possible the writing of this report.

Valuable assistance was received from Dr. G.A. Price as evidenced by his authorship of Section II, which contains the nuclear description of the core and critical experiments. I am indebted to Mr. John Sears for his comments on the rough draft.

The following persons contributed to this report in the manner indicated: Mr. Carl Cante[illegible]a, drawings and illustrations. Mr. Charles Meinhold, radiation survey information. Mr. Daniel Oldham, process data. Mr. John A. Penney, fuel element inspection data. Mr. D.G. Pitcher, control rod information. Mr. Willis Sceviour, drawings and illustrations.

I wish to thank Miss Elaine Daniels for typing and assembling the manuscript.

LIST OF MAJOR CONTRACTORS FOR THE MEDICAL RESEARCH REACTOR

Nuclear Development Corporation of America – preliminary design studies
Eggers & Higgins – architect-engineers
Syska & Hennessy, Inc. – mechanical engineers
Weiskopf & Pickworth – structural engineers
Baldwin-Lima-Hamilton Corporation – shutters, thermal shield, ducts, and steel doors
Daystrom, Inc. – reactor contractor: control rods and drives, instrumentation, console, core components
Malan Construction Corporation – general contractor
Sylvania-Corning Nuclear Corporation – fuel elements
Aluminum Company of America – reactor vessel

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