LOS ALAMOS SCIENTIFIC LABORATORY

OF THE UNIVERSITY OF CALIFORNIA
LOS ALAMOS, NEW MEXICO

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LOS ALAMOS SCIENTIFIC LABORATORY
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THE LOS ALAMOS FAST PLUTONIUM REACTOR

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REACTORS-RESEARCH AND POWER
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ABSTRACT

The Los Alamos Fast Plutonium Reactor is a low-power reactor built primarily (1) to demonstrate the feasibility of a reactor operating on unmoderated or "fast" neutrons, and (2) to serve as an experimental facility. The operating power level of 25 kw produces a fast neutron flux of approximately 4 x 10^{12} neutrons per cm^2 per sec. The reactive region consists of a lattice arrangement of metallic plutonium fuel rods surrounded by normal uranium reflector material and cooled by flowing mercury. Experimental facilities consist of numerous fast neutron ports and a graphite thermal column. Construction of the reactor was begun in December 1945, and full power operation was first attained in March 1949.

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PREFACE

This report attempts to record a complete description and fabrication history of the Los Alamos Fast Plutonium Reactor. Much of what is described is now only of historical interest, however, since the reactor was completely dismantled in the spring of 1953.

It would be proper to record here briefly some of the later history of the Fast Reactor. From March 1949 a full operating schedule was maintained for nearly a year, during which time several experiments made good use of the reactor as a neutron source. In March 1950 the reactor was shut down to correct a malfunctioning which had developed in the operation of the control and shim rods, and during the shut-down period a ruptured uranium core reflector rod was detected and replaced. As explained in LA-1163, because of this experience the core was modified to eliminate all the canned uranium rods.

Reactor operation was resumed in September 1950 and continued until December 1952, when it became evident that a plutonium fuel rod had ruptured, thereby releasing plutonium into the mercury coolant. The hazard created by this situation and indications of serious abnormal behavior of the reactor material prevented further operation of the reactor and prompted the decision to proceed with a complete disassembly. Details of the disassembly, completed by June 1953, are given in LA-1575.

May, 1954

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INTRODUCTION

The construction of a fast plutonium reactor at Los Alamos was first proposed in 1945. It was felt by the Laboratory that it would be worth while to explore the use of plutonium with respect to adaptability for small reactors, breeding purposes, and future power reactor studies. The fact that sufficient plutonium existed solely at Los Alamos also influenced the original thinking as to the selection of fissionable material.. The following premises were applied to the considerations of the reactor:

1. Delta-phase plutonium was selected for use because it is stable against temperature changes, the heat conductivity and thermal expansion are better than for other phases, and the metallurgy is fairly well known.

2. The reactor should be a "fast" machine, that is, the controlled fission would occur by high energy or fast neutrons. This would mean that the reactor could be of small size since no moderating material would be used. Furthermore, since the neutrons would be unmoderated they would have a spectrum determined by the fission spectrum and inelastic scattering in active material and in a minimum of inactive heavy materials. High intensities of such neutrons which are characteristic of the bomb and which are useful for breeding purposes were at that time not available. Because of the small size of the reactor, the fast flux could be comparable to the Hanford reactor flux.

3. The reactor should operate at about 10 kw. This power would produce an adequate neutron flux for the many uses to which the reactor would be put (see paragraph 6 below), and yet not much difficulty would be experienced in the over-all design of the reactor, especially in the cooling system and the shield.

4. The reactor would be cooled by circulating mercury because an unmoderating coolant was indicated for the fast fission. It was recognized that mercury is not an ideal heavy-metal coolant and that Na-K alloy or Na are superior because of lower absorption and scattering cross sections, but the technology of Na-K alloy was not well developed. It seemed more reasonable and expedient to use a simple though inferior coolant.

5. The design and construction would be done by the personnel at Los Alamos. This would minimize the cost and effort of the undertaking.

6. The benefits to and facilities for the Laboratory which would become available upon completion of the reactor were

   a. High intensity source of fast neutrons for nuclear research.

   b. High intensity source of fission spectrum neutrons for examining principles of the bomb.

   c. Device for studying methods and ease of control of a fast reactor.

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d. Device for studying principles of breeding for future production of fissionable material.

e. Device for studying principles of power production from fast reactors with a view to future large scale power plants.

These proposals were submitted to the Director of the Los Alamos Scientific Laboratory, Norris E. Bradbury, who submitted them in November 1945 to the Manhattan Engineer District for approval. In December 1945 the approval to build the reactor was granted and work was immediately begun, as several design conferences had been held since November.

The question as to the location of the reactor was discussed and two suggestions were offered. The reactor could be built in the original Omega Building due south of the Water Boiler, or a new room could be built west of the original Omega Building. The highly desirable decision to build a new building at Omega Site was made by the District in April 1946. The new building was planned to connect with the original Omega Building in order that shop and other facilities could be shared by the Water Boiler and Fast Reactor groups. The housing of the reactor in a separate building meant that the construction of the reactor would not interfere with the Water Boiler work and that when the reactor was completed both machines could operate simultaneously and thus more efficiently. Construction of the new building was started in May 1946 and finished in August 1946.

During the interval from December 1945 to August 1946, some of the design, fabrication, construction, and procurement of the reactor parts were done. The actual construction of the reactor was started the latter part of August 1946, and the structure was built to include the lead shielding which surrounds the steel reflector. On November 21, 1946, the first critical assembly of the reactor was made at this construction stage. Nuclear measurements were performed at 1 watt power without further construction during December 1946, and January and February 1947, with emphasis placed on experiments concerning critical mass vs plutonium configuration, effectiveness of control of reactor, temperature coefficient of reactor, and fraction of neutrons which are delayed in the fast fission of plutonium. The experiments were done at this time so that in the event that performance was not as expected, necessary changes could be made before the shielding was completed.

In March and April 1947, the aluminum envelope surrounding the lead shielding was assembled and part of the laminated shield was erected; construction work was again halted in order to test the effectiveness of this portion of the shield before the concrete shield was poured. Neutron distributions in the active material, reflector, and boron-plastic shield were made in May. The neutron measurements continued for one month and the laminated shield

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work was resumed in June and finished by July.

In June a mock-up of the mercury system was assembled and performance tests were started.

From July to September 1947, work was mainly confined to construction of the steel framework for the mercury cabinet fabrication, installation of the mercury cabinet, and pouring of the concrete shield and top shielding blocks. The thermal column was build in November 1947, and part of the top shielding completed. The pot was received in December and a critical assembly with peripheral loading of plutonium was made.

During the time from November 1946 to February 1948, the heat exchangers and pump for the mercury system were redesigned and constructed in the shops, the pump being finished in February 1948. It was also found necessary to redesign the pot and to have it fabricated at Project Roger. The safety circuits and control-rod mechanisms were also redesigned and built. The mercury flow indicators were designed, tested, and calibrated using the pressure drops across a thin plate orifice and venturi tube.

From December 1947 to June 1948, work was again confined to nuclear measurements with the following type made using the peripheral array: the effect of alpha-phase plutonium upon reactivity, neutron distributions in the reactor pot, temperature coefficients, danger coefficient measurements, activation cross sections, neutron spectra and photographic film technique development.

In June 1948 the plutonium was loaded in a central array and several further internal nuclear measurements were done. This work continued until January 1949, when the reactor was disassembled in preparation for final assembly. The reactor was loaded and welded closed on January 28, 1949. The month of February was spent in reassembling the control-rod and safety-rod mechanisms, installing the remaining shielding blocks, and connecting the mercury system to the reactor. The reactor was brought to full power in March 1949.

The procedure during the three years had been to do as many low-power experiments as possible when the fissionable material was accessible and the reactor more versatile. With the reactor pot welded closed as is required for high-power operation, the fissionable material and center of the reactor are inaccessible. Actual construction work time during which it was not possible to use the reactor involved 20 months. Twenty-one months were spent doing reactor experiments during the 3-1/2 years. The mercury system required 22 months for construction and the operating conditions which were demanded. The reactor could have been put into power-operating condition by September 1948, insofar as construction was concerned, but it was decided to keep the reactor open for 6 months until some experiments were finished.

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Chapter 1

CONSTRUCTION AND FABRICATION

1.1 General Description of Installation

The Los Alamos Fast Reactor is a small nuclear reactor which operates on the fission of plutonium (Pu^{239}). The neutrons from the reaction are not moderated and the chain reaction proceeds by the high energy or fast neutrons from the plutonium fission, producing further fissions. The plutonium is in the form of small rods, canned in steel jackets, around which mercury coolant flows at the rate of approximately 9 liters per minute. The plutonium rods are held vertically in a lattice arrangement at the bottom of a cylinder 6 in. in diameter. Surrounding this active material region is a 6-in.-thick reflector of natural uranium, most of which is silver-plated. This cube is surrounded by an aluminum jacket 1/4 in. thick containing embedded cooling tubes. Water flows through these tubes at the rate of about 1 gallon per minute to provide cooling for the uranium blanket. A 6-in. steel reflector surrounds the cube, followed by 4 in. of lead shielding. The reflector volume, excluding the lead, is thus a 30-in. cube. Surrounding the lead shield is a 1/32-in. welded aluminum jacket encasing the entire reflector and lead shielding in a gas-tight envelope. The envelope contains helium which flows slowly through the reflector, providing an inert atmosphere to prevent corrosion of the uranium blanket and for carrying away any fission products from the unplated parts of the uranium blanket.

Each of the four vertical sides of the reactor has a special function by virtue of the reflector construction. One side contains a thermal column of graphite and on this side a bismuth block 4 x 4 x 15 in. extends through the lead, steel, and uranium blanket from the aluminum envelope to within 4 in. of the center of the reactor. A neutron "window" is thus provided since bismuth is a good gamma absorber but allows neutrons to be transmitted with relatively little attenuation. On the side opposite the thermal column is a cylinder of thorium 11 in. long and 6 in. in diameter which extends from the lead-steel interface to within 4 in. of the center. The cylinder contains a central experimental hole. The other two vertical sides contain (1) a uranium block 8 x 8 x 11 in. extending the same distance as the thorium block and having a central experimental hole, and (2) a steel block which merely completes the steel reflector but also contains a central hole.

Numerous experimental holes are located in the reflector to provide access for irradiations, removal of beams, and location of monitoring counters and chambers.

The shielding begins after the aluminum jacket and is accomplished by use of alternate layers, each 3 in. thick, first of steel and Masonite, then of steel and boron-plastic, for a

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total of 30 in. on three sides. This laminated shielding is enclosed in an 18-in. wall of heavy aggregate concrete. The fourth side contains the graphite thermal column which extends 6 ft from the cube and is shielded on the face and sides by boron-plastic, cadmium, and concrete. The top of the reactor is shielded by removable sections of the laminated steel and boron-plastic shielding and by removable concrete blocks. The over-all dimensions are approximately 11 ft x 15 ft x 9 ft (high), and the total weight is about 220 tons, of which more than half is shielding.

Control of the reactor is effected by the positioning of certain reflector parts so that the control is positive as distinct from the poisoning method used in conventional reactors. A block of uranium can be raised into its position directly against the bottom of the active material and will drop out of this position upon suitable signals, thereby acting as a safety block. Two rods, each composed of a section of uranium and a section of B^{10}, act as safety rods. These are pulled vertically into position in holes adjacent to the active material and are positioned such that to act as "safeties" the uranium drops out of the adjacent region and the B^{10} comes into this region. Two other uranium rods act as control rods in the same manner.

The cooling system utilizes mercury as the heat transfer medium, mercury being pumped through the active-material region by means of an electromagnetic pump. The mercury flows through two heat exchangers where it is cooled by water.

The reactor operates at 25 kw, which produces an available high energy flux of 4.3×10^{12} neutrons/cm^2/sec. The neutrons are unmoderated and therefore have a slightly degraded fission spectrum. Thus, high intensities of neutrons which are characteristic of the bomb and which are also useful for breeder pile studies are available.

Figure 1 shows a picture of the reactor, Fig. 2 is a section drawing through the center of the reactor, and Fig. 3 is a floor plan of the reactor building showing the location of the reactor.

The following sections of this chapter describe in detail the substructure, complete structure of the reactor, and the cooling system design.

1.2 Substructure

1.2.1 Foundation, Pier, Safety-mechanism Channel and Service Channel

Foundation. The foundation of the reactor is a reinforced concrete pouring, physically detached from the reactor building itself. The top of this pouring is flush with the top of the 6-in.-thick concrete floor of the building, and is separated from the floor by a 1/2-in. mastic joint. The horizontal dimensions of this foundation at the floor level are north to south 15 ft 3 in., and east to west 11 ft 2 in. At the level of 4 ft 9 in. below the top of

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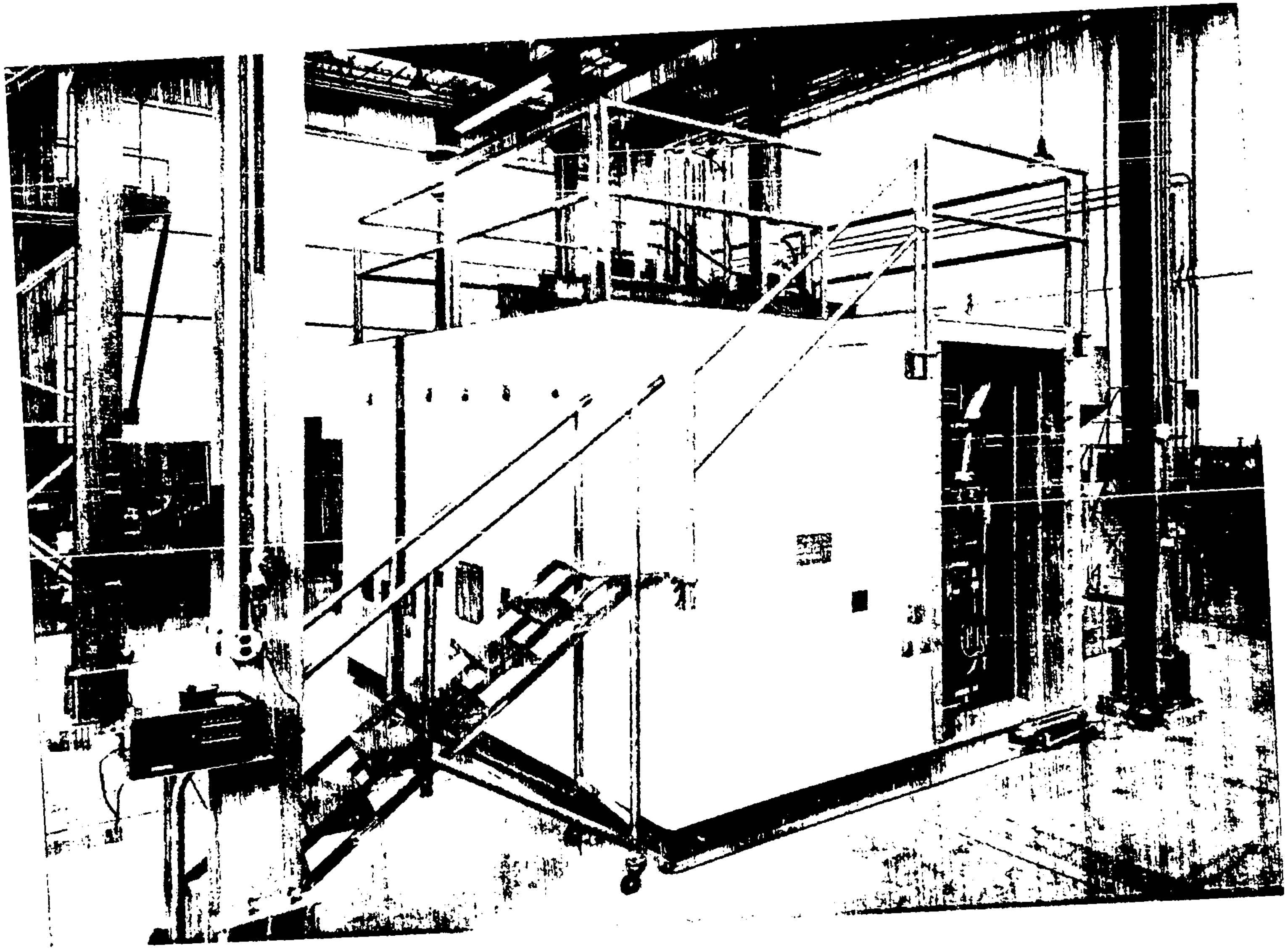

Fig. 1. Exterior of the reactor.

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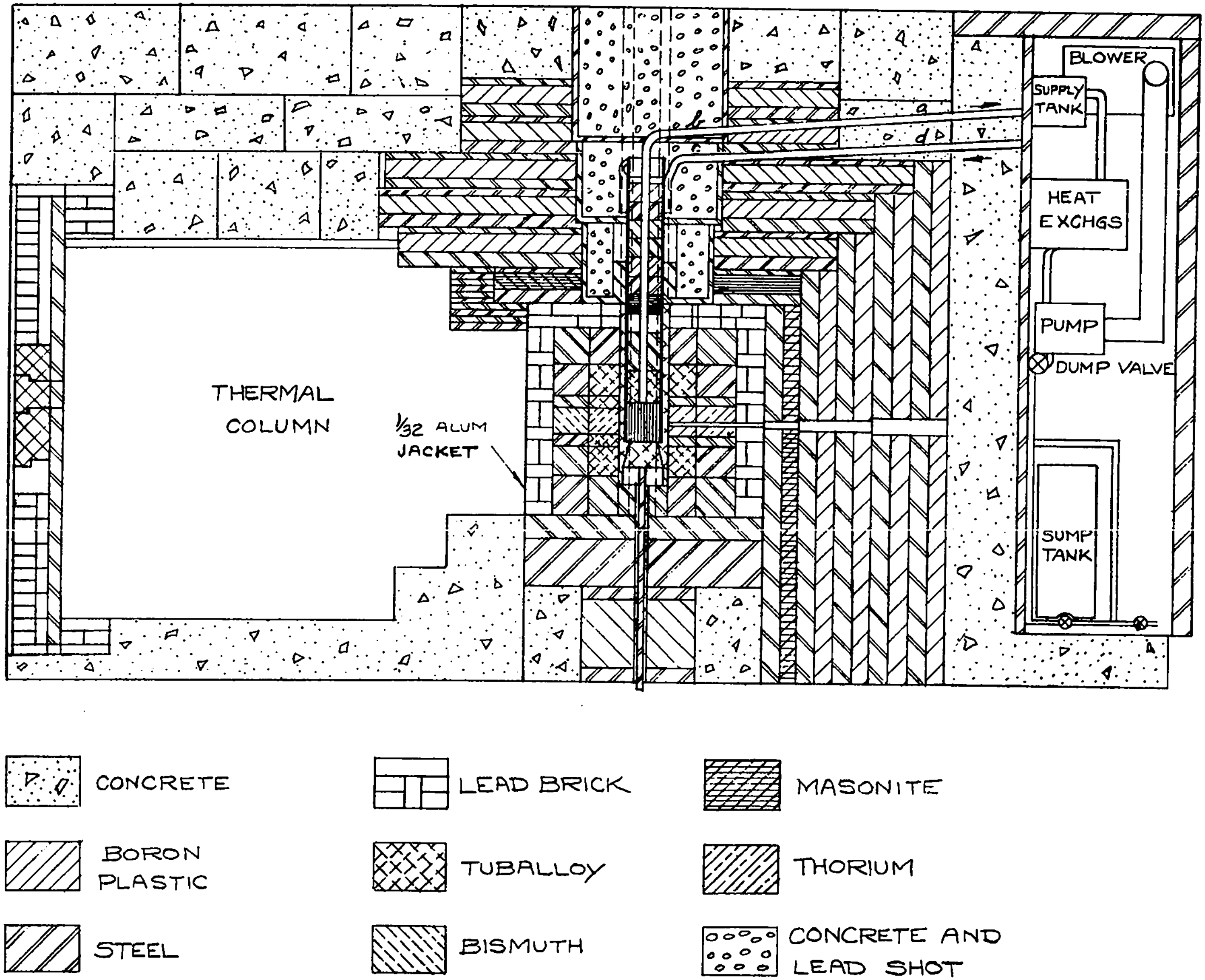

Fig. 2. Cross section through the reactor.

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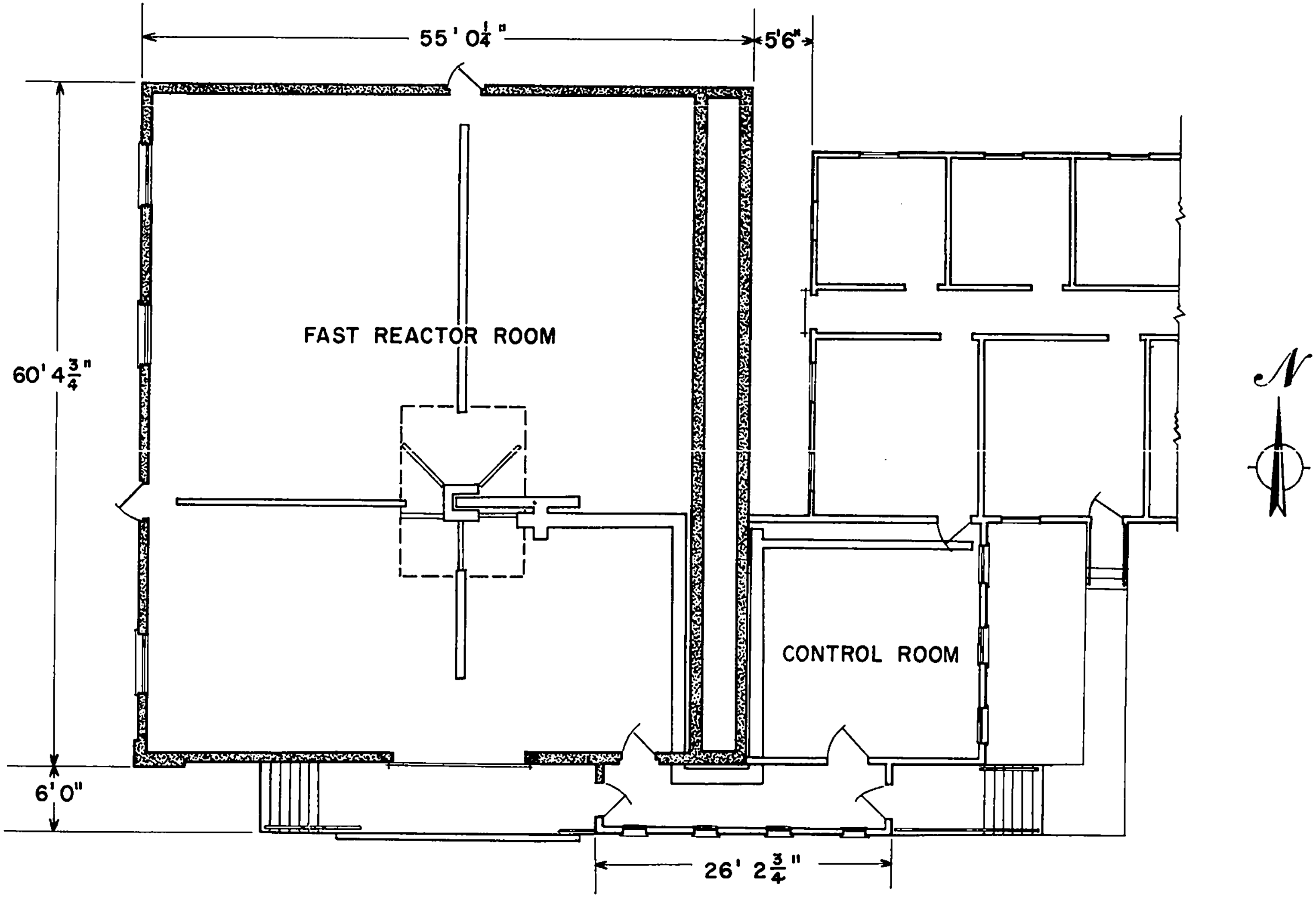

Fig. 3. Floor plan of the reactor building.

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the foundation, the pouring has step-footing which projects horizontally about 3 ft and also extends downward a distance of 2 ft. Figure 4 is a plan drawing of the foundation, etc., and Fig. 5 is a photograph made during the process of construction.

The reactor foundation, including footings, consists of approximately 150 tons of concrete (1 part cement, 2 parts sand, 3 parts gravel) and 1.85 per cent by weight of 1-in. steel reinforcement rods, or about 5000 lb of rod. Actually the foundation is not the simple geometric figure described above, but in one region extends deeper to reach bedrock.

Pier. Poured atop the foundation, and tied to it by 1-in. reinforcement rods, is the pier on which the inner structure of the reactor is built. This pier consists of a U-shaped pouring with the opening towards the east. In plan the pier is a square, 38 in. on one side, with a 10-in. wall on three sides, making the cavity 28 in. from east to west and 18 in. from north to south. The height of the pier is approximately 15 in., and through the top surface of the 10-in. wall there extend seven 1-in. machine bolts; these bolts were poured in the pier and foundation and are enclosed in the latter, by right-angle bends, at a depth of about 3-1/2 ft below the top of the pier.

The E-W center line of the pier lies 6 ft 7 in. north of the south edge of the foundation; the center point of the 38-in. square lies on the N-S center line of the foundation.

Safety-mechanism Channel. The top surface of the foundation, coplanar with the floor of the building, is continued inside the pier to form a flooring there. Sunk into this floor for a depth of 15 in. and coaxial with the E-W center line of the pier is the rectangular channel for the safety-block mechanism. This open channel has side walls 12 in. apart; its back wall (12 by 15 in.) lies 6 in. west of the N-S center line of the reactor, and the channel extends from this point eastward through the foundation and continues in another concrete pouring to a distance of 5 ft 0 in., where the east end of the channel is closed by the concrete. The purpose of this channel is to provide space directly under the reactor for the safety mechanism; the 5-ft extension of the channel to the east of the reactor provides space for the removal and servicing of the safety mechanism. The safety-channel extension was poured separately from the foundation and is part of the floor of the reactor building.

For reasons to appear later, it was necessary to provide means for sealing off that part of the safety channel lying within the pier up to the east edge of the foundation proper; the extension outside the foundation need not be so sealed. To accomplish this purpose, two seals were provided:

1. A welded-steel door frame was set into the concrete with its face plate lying in a vertical plane; the western face of this frame lies in the plane of the eastern face of the foundation proper. This frame is provided with welded studs--projecting into the safety-

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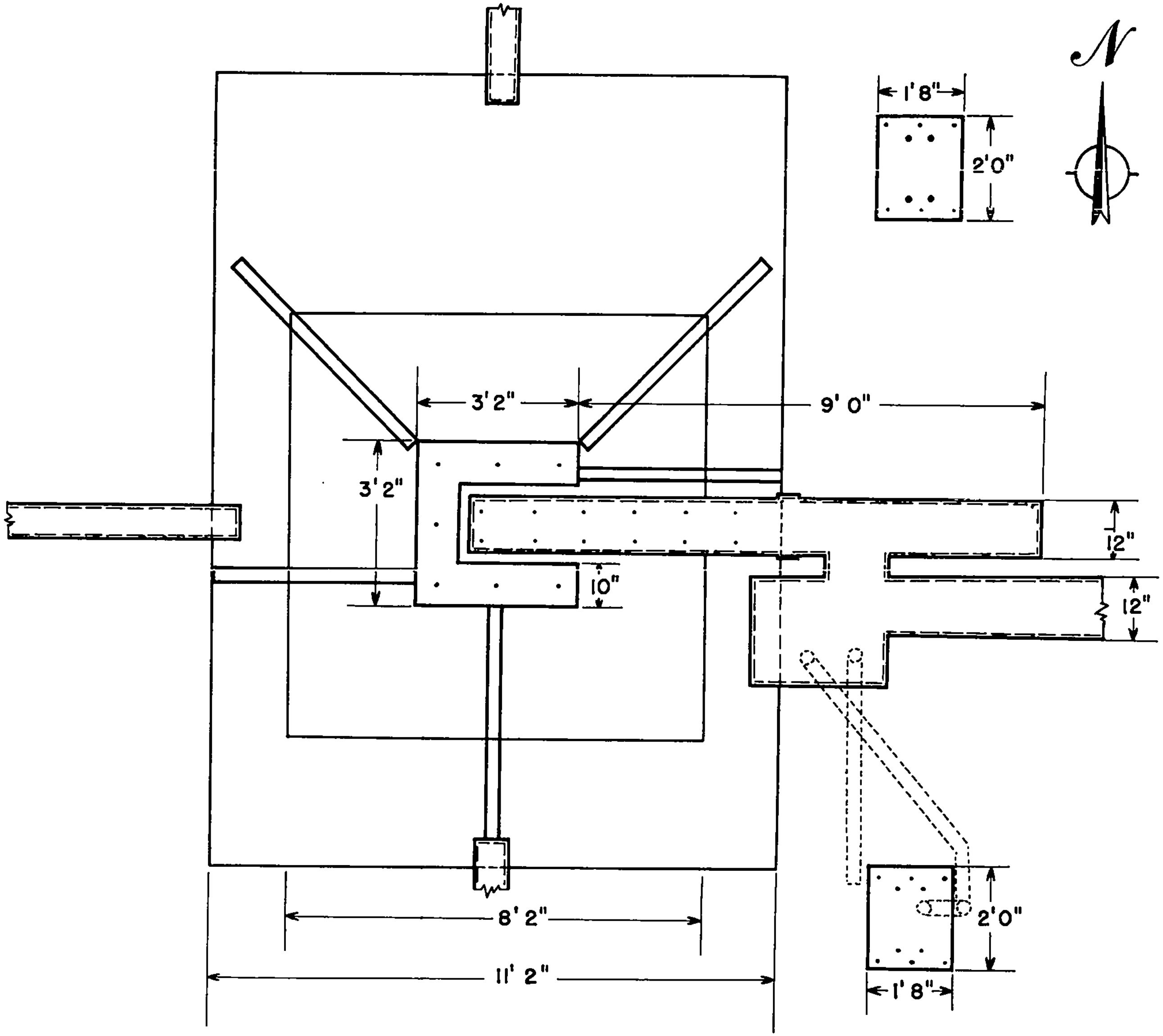

Fig. 4. Plan drawing of the reactor foundation.

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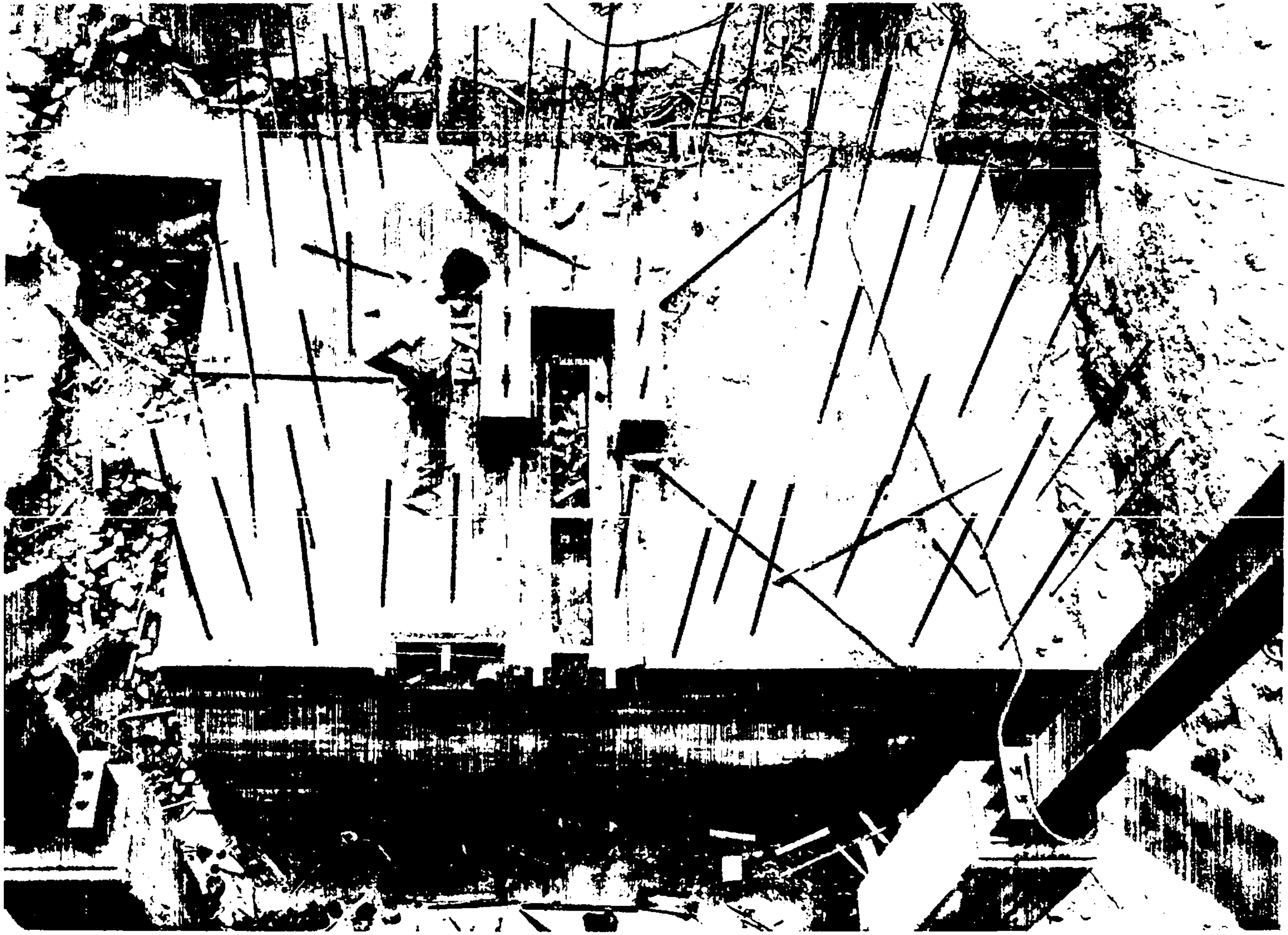

Fig. 5. Reactor foundation.

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channel extension--in order that a sealing plate or door may be gasketed on to the eastern face plate of the door frame. The clear opening in the door frame as seen from the channel extension is rectangular, 10-3/4 in. wide by 12 in. high.

2. A steel strip--provided with a shallow ledge 3/8 in. deep and 1 in. wide--was welded to 1-in. reinforcement bars 7 in. long, and set into the concrete border of the channel. This steel strip runs around the edge of the safety channel (both main channel and extension) and provides a recess into which the 3/8-in. steel cover of the channel can be laid flush with the floor. In order to complete the seal, the cover was welded to the steel strips. The depth of the safety channel, measured from the bottom of its cover, is approximately 1 ft 2-5/8 in.

Service Channel. On the south side of the safety-channel extension, there is a service channel. This channel begins at a small pit (dimensions 12 in. deep, 24 in. N to S, 30 in. E to W) and runs, perpendicular to the N-S face of the foundation, in the E-W direction, to the vicinity of the east wall of the reactor room; there it makes a right-angle turn, and runs to the south wall of the reactor room. The channel is 12 in. wide (between its vertical walls) and 12 in. deep. It is provided with a steel ledge and cover plate, as in the case of the safety channel, so that its clear depth is 11-5/8 in.

Water drains and other connections related to the water-cooling and helium systems of the reactor are provided in the pit. The purpose of the channel is to provide a connecting service channel between the reactor and the control room. The service channel and pit were poured as part of the floor of the reactor building.

1.2.2 Base Plates of Reactor, Channel Shielding

The materials comprising the reactive region and reflecting blanket of the reactor are supported on the pier described above. Altogether the central region and blanket of the reactor (hereafter referred to collectively as the reactor "cube") constitute a large mass. The solid platform for this heavy cube is a pair of steel plates set one over the other on the pier.

The lower of these plates is a 38 in. square, 7-7/8 in. thick. It is provided with seven holes, counter-bored on top for appropriate nuts, so that the plate could be set down over the tie-bolts projecting from the top of the pier. At the geometric center of this plate there is located a hole to accommodate the vertical shaft of the safety block.

The second, or upper, plate is also a 38-in. square. The purpose of this plate is to provide an easily machined piece onto which can be accurately located certain parts of the cube, and also to provide for adjustment in thickness required to bring the base of the cube to its specified level. The adjusted thickness of this plate was 3-1/2 in. The plate also

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contains borings into which are positioned the guide tubes for the safety and control rods. Slots were milled in the top of this plate radially from the center hole (for the safety-block shaft) to the holes for the guide tubes, in order to allow the flow of the helium.

Since some shielding is required between the reactor and the safety mechanism, a pair of steel and boron-plastic shield blocks were fabricated to fit the space between the base plates and top cover of the safety channel. These blocks involve a total of 4 in. of steel, measured vertically, and 11 in. of boron-plastic. Both blocks were bored to allow passage of the safety-block shaft and sealing tube (both described hereafter).

The first base plate (referred to as the "8-in. plate") was set in the following manner. A thick layer of very rich grout (cement, fine sand, and water only) was poured over the top surface of the 10-in. walls of the pier. The 8-in. plate was then lowered over the pier and the bolts started into their holes; then the plate was dropped from a height of a few inches onto the wet grout. By turning the nuts on the tie-bolts, the plate was leveled to within about 1/4 mil per foot, as measured along the two diagonals of the square. Since this leveling was done while the grout was wet, short wedges were driven between the 8-in. plate and the pier in order that the plate should not settle. Inside the U of the pier, a slot was scraped in the wet grout so that later a lead sealing fillet could be beaten into the grout all along the line of contact between grout and plate.

A day later the wedges were pulled, the nuts on the tie-bolts were again taken up slightly, and the level of the plate corrected to the same accuracy as mentioned above. One week later the sealing fillet was beaten home between grout and 8-in. plate. After this seal was made, the whole interior of the pier, safety channel, etc. were given several successive coats of red-lead paint. A general view of this situation is seen in Fig. 6.

As described in the introduction, the gas in the helium system is to pass from the safety-mechanism channel, around the shaft of the safety block, and thence upward through the control- and safety-rod tubes. Though some attempt was made to seal off the cavity in the pier under the base plate (lead fillet, red-lead paint), such a seal could not be trusted, especially in view of the fact that no reliable seal was available for the open (east) end of the pier cavity.

In order to provide additional sealing, the following device was used. A steel tube was provided that could be passed through the center hole of the 8-in. plate and through the two steel-boron-plastic shield blocks. This tube was provided at its upper end with a flange that could be bolted to the top of the 8-in. plate. At the lower end the tube had a gasket groove holding a neoprene gasket. The length of the tube was made such that when the upper flange was pulled down onto the 8-in. plate by the bolts, the lower gasket was pressed very tightly

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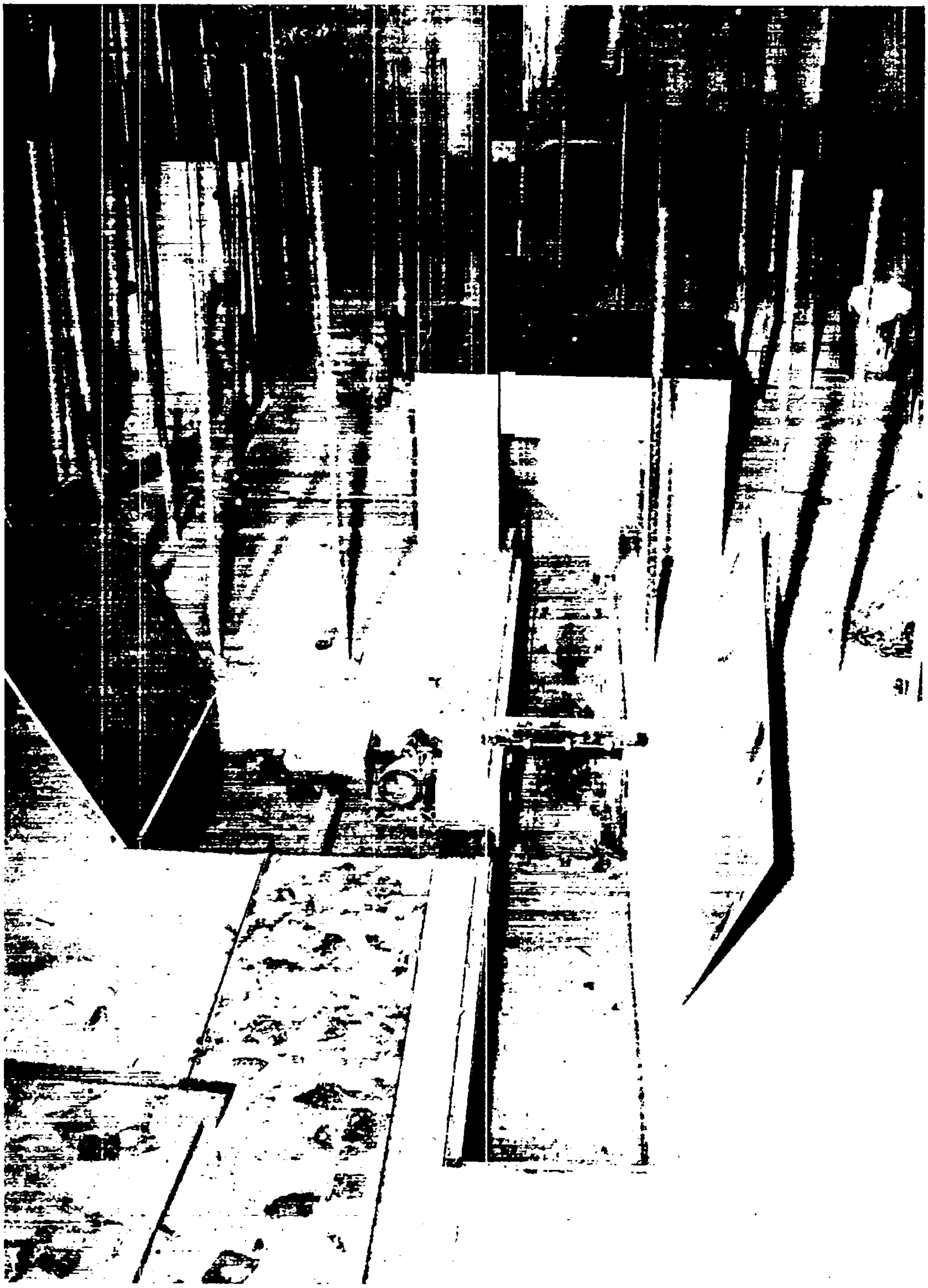

Fig. 6. Pier and safety channel.

against the welded 3/8 in. cover plate of the safety channel. In this way the cavity of the pier contained no helium until such time as the neoprene gasket developed a leak, after which the other seals should prevent leakage. Since the pressure driving the helium will be only a few inches of water, such a leak will probably not be serious.

Up to this point the order of assembly has been (1) welding of safety-channel cover, (2) location of 8-in. plate, etc., (3) insertion of steel-boron-plastic shielding blocks (these are held securely in position by wedges and spot-welds), (4) insertion and adjustment of sealing tube.

The second base plate was now set into position. Since there is still the possibility of a gas leak between the two plates, a seal was provided there. This seal was made in the following way. A gasket groove was made in the upper plate, and a fuse-wire gasket laid into it; the depth of the groove had been chosen so that the wire lay partly below the lower surface of the top plate. In addition, a counter bore was made in the bottom of this plate to receive the top flange on the 8-in. plate. Then the lower plate was painted with red lead and the upper plate lowered into position. No bolts were used to tie the two base plates together, the upper one being sufficiently massive; in order to prevent any horizontal displacement, however, one tap hole on each side of the square was made at the line of contact of the two plates, and 1/2-in. Allen-head screws run in.

To complete the structure of the pier, base plates, and seals, a shallow box of 1/16-in. steel plate was tailored to fit into the opening (eastern) of the cavity in the pier. This box provided a secondary seal of this region.

In concluding this section it should be remarked that no exact dimensions have been given here because none of the actual dimensions are critical information. In later sections relevant dimensions, etc., will be given to the accuracy available.

1.3 Structure

1.3.1 Core Region

Fuel Rods. The fuel rods for the fast reactor are machined rods of stabilized delta-phase plutonium, each weighing about 450 g. These rods are nickel-plated and canned in a mild steel jacket to allow handling and prevent corrosion from contact with the mercury coolant (Fig. 7). The following account briefly describes the procedures used in preparing the slugs for use in the reactor.

Plutonium metal was cast in delta phase ($\rho = 15.8$ g/cm^3), machined to tolerances, and the surface of the rod plated with a 0.003-in. nickel coat by decomposition of nickel carbonyl. The dimensions of a plated rod are 0.647 in. ± 0.002 in. diameter and 5.500 in. ± 0.005 in. long. These operations were performed at D.P. Site by CMR Division. The

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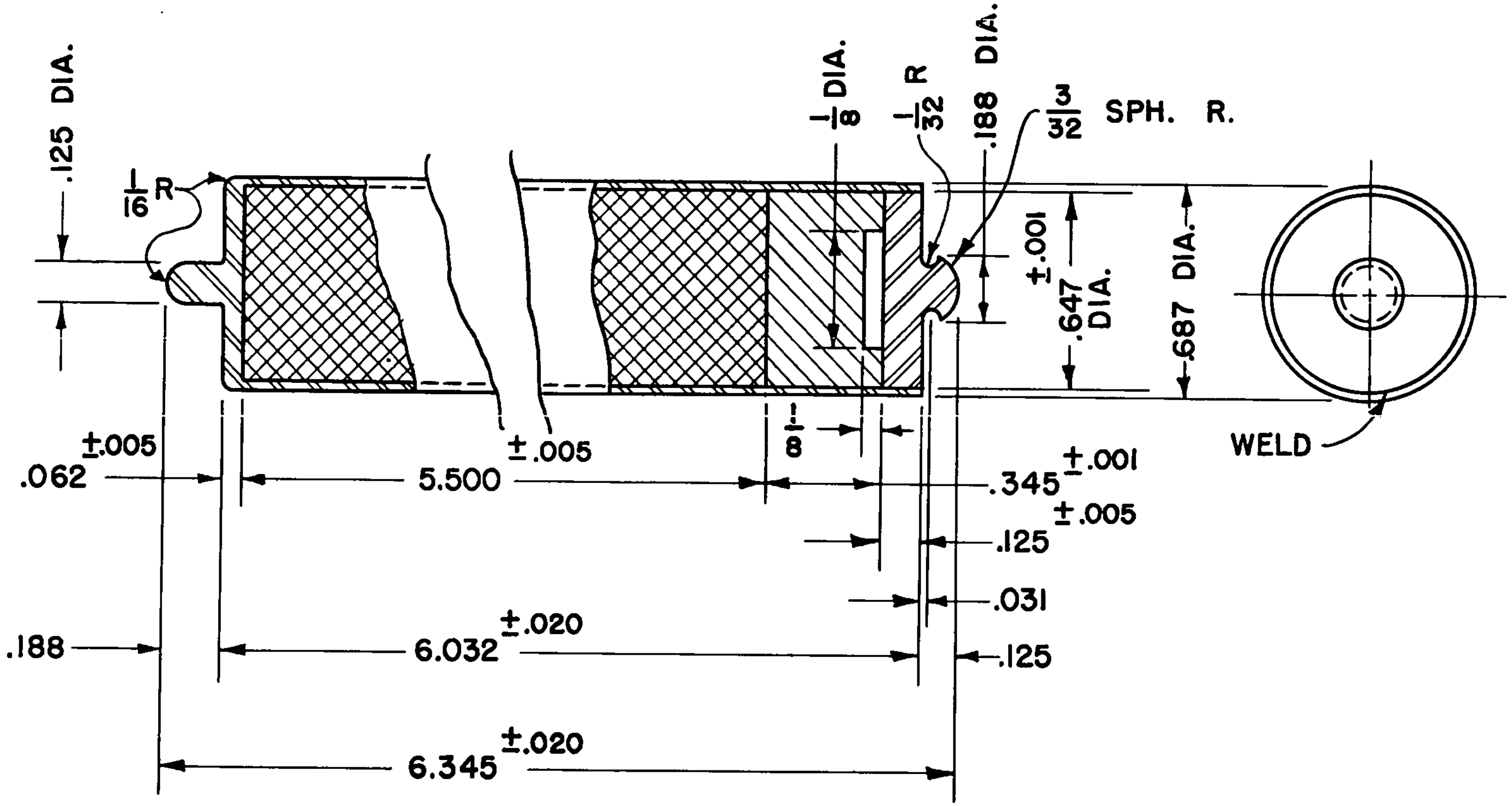

Fig. 7. Fuel rod.

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slugs with satisfactory tolerances and coatings were accepted for further canning at D Building, where all subsequent operations were performed in a helium atmosphere. The first step was to place the plutonium bar in a machined can of 1020 steel having an inner diameter of 0.652 in. ± 0.001 in. and 0.020 in. wall thickness. These cans have a bottom thickness of 0.062 in. and are made with a centering pin 1/8 in. diameter and 3/16 in. long. All steel cans had been annealed in hydrogen atmosphere after machining to remove strains. A wafer of normal uranium 0.345 in. thick was used to cover the plutonium rod to prevent poisoning of the weld. This uranium wafer has a recess 1/16 in. deep by 3/8 in. diameter in which fission gases can accumulate. The final steel cap for sealing the can was then placed on top of the wafer. The assembled rod was painted with a drawing compound and pressed through a sizing die to give a diameter of 0.686 in. The sized can was then trimmed to proper length and arc-welded in the helium atmosphere.

After canning, the rods were tested for leaks in the welds by two methods. (1) The canned rods were soaked in Zyglo (fluorescent) oil at 150 psi for 3 days, then removed, cleaned, and examined under ultra-violet light for oil seepage; this test was repeated four times on each can. (2) The cans were soaked in helium at 90 psi and then placed in a vacuum chamber connected to a mass spectrometer leak detector. The Zyglo method is reported to detect holes 3×10^{-10} cm^2, whereas the mass spectrometer method can detect 1×10^{-11} cm^2 holes.

The central plutonium rod is of special design and contains a hole 1/8 in. in diameter extending 2 in. into the rod. A thermocouple, described in Sec. 2.3.2, is housed in a reentrant tube fastened to the steel can.

Reflector Rods. In addition to plutonium fuel rods, the central active core contains a number of reflector rods of normal uranium. These rods are identical in outward appearance with the fuel rods and act (1) to preserve the symmetry of flow of the mercury coolant, and (2) to reduce the number of fuel rods required for operation.

In the loading of the reactor, considerable flexibility was obtained by interchanging the positions of the fuel and reflector rods. In this way some properties of several different types of loadings were investigated prior to the final loading.

The preparation of the uranium reflector rods was identical to that described for plutonium with the one exception of the nickel-plating.

Fuel Rod Cage. The rack or cage for holding the fuel and reflector rods in position is a mild steel affair, shown in Figs. 8 and 9. This rack is designed to hold the rods in a close-packed array (center-to-center spacing of 0.718 in.) with a minimum of motion and to provide for mercury circulation among the slugs.

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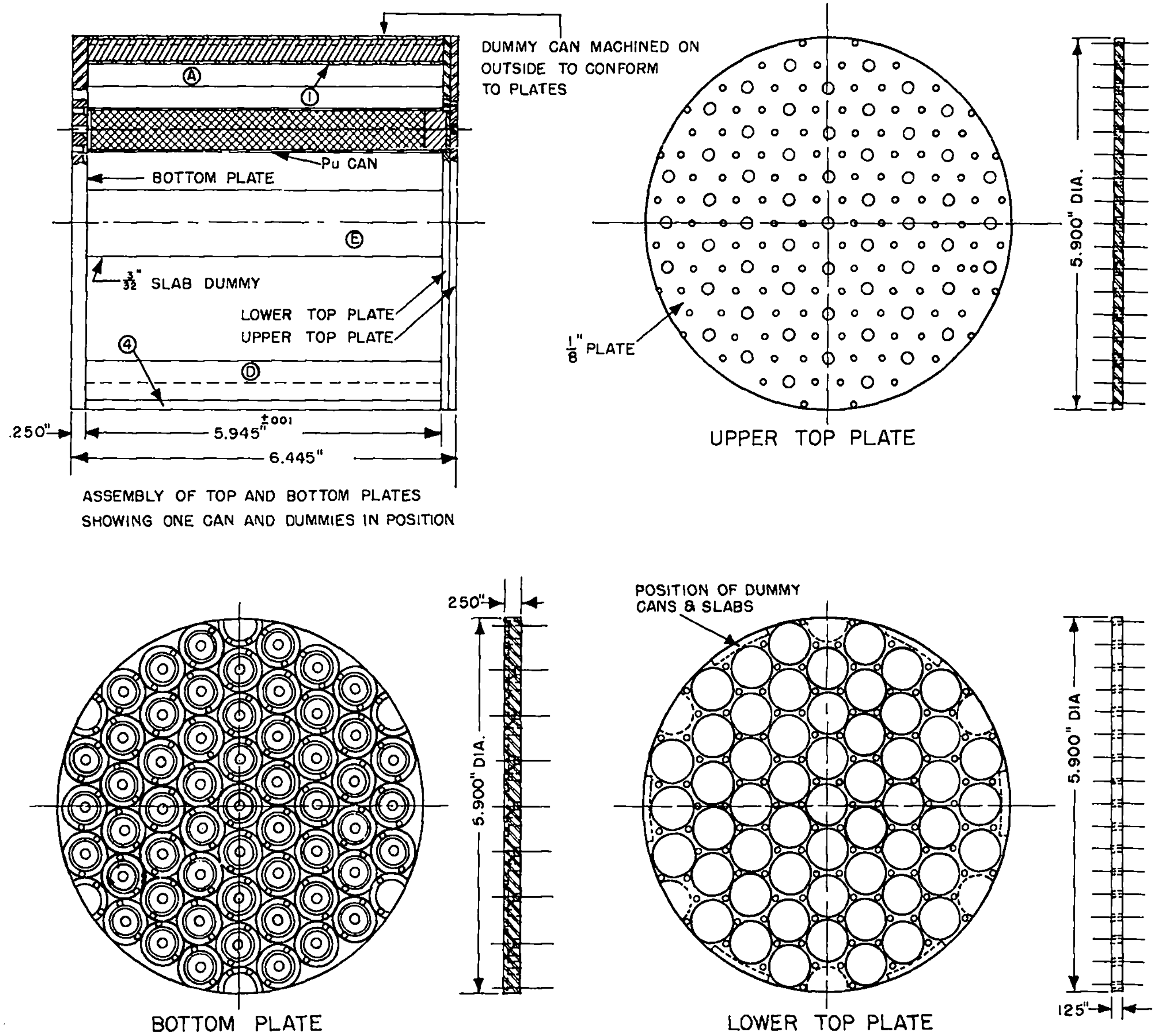

Fig. 8. Drawing of the fuel rod cage.

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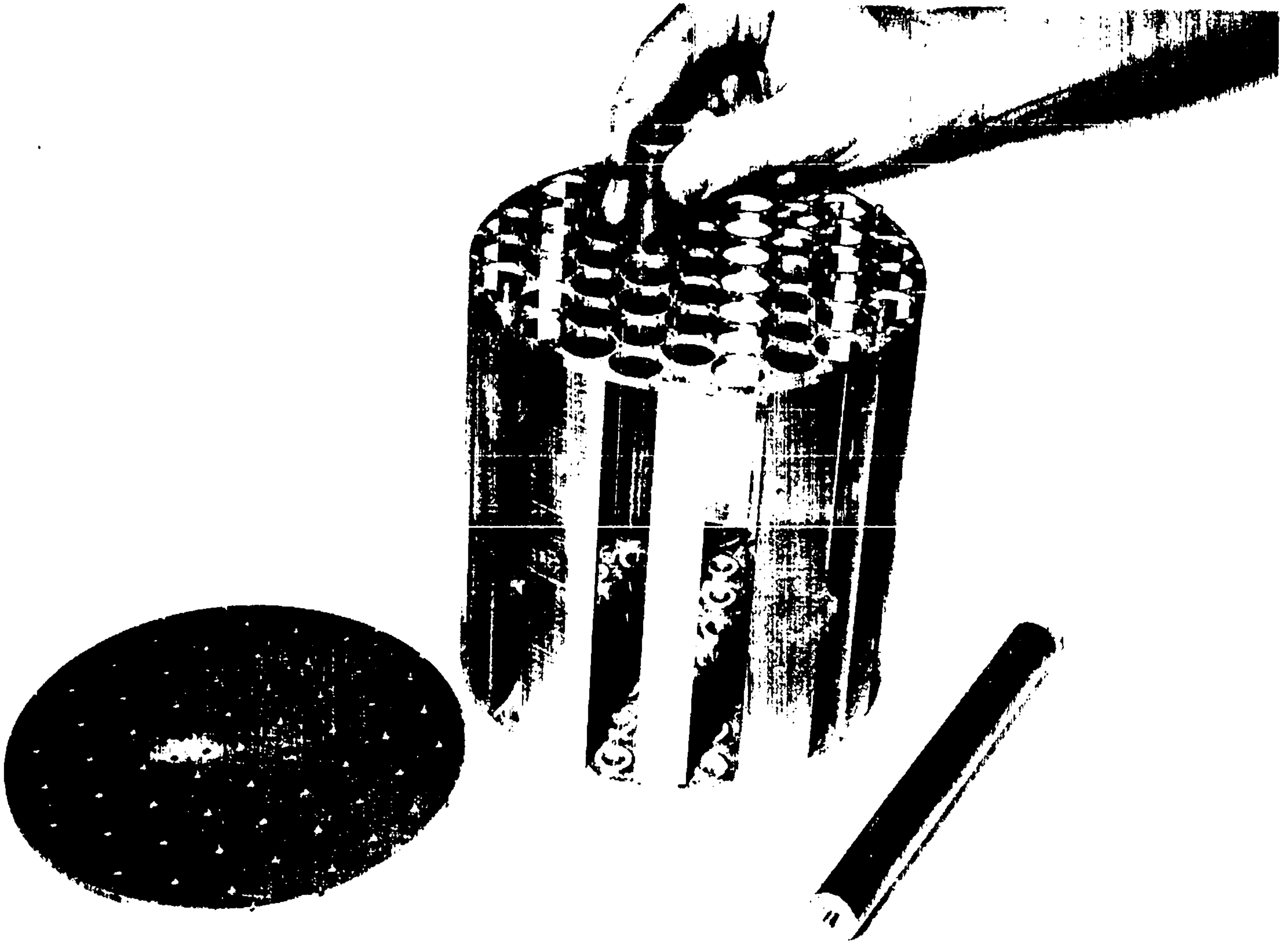

Fig. 9. Photograph of the fuel rod cage.

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The essential features of the cage are (1) holes in the bottom plate to locate the fuel rods by means of locating pins on the bottoms of the rods, (2) holes in the top and bottom plate for mercury circulation, and (3) removable top plate which serves to position the fuel rods and also allows access for loading.

Pot and Top Reflector. The reactor pot is designed to contain the fuel cage and the shielding immediately above the fuel in such a way that the whole assembly is gas-tight and that the mercury cooling is still possible. It consists of a mild steel cylinder 46 in. long, 6.20 in. OD, and 6.000 in. ID. The fuel cage rests on the bottom of this cylinder, and immediately above the cage, filling the space to the top of the pot, is a removable plug of reflector and shielding material contained in a separate mild steel cylinder with a wall thickness of 1/4 in. The outside surface of the plug has been machined to give a snug fit into the pot.

The materials in the plug have been chosen to conform as closely as possible to the arrangement of the materials in the reflector and shield proper. Thus, beginning from the bottom of the plug, the following order of materials is found to constitute it: 5 in. of tuballoy, 6 in. of steel, 1-1/16 in. of steel, 2-3/4 in. of Masonite sheets, 3 in. of steel, 3 in. of boron-plastic, 3 in. of steel, 3 in. of boron-plastic, 3 in. of steel, 2-1/4 in. of boron-plastic, and 4 in. of steel. The top steel section is welded to the wall of the plug enclosure. Adding the thicknesses of material given above will show that the outer surface of this last steel plug is some 2-5/8 in. below the end of the container wall, which has a total length of 38-11/16 in.

Mercury coolant enters the pot through two 3/4-in. ID steel pipes, each welded along opposite outer sides of the pot. These pipes have been machined in such a way that they present a 1-in. flat surface to the pot wall for clean welding, i.e., in cross section the pipes would look like half a 1-in. square fitted to a 1-in.-diameter semicircle, with a 3/4-in.-diameter circle removed from the center of the figure. Near the bottom of the pot a 3/4-in. hole in the flat side of each of the pipes lines up with a 3/4-in., hole in the pot wall to allow the mercury to flow radially into the pot, and the bottoms of the pipes are closed off with the same piece of steel which forms the pot floor. Mercury flow out of the pot is through a single 3/4-in.-ID mild steel pipe passing up through the center of the top reflector and shielding plug. This pipe has been welded to the bottom plate of the plug and to the topmost steel shielding layer in it.

In its assembly the contents of the pot are not bolted in, but rather are just set in, with the top plug supported by the fuel cage. The last operation of the assembly is to lay a bead weld over the matched ends of the nested top plug and pot. Figure 10 is a view

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Fig. 10. Reactor pot and unfilled top plug.

down into the pot, at the right, and of the top plug before it has been filled at the left. Figure 11 shows the top plug and the pot laid out side by side, with the cage placed roughly at the position it occupies relative to the plug after assembly.

1.3.2 Reflector

The main features of the reflecting blanket of the reactor are (1) an inner cube of uranium (within which is located the safety block, etc.), surrounded by (2) a 3/8-in.-thick aluminum case containing the reflector cooling system, which is in turn surrounded by (3) a 6-in.-thick layer of steel shielding (except on the bottom of the assembly), outside which is a 4-in.-thick layer of lead, the whole contained in (4) an aluminum gas-tight envelope, pierced by (5) re-entrant sealed experimental holes. These parts fill out a rectangular volume which measures 38 x 38 in. in a horizontal plane and 34 in. high, and constitute the assembly that has previously been referred to as the reactor "cube." The detailed description of these parts is given below in an order that corresponds roughly to that of actual assembly. In order to avoid confusion, no particular mention of experimental holes will appear; a complete tabulation of these is given in Table 16.

Uranium Reflector and Safety Block. As described in Sec. 1.3.1, the fuel rods and coolant were designed to be carried in a large vertical steel cylinder, referred to as the "pot," with the fuel rods assembled in its lower end. For assembly, the pot was designed to be slipped vertically into the center of the uranium reflector after the completion of the latter. To provide for this method of assembly and to attain satisfactory rigidity in it, the reflector was fabricated in essentially two parts: (1) the center column and (2) the remainder of the uranium reflector. A detailed discussion of these two parts follows.

1. The Center Column. The requirement of rigidity in the center column is of paramount importance since within it move the control rods, the safety rods, and safety block.

The center column is built up of six blocks which are all rectangular in any horizontal plane and of dimensions 8 in. (with some slight variations in design) on each side. The principal borings in these blocks are as follows:

(a) All blocks, except the lowest pair, have an axial boring of diameter 6.295 ± 0.002 in.; the axes of these borings are concentric to within ±0.002 in. The purpose of these borings is to admit the pot. Since the flow of the mercury coolant into the pot is through two vertical pipes running down opposite sides, two slots were milled into the walls of the large bore in the center column blocks. These slots, situated in a single diameter, have flat walls spaced by 1.032 in., and finished out with surfaces of 9/16 in. radius. The diameter connecting the slots lies in the direction of 26° north of east (as defined by

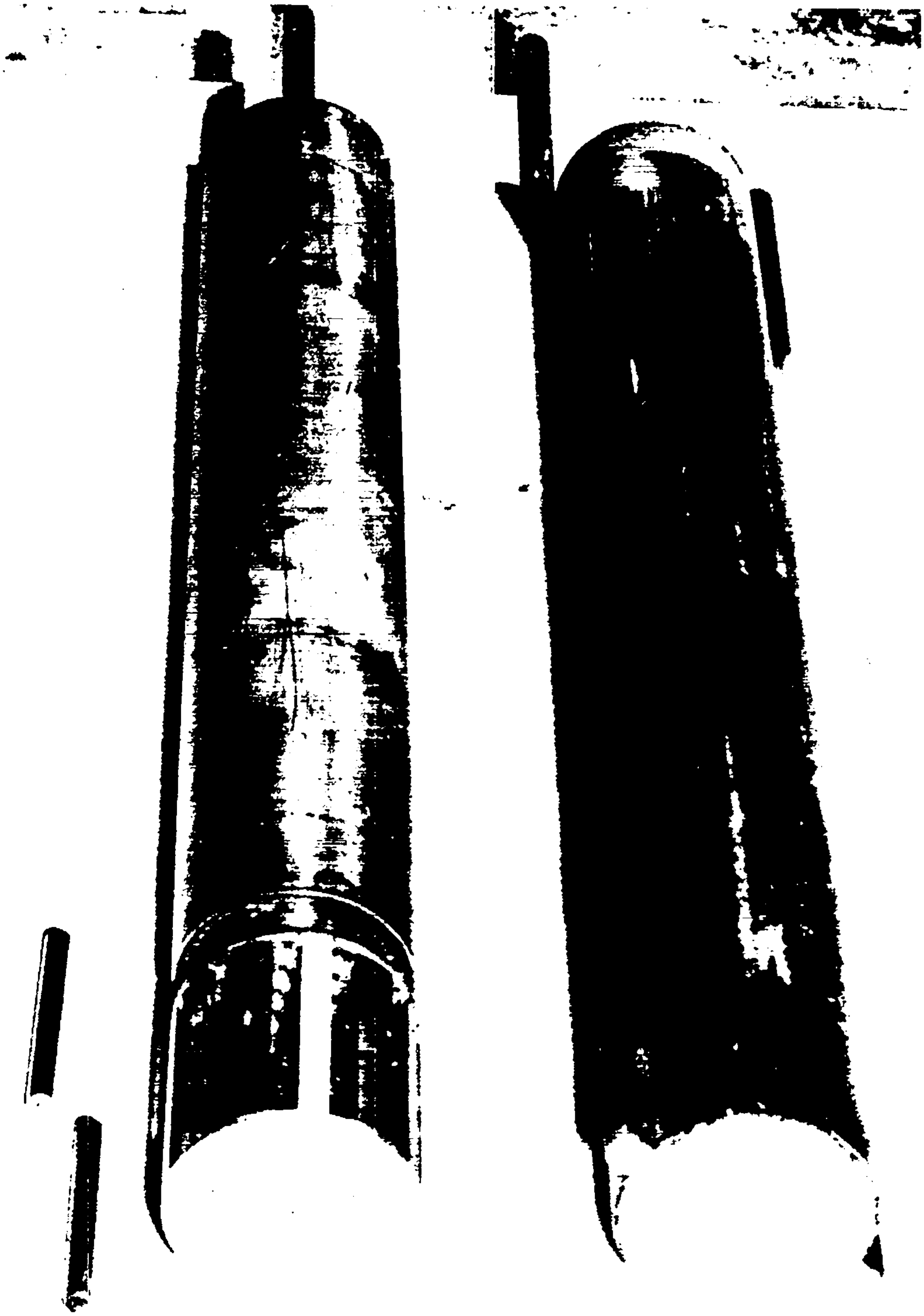

Fig. 11. Reactor pot, top plug, and cage.

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faces of the uranium reflector cube).

(b) All six blocks have four borings each, of diameter 1-17/32 in., accurately located at the corners of a square, the half-dimensions of any side of which were specified to be 3.000 in. ± 0.002 in. with, as center of reference, the axis of the center boring mentioned above. These four borings thus form four cylindrical holes with axes parallel to each other and to the main bore and perpendicular to the base plate of the reactor. They admit the guide tubes of the two central and two safety rods.

All center-column blocks were dowelled together or to the base plate by four 1/2-in. steel dowels at each pair of surfaces; these dowels were press-fitted into their holes at half the surfaces, and at the opposite surfaces the holes were made slightly better than snug fits. A top view of part of the assembly shows in Fig. 12.

Further details of these center-column blocks and the safety block are as follows:

(c) Block No. 1, of steel, has a center bore, diameter 1-9/32 in., passing perpendicularly through it; concentric with the hole there are two counterbores, diameter 1-3/4 in. and depth 1-3/4 in., one in the upper end and one in the lower surfaces of the block. Into these holes are press-fitted brass bushings which guide the hardened steel shaft of the safety block. The outer diameter of the shaft is 1.250 in. ± 0.001 in., and the inner diameter of the bushing is 1.255 in. (+0.001 in., -0.000 in.). Considerable care was exercised in aligning the center lines of this block and the center hole of the base plate.

(d) Block No. 2, of uranium, contains the movable safety block (of circular symmetry around the axis of the center column and pot) and also carries the weight of the pot. A diametral cross section of block No. 2, and the safety block and its shaft are shown in Fig. 13. The main features of Block No. 2 are (1) at the bottom of the block, a right cylindrical boring, diameter 6.760 in. ± 0.001 in. and height 3.250 in. ± 0.002 in.; (2) a right conical boring of height 2.991 in. and half apex-angle 15°; (3) a right cylindrical boring of diameter 5.135 in. (+0.002 in., -0.000 in.), height 0.479 in., (4) a right cylindrical boring of diameter 4.230 in. ± 0.001 in. and height 0.365 in. Into the last-mentioned (shallow) boring is to be seated a cold-rolled steel ring with an inside diameter of 4.250 in. ± 0.001 in. secured by six machine screws; the purpose of this ring will be stated presently.

(e) The uranium safety block has a diametral cross section as shown in Fig. 13, and a photograph of it is shown in Fig. 14. The clearances of right cylindrical sections, between the safety block and block No. 2, amount to about 0.020 in. on the radius, and about 0.007 in. for the conical surfaces. The purpose of the above-mentioned ring is to provide a flat surface against which the block will stop (when pushed up by the safety mechanism) rather than having it stop by driving two conical surfaces together. The latter case

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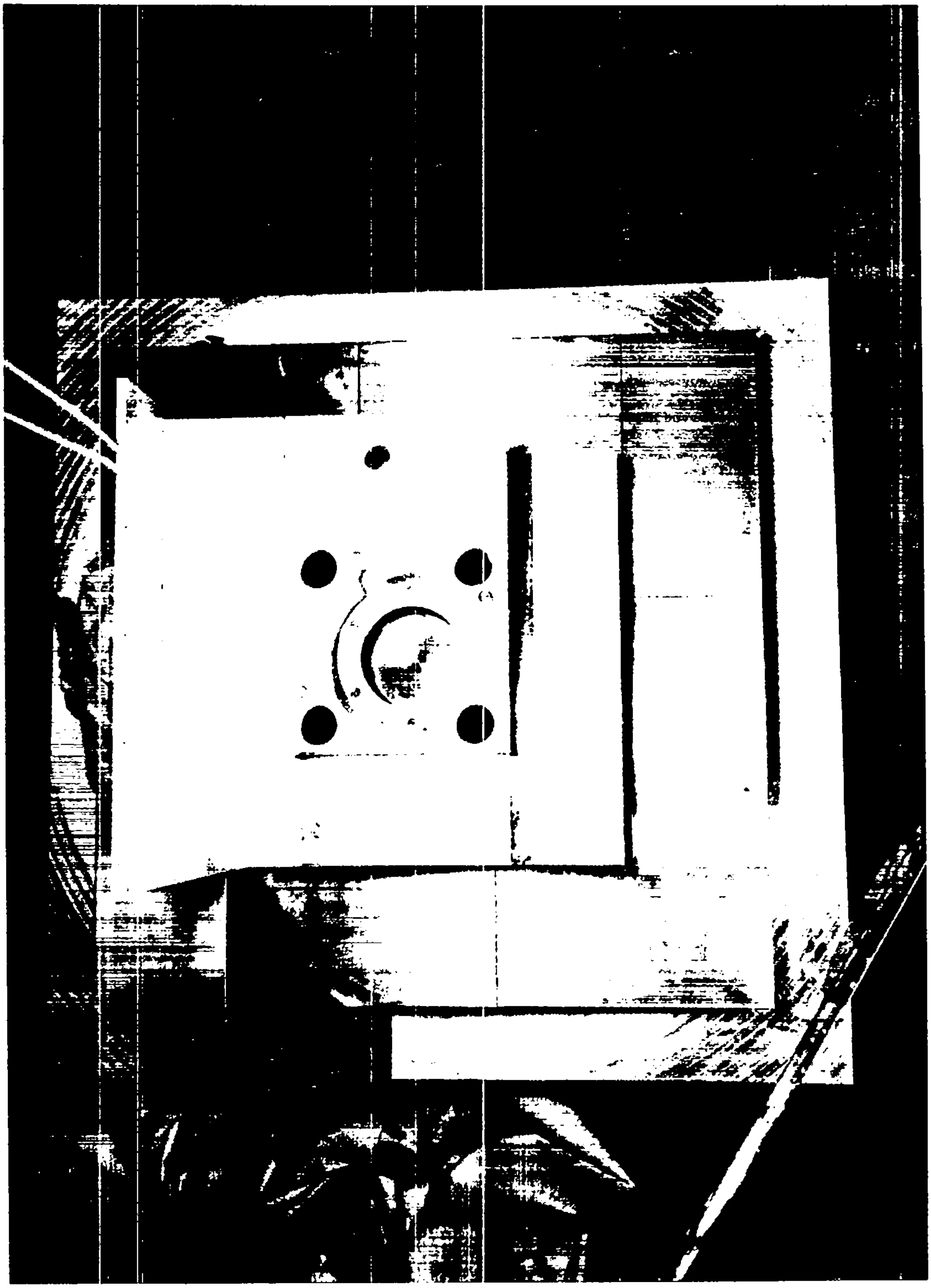

Fig. 12. Top view of the center column.

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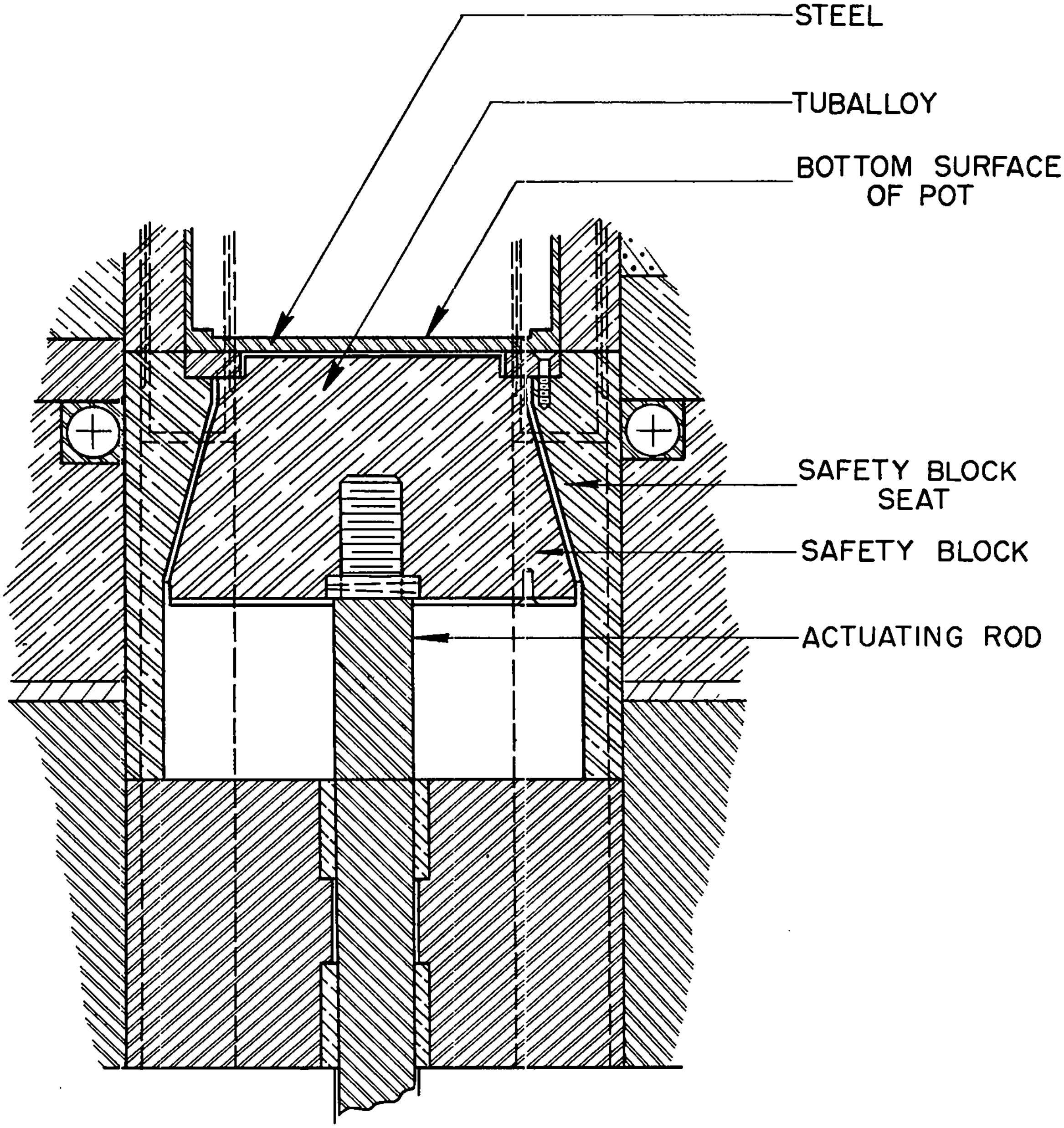

Fig. 13. Cross section of safety block.

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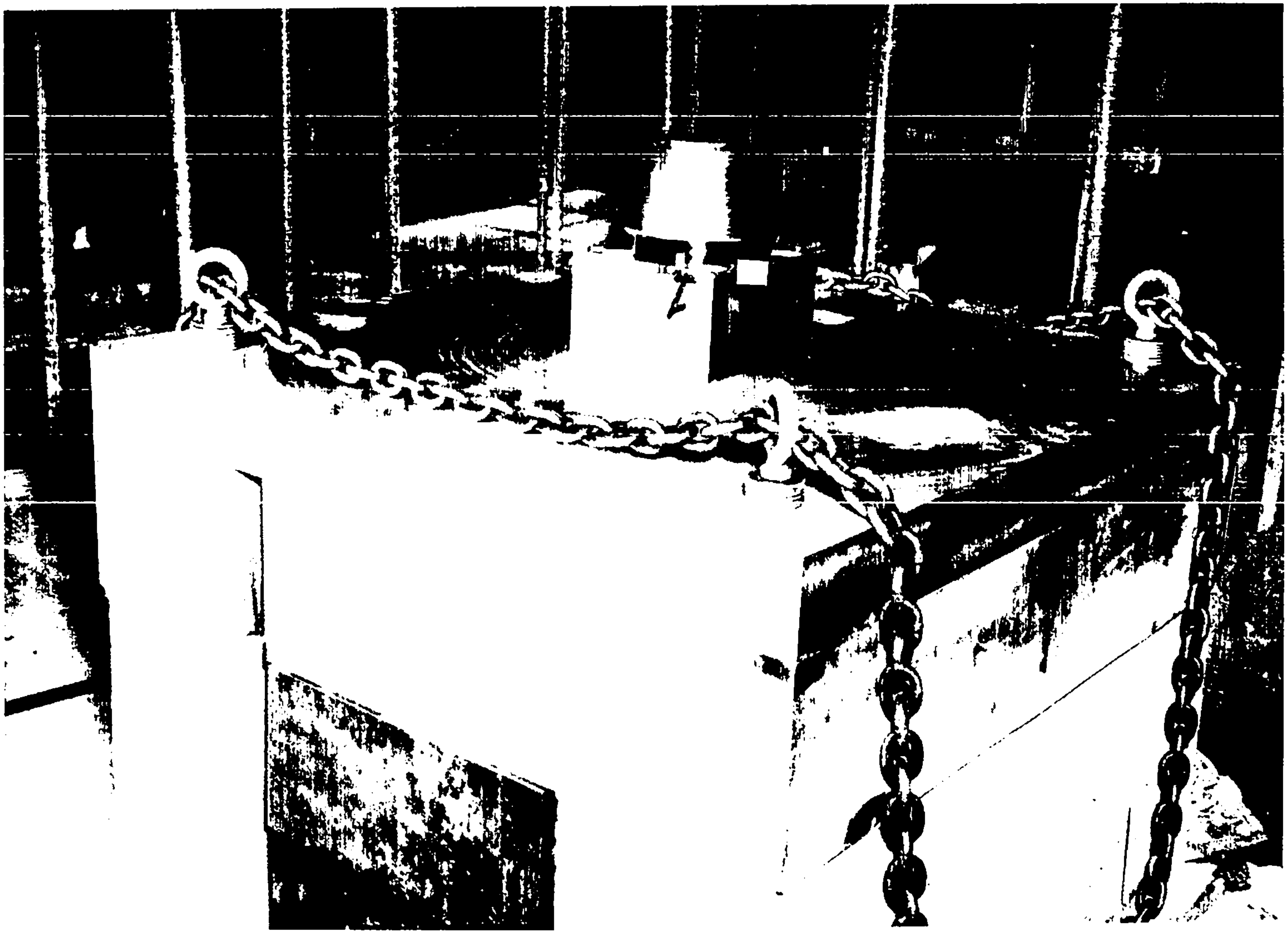

Fig. 14. Photograph of the safety block.

was to be feared since then there might be some tendency of the safety block to stick in the "up" position when the reactor should be scrammed. For this reason the stop-ring was adopted and plenty of clearance allowed between all other contiguous surfaces. A partial view down the main bore of the center column of the top of the safety block and the stop-ring is shown in Fig. 12. It is also worth mentioning that the outer diameter of the stop-ring was chosen large enough so that the pot would stand on it, thus preventing any motion of the ring in the event the machine screws should loosen.

The safety block itself is carried on a hardened steel shaft, 1.250 in. diameter, which is anchored by 1-in., 14 stud-fit thread, about 1-3/4 in. long. To the base of the block is bolted a disk of 1/8-in. steel stock. The length of the steel shaft, measured from the outer surface of this steel disk is 56 in.

At this point it should be recorded that after the whole cube had been assembled in final form, the vertical motion of the safety block was accurately measured and found to be 2.874 in. ± 0.001 in.; similarly, the distance between the bottom of the steel shaft (in the down position) and top of steel base plate of the safety channel was measured to be 8.434 in. ± 0.002 in.

2. The Remainder of the Uranium Reflector. After the center column had been assembled, the base layer of steel blocks and the base plate of the aluminum-blanket cooling system were assembled; then the remainder of the uranium blanket was stacked. Since the blanket had been designed to fill out a cube 17.250 in. on a side, the uranium was fabricated in the form of 23 rectangular blocks of different sizes chosen to produce a somewhat optimum condition of stable interlocking. A few special blocks were also used, as described below. Considerable effort was made to obtain very close fits between the blocks; that is, to leave negligible air space in the blanket.

In connection with the fitting of the reflector blocks, it should be mentioned that nearly all pieces of uranium going into the reflector, including center cube, were electroplated with silver. This plating was done to prevent the escape of fission fragments from the uranium and to discourage corrosion of the uranium. The thickness specified for this silver coat had been 0.010 in., and allowances in the machine dimensions of the blocks had been made accordingly. It turned out, however, that since only a small tank was available for the electroplating, the resulting coat was of nonuniform thickness and was especially large at the sharp corners. In addition there were some blisters and growths. All plated blocks were therefore carefully dressed down with fine files and lightly polished with crocus cloth; in addition all pieces were thoroughly washed with carbon tetrachloride before assembly. Pieces not plated were the safety block and the inside surfaces of block No. 2; no coats

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were desired here because of the likelihood of eventual peeling of the silver which would doubtless act to impair the proper operation of the safety block.

Figure 15 is a photograph of the completed assembly of the uranium reflector (one special block is missing); it also shows the two upper steel blocks of the center column. Other features seen are the lower and one vertical plate of the reflector cooling system, the complete set of steel base blocks, and some of the experimental holes.

As final features of the uranium blanket, there are four special blocks, one centered on each of the four vertical faces of the uranium cube. These are, together with their dimensions in a vertical plane,

(1) South side: thorium, a cylinder of 6 in. diameter, 11 in. length
(2) West side: uranium, 8 x 8 in. square, 11 in. length
(3) North side: bismuth, 4 x 4 in. square, 15 in. length
(4) East side: steel, 6 x 6 in. square, 6 in. length.

The horizontal center lines of these special blocks lie in a single plane, which is thought of as the reference plane of the reactor. The thorium, uranium, and bismuth blocks all butt against the uranium blocks of the center column; the steel block is separated from the center column by a 4-5/8-in. uranium block. All blocks extend to the inside surface of the 4-in.-thick lead shield, except the one of bismuth (directed towards the thermal column) which emerges from the lead shield, but is contained in the aluminum envelope.

Reflector Cooling System. The reflector cooling system (Fig. 16) consists of six 0.3525-in. dural plates; into each of these plates there are milled grooves of size suitable to allow 1/4-in. aluminum tubing, 1/16-in. wall, to be peened in. These tubes were arranged in such a way as to connect in series three pairs of plates. The series pairs were west side and top, east and south sides, north side and bottom plates. Six open-ended tubes were therefore brought out on top of the NE corner of the assembled cooling system.

As mentioned above, all the uranium blocks of the reflector were silver-plated; the specifications for the sizes of the aluminum plates, however, were determined after allowances had been made for the silver coat in these blocks. The resulting assembly was surprisingly snug, with direct contact between silver and aluminum over an estimated 50 per cent of all possible surfaces; where air spaces did occur, they are estimated to be not larger, on the average, than 0.005 in. A photograph of this assembled system is shown in Figure 16, and the holes for the experimental tubes and special blocks, etc., can be seen. All plates were carefully washed with carbon tetrachloride before assembly.

In order to connect this cooling system to the water system brought into the service pit, allowance was made in the outer steel and lead blocks for bringing the aluminum tubes

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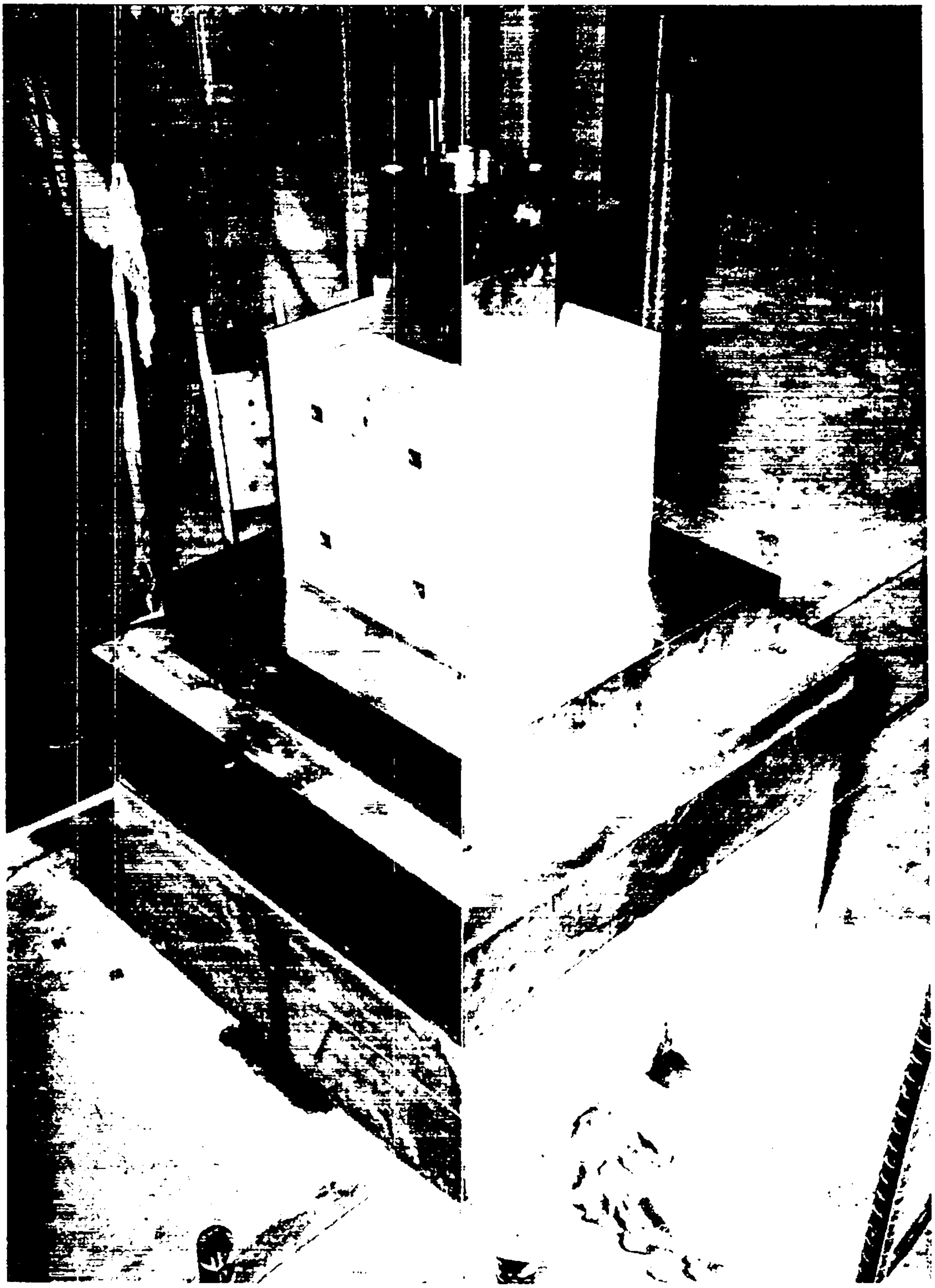

Fig. 15. Completed uranium reflector layer.

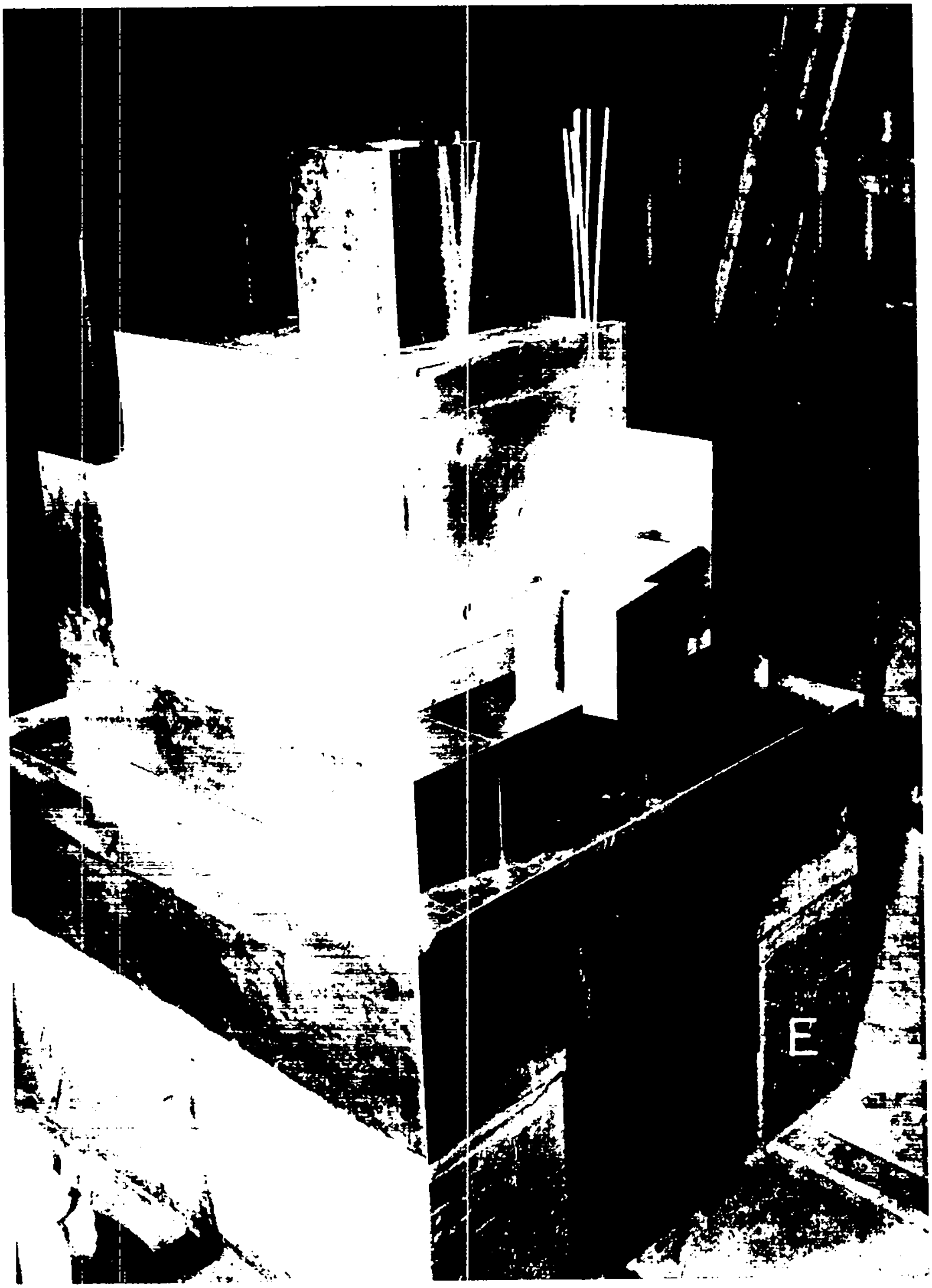

Fig. 16. Reflector cooling system.

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over the top of the reflector within the upper half of the 4-in.-thick lead layer, through the east side of the air-tight envelope, and thence down the east face (south edge) of this envelope, and thence to the pit. As may be seen in Fig. 20, the aluminum tubes, in portions of their length, pass near steel and concrete; in order to prevent leaks due to electrolytic action, the aluminum tubes were laid in aluminum channels to prevent contact of dissimilar metals, etc.

Steel Reflecting Layer, Lead Shield. This layer is made up of 50 steel blocks of various sizes and shapes. These blocks fitted snugly around the plates of the reflector cooling system, and a high quality fit was attained since all blocks had been surface-ground and polished. The 6-in.-thick layer of steel thus formed completely surrounded the reflector cooling system, and formed a cube 30 in. on a side. All blocks were carefully washed before assembly. Figure 17 shows the completed steel layer as seen from the southwest corner; on the west side (at left in the photograph) the special uranium block can be seen; on the south side (at right in the photograph) the special thorium block is missing.

Outside the steel layer there is a 4-in.-thick layer of lead bricks of the regular variety (2 x 4 x 8 in., weighing approximately 26 lb). Since this layer was introduced specifically as a gamma-ray shield, effort was made to eliminate cracks between the two successive 2-in. layers. The lead layer covers all outer faces of the steel layer, except the bottom, in which direction--from the active assembly--gamma-ray shielding was of no special interest. Much cutting and fitting had to be done because of experimental holes, etc., in order to get a highly compact assembly. As before, all pieces were thoroughly washed before assembly. As the assembly proceeded and after its completion, the bricks were beaten home with a mallet. After the assembly was completed, all sides and top were covered by 1/16-in. steel plates, each cut 1/2 in. smaller than the face to be covered, and the whole was banded together with 1/2 x 1/32-in. steel bands. The lead-brick assembly without the steel plates is shown in Fig. 18, which is a photograph taken from the southeast corner of the cube.

Aluminum Envelope. As described in Sec. 1.3.2, paragraph 2, substantially all of the uranium pieces in the reflector were silver-plated to prevent escape of fission fragments. Since it was considered that these silver coats might not be entirely successful, and since it was realized that other gases might be released by the breakdown of foreign material under neutron bombardment, it was decided to surround the whole reflector with a gas-tight aluminum envelope. This envelope, however, was designed so that it could be slowly flushed out by admitting helium.

The construction of this envelope, of 1/16-in. 2S-aluminum, was as follows. A pan,

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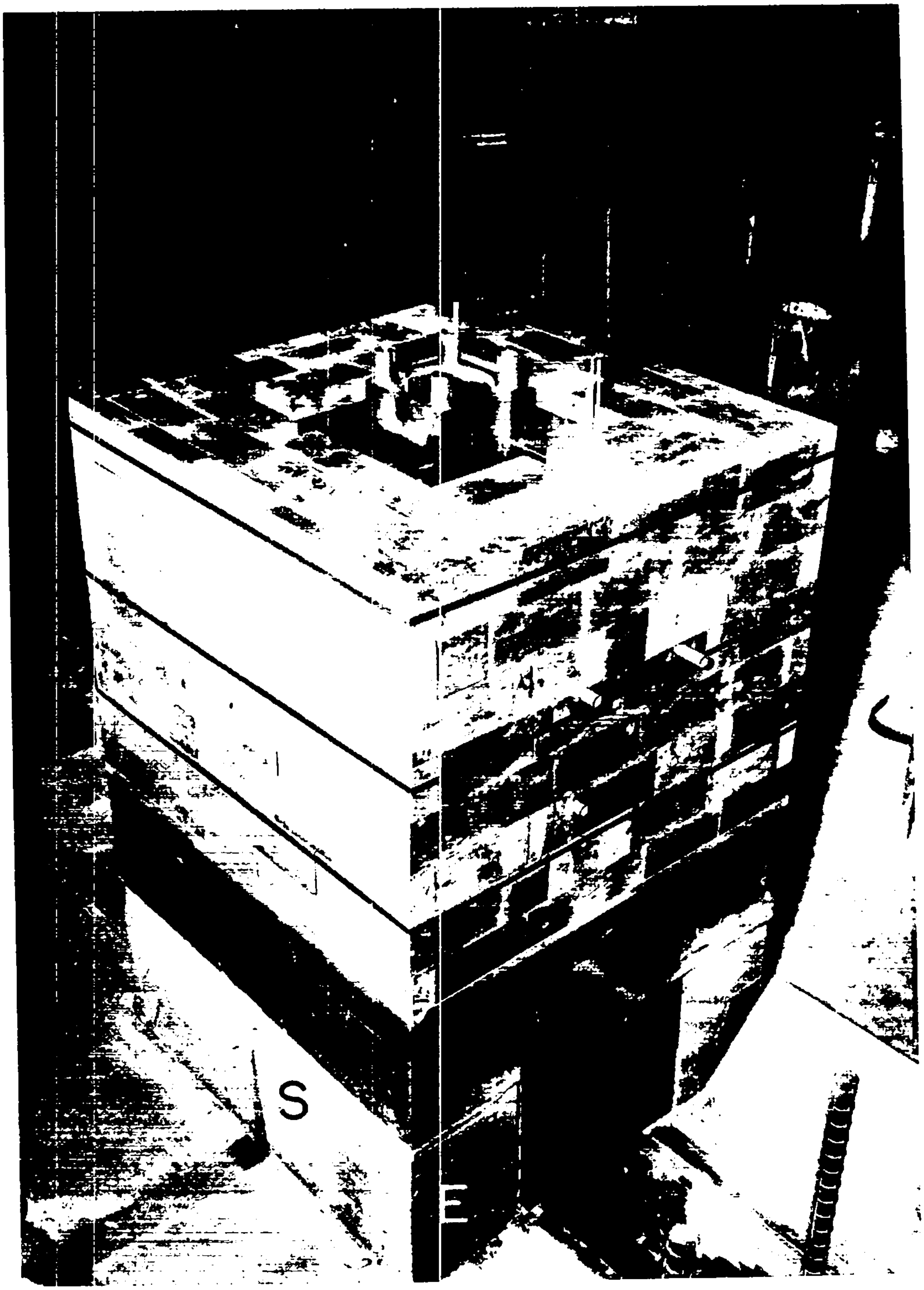

Fig. 18. Completed lead reflector shield.

4 in. wide with a turned-up edge 1/2 in. high, was cut to fit around the steel blocks and onto the upper steel base plate. In actual assembly, it was put down before the lead shield was assembled. To make a seal between the base plate and the envelope, the bottom of the pan was heavily painted with red lead, and immediately after it was set into position, the stacking of the lead brick was started; it was believed that by stacking a wall of lead 4 in. thick and 34 in. high on the flat pan, together with the red lead, a seal would be made strong enough to withstand a gas pressure of a few inches of water. The inside dimension of the pan was 38-7/16 in., so chosen that when the rest of the 1/16-in.-thick aluminum envelope with outside dimensions of 38-7/16 in. was slipped over the assembly, it would fit inside the upturned edge of the pan. The extra 1/2 in., over 38 in., was found necessary because in stacking the lead bricks the specified dimension of 38 in. could not be held. A fillet-weld then completed the aluminum envelope proper. The pan, without lead, can be seen in Fig. 17.

Experimental Holes. Additional welding of the envelope was required around some of the horizontal and vertical experimental holes, and also around the hole through which emerge the six 1/4-in.-OD aluminum tubes of the reflector cooling system. In order to simplify the job of fitting the envelope, it was fabricated with the required number of holes, properly placed, which were made somewhat oversized; this procedure rendered the positioning of the envelope much less fussy.

The situation which then existed was as follows:

1. Four horizontal experimental holes ran completely through the reactor from east to west. Holes for these had been bored in eight pieces of 1 in. square steel stock, each 8.625 in. long; two such blocks were made for each experimental hole, the uranium cube being 17.250 in. on a side. In machining the uranium blocks, and before silver-plating, square grooves were milled in them to take the steel blocks. In this way four cylindrical holes were formed which passed through 17.250 in. of uranium, and which terminated just inside the dural plates of the cooling system; corresponding holes had been bored in these plates. Matching holes had been bored in the blocks of the steel layer, and similarly in the lead shield. Thus these four experimental holes passed right through the cube (from east to west, as above stated). Figure 16 shows (from the southeast corner) the holes in the dural plates, Fig. 17 shows the holes in the blocks of the steel layer and Fig. 18 shows the holes in the lead layer. A schematic drawing of these liners and surrounding materials is shown in Fig. 19.

2. Three horizontal (one through the east side into the special steel block, one through the south side into the special thorium block, and one through the west side into the special uranium block) and ten vertical experimental holes passed through the cube in various positions. These holes penetrated the inner uranium reflector to various depths, but were all closed there.

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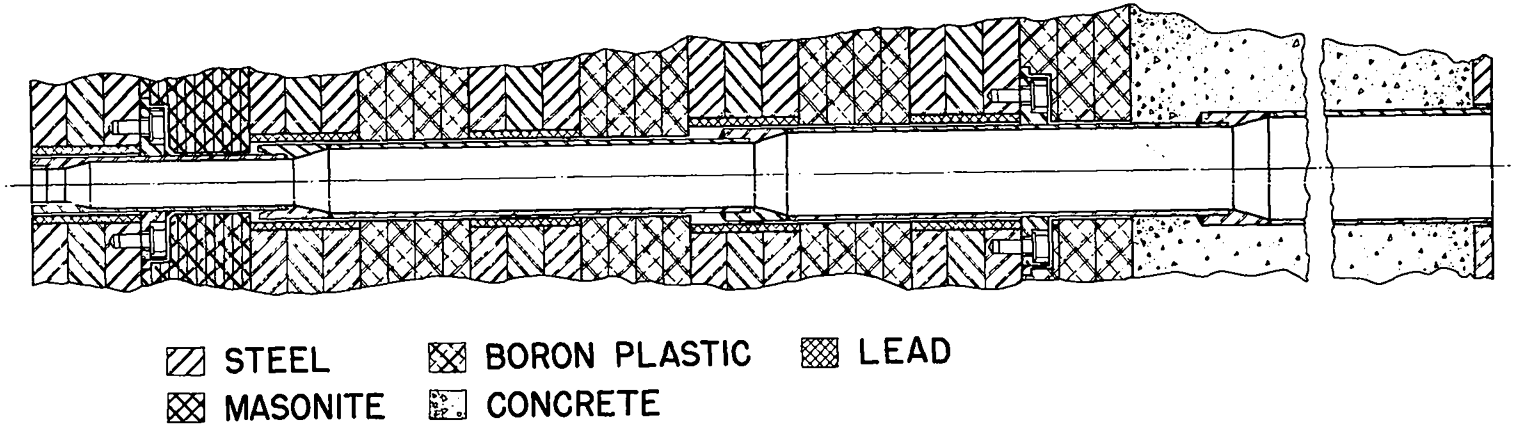

Fig. 19. Drawing of typical port liner.

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In case 1, the seals were made by running liners of solid 2S-aluminum tube through each of the four holes; large aluminum flanges were slipped over each projecting end, and the flanges were then welded to the tubes, and then to the envelope. The large flanges greatly facilitated the welding by leaving good-sized distances between welds. The ends of the tubes were then reamed out carefully, and dressed down to the required length; as will be described later, stainless-steel fittings were designed to fit snugly over these ends (see Fig. 19) to make the experimental holes properly accessible.

In case 2 the bottoms of the liners had to be closed, and then specially reinforced to prevent a leak from being sprung in them if an object was pushed too hard into the hole. A sketch of a typical tube is shown in Fig. 19; there it will be seen that the method of closure was to counterbore the end of the tube, set in a tightly-fitting disk, and then to weld the end of the tube to the disk, after which the end of the tube was dressed off. In assembly the closed-bottom tubes, of adjusted lengths, were inserted into the holes and pushed snugly (but not tightly) against the end of the borings in the uranium, and then the flanges were welded into place. As in case 1, allowance was made for stainless-steel couplings (see Fig. 19).

The final condition of the aluminum envelope is shown in Fig. 20, which is a photograph taken of the southeast corner. Here, in the east (at the right in the photograph) are seen the four holes of type 1 arranged in a square; the hole in the center of the square is a type 2 hole. As described above, the four holes--arranged in the square--pass completely through the reactor and emerge on the west side. In the south face of the envelope (at the left in the photograph) can be seen the type 2 hole of the thorium block. Atop the envelope are seen the 10 vertical holes and many of the sealing flanges. The method of welding in the six 1/4-in.-OD aluminum tubes is obvious; the aluminum covers for these tubes are not shown.

When the envelope was finally completed, the whole assembly was leak-tested by temporarily closing the hole for the safety-block shaft (in the safety-mechanism channel), also the top of the center column (see Fig. 20), and by using a soap solution as leak indicator. No leaks were found at any of the welds or along the seal underneath the pan.

1.3.3 Reactor Shield

In order to achieve an effective and yet compact shield against fast neutrons and gamma rays a combination of materials has gone into the Fast Reactor shield. Thus, near the core region, the shielding consists of alternating layers of steel, hydrogenous material, and boron-plastic, whereas near the outside edge the shield consists of heavy-aggregate poured concrete. Most of the shielding against fast neutrons is done in the laminated sections of

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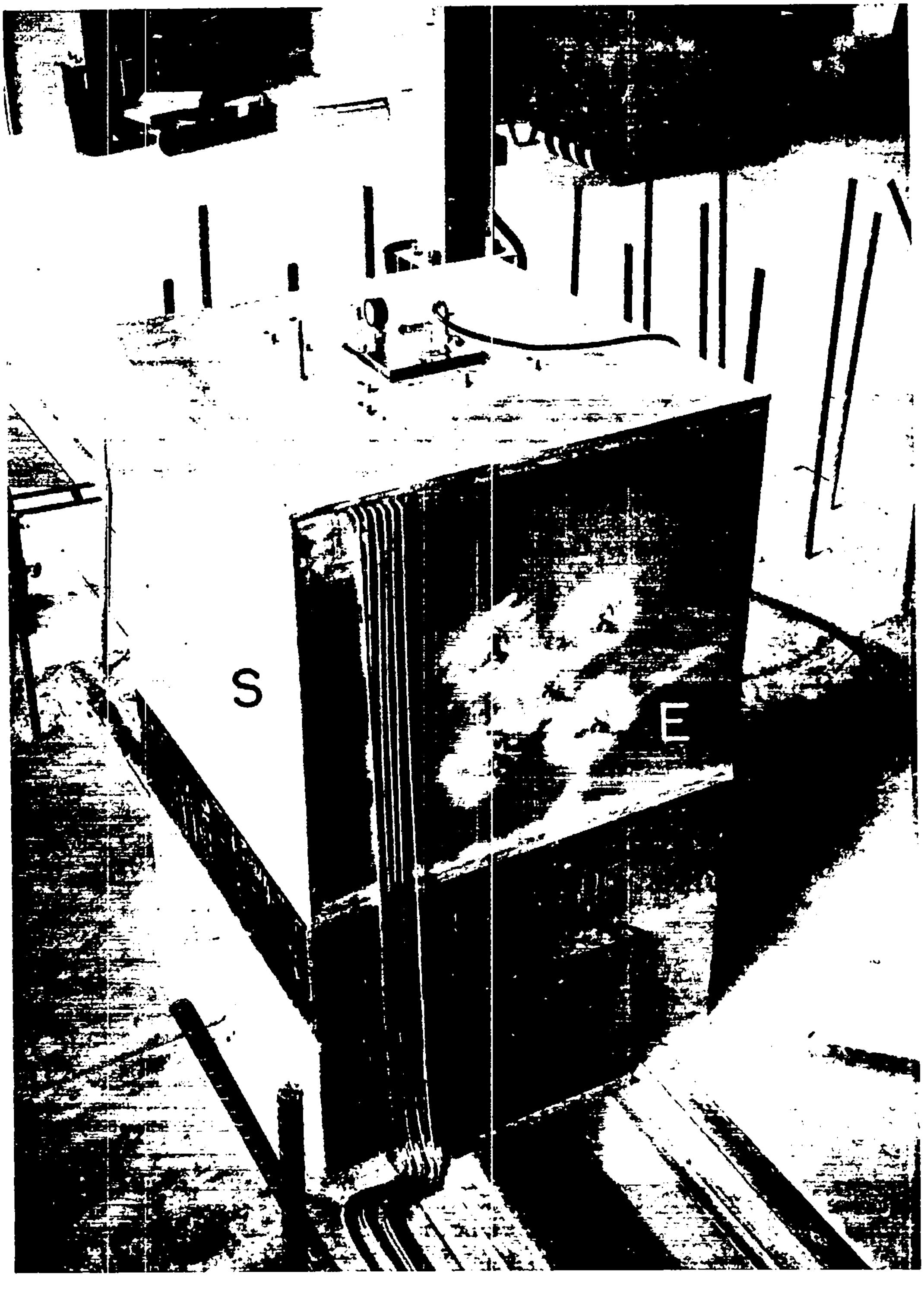

Fig. 20. Aluminum reflector envelope.

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shielding, in which neutrons in the nearly virgin fission spectrum are slowed down and captured. The average density of this part of the shield is quite high, and it thus serves as an effective shield against gamma rays. The fast neutron leakage through the laminated shielding is low enough so that further shielding is mainly against gamma rays, and the heavy-aggregate poured concrete was used.

For construction the shielding was divided into two parts, side shielding and top shielding. The side shielding is the permanent assembly of Hanford laminations and concrete which acts also as a retaining and supporting wall for the parts of the reactor. The top shielding is made up of a series of variously shaped blocks, of the same materials as above (in order of assembly and in approximate thickness), which with the crane can be piled over the reactor cube. The permanent construction shields the reactor on three sides, the fourth (north) side being designed to contain the thermal column. Through this shielding run the steel guide tubes which are connected to the several experimental holes.

Extra shielding is needed behind the mercury cabinet, as its presence robs part of the poured concrete. The thermal column also requires special shielding (see Sec. 1.3.4).

Laminated Shield. The Hanford-type shielding consists of 10 vertical layers, each nominally 3 in. thick, assembled around three sides (east, south, and west) of the finished cube of the reactor. The first layer, fitted snugly around the cube, is of steel, as are also the third, fifth, seventh, and ninth layers. The second layer is of Masonite, while the fourth, sixth, eighth, and tenth are of boron-plastic. The vertical shielding is shown in Fig. 21, which shows the completed assembly. All in all, the Hanford shielding is 30 in. thick, being made up of a total of 15 in. of steel, 3 in. of Masonite, and 12 in. of boron-plastic.

The construction of the vertical shielding followed along obvious lines; the details given below are chosen to indicate either essential precautions taken or to record items that may be of special interest in future operation of the reactor. No description will be given here of the details of the construction or assembly of the stainless-steel sleeves that pass horizontally from the mouths of the experimental holes (at the faces of the cube) as these will be described later. Great precautions were taken in the work in order to attain the best possible assembly of these sleeves, and also to prevent any damage to them or to the delicate welds (by shock, etc.) in the aluminum envelope of the cube. Similarly, pains were taken throughout the assembly of the steel, Masonite, and boron-plastic to eliminate all radial cracks.

All in all, 15 steel slabs were assembled in five separate layers on three sides of the reactor; each of these 15 slabs was fabricated, in advance, of three 1-in.-thick boiler plates. The plates of each slab were welded along the edges to form a whole. In erecting the slabs

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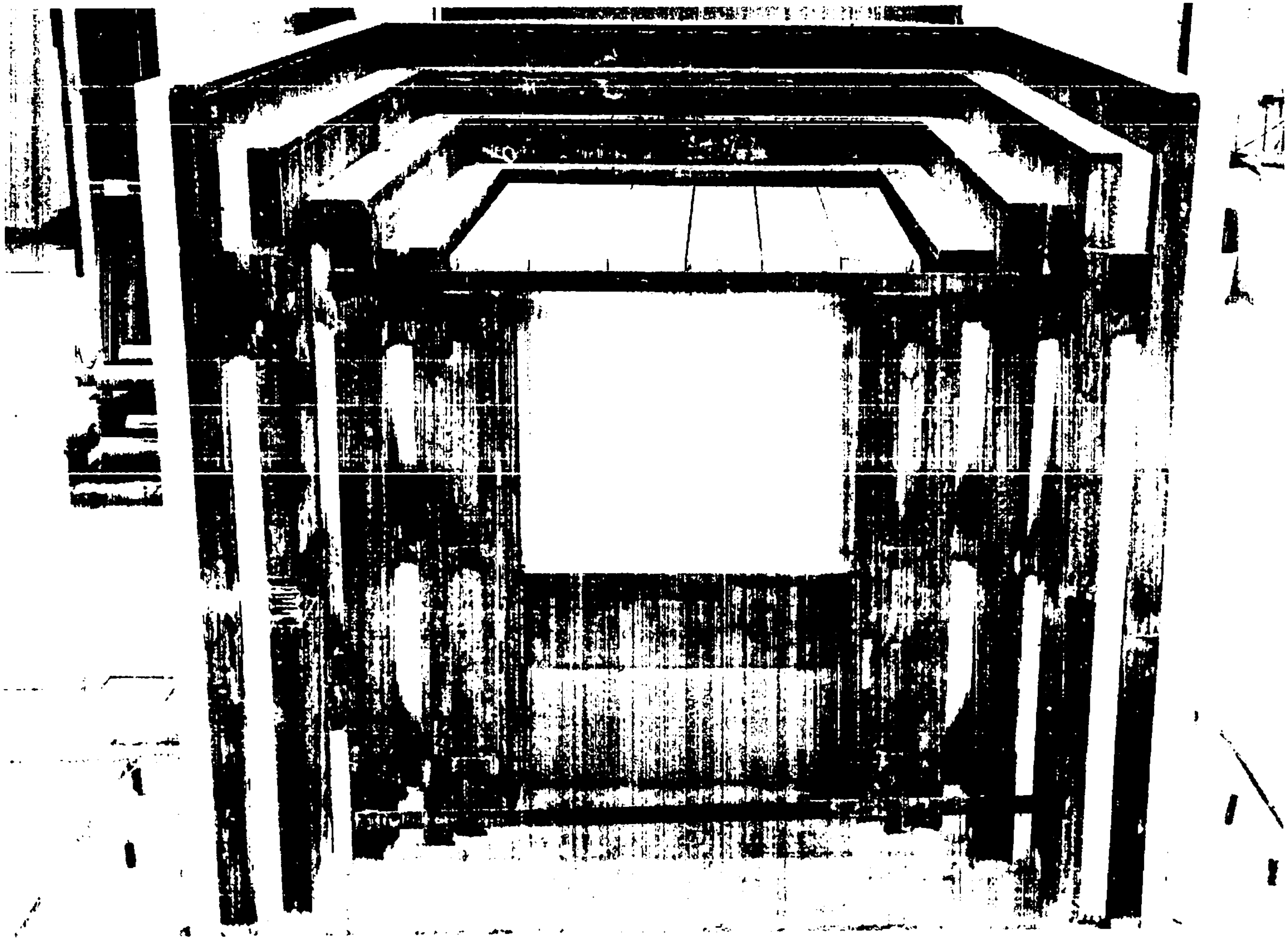

Fig. 21. Laminated shielding sections.

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(south slab first, to which were abutted the east and west slabs), they were hoisted by crane, set down on shims, levelled and squared up, then tack-welded into position. Grout was next hammered between the foundation of the reactor and the bottom edges of the slabs so that they could not settle; 1 day later, the abutting edges of the slabs were tied together along their full lengths with 1/4-in. welding fillets. The first set of slabs, erected snugly around the cube, were also welded to the 8-in. base plate of the reactor, and further tied with a bar across the open north end of the shielding. The other layers of steel were assembled (after the assembly of intermediate materials) in the same manner, and in addition successive steel slabs were tied to the preceding ones by 1 x 6 in. steel bars. Although it was quite impossible to keep the 1-in. boiler plate stock quite flat, the construction of the steel slabs was such that in the final assembly the vertical air gaps were probably held to 1/16 in. on the average.

Since the top shielding of the reactor was designed to be removable, radial cracks were eliminated in it by increasing the successive heights of the vertical steel slabs by steps of 6 in.; these steps can be seen in Fig. 21. In order to provide, simply and easily, flat bearing surfaces along the top edge of each steel slab, each one was capped along its full horizontal length with 1 x 3 in. bar stock; these bars were shimmed, levelled to 1/16 in. or better, and welded. In Fig. 21 it will also be noted that each intermediate layer of Masonite or boron-plastic is built up to a height equal to that of the preceding steel slab; thus five steps were formed, each riser of which is faced with a 3-in. thickness of steel.

The dimensions of the steel slabs are given in the table below, each line of which corresponds to a layer of the shielding; the east and west slabs have the same dimensions, though not the same as those of the south slabs. Note that the "steps" are indicated in the successive heights. The total weight of the steel is 32.4 tons.

TABLE 1. DIMENSIONS OF STEEL SHIELDING COMPONENTS (inches)

East and west slabs		South slabs	
Height	Length	Height	Length
60	48	60	44
66	56	66	56
72	68	72	68
78	84	78	84
84	92	84	92

It will also be noticed from Table 1 that the sucessive vertical layers increase regularly in their north-south dimensions; the purpose of such design was to increase the northern

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extension of the shielding as much as possible and yet not interfere with the thermal column. The dimensions of these layers as given in the table are reference values only; as a purely practical matter they were held to about 1/4 in.; the heights of the steps, however, were held to slightly better than 1/16 in.

The assembly of the intermediate layers of Masonite and boron-plastic was mainly a hand-tailoring job. Since there were only three slabs of Masonite (3 in. thick) to be assembled, these were prefabricated and bolted to the face of the preceding steel slabs; bolts were spaced about 12 in. The boron-plastic (in sheets 3/4 in. thick) was assembled in four successive layers to make up 3 in.; the first layers were bolted to the steel, then following layers to the preceding ones; bolts and wood screws were used in profusion over the entire surfaces and were spaced by about 12 to 14 in. The purpose in using so many fastenings was to prevent collapse of the boron-plastic shielding at some future time should the plastic break down in the radiation field.

Poured Concrete Shielding. Prior to pouring the concrete side shielding, several design features and facilities were installed. These include mainly the steel substructure, mercury cabinet, and lead storage coffins. Other facilities of a more ordinary variety were provided, such as water lines, power conduit, and cable channels, and many of these can be seen in the accompanying figures.

1. Steel Substructure. The base of the concrete outer shielding was designed to be outlined at floor level, except on the north side, by a framework of vertical 8-in. I-beams; the recess thus formed, about 3 in. deep and 7 in. high, was provided in order to leave space available between the reactor shield and experimental equipment for such things as cables and water lines. Projecting out of the recess and spaced at intervals of about 3 ft there are 3/8-in. machine bolts for the purpose of securing equipment. The general outline of this steel substructure can be seen in Fig. 22. Wherever possible the I-beams were welded to the reinforcing rods that project from the foundation.

2. Mercury Cabinet. The mercury cabinet is designed to provide a well-shielded recess, 42 in. wide x 93 in. high x 21 in. deep, to house the reactor's cooling system components, including the pump, heat exchangers, storage tanks, etc. The cabinet is located at the east end of the south face of the reactor shield. Its side and back walls are actually triple-walled affairs, each sub-wall being made of 1/2-in. steel plate. The two spaces formed between the partitions in the walls are 1-1/2 in. wide and are filled with lead. Thus the walls of the cabinet are a total of 4-1/2 in. thick, of which thickness 1-1/2 in. is steel and the remaining 3 in. is lead. Because of the rather large weight of this structure, an especially stout supporting base was provided for it. Five short I-beams were laid parallel to

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each other and each was welded at one end to the circumferential I-beam substructure described above. The other ends of the short I-beams were welded to an I-beam laid parallel to the substructure member and running the full east-west distance of the reactor shield. This arrangement of I-beams can clearly be seen in Fig. 22.

3. Lead Storage Coffins. The lead storage coffins are designed to serve as a convenient temporary storage place for dangerously radioactive materials, such as freshly irradiated samples, chambers, and parts from the core region of the reactor, which might be removed from the top side of the reactor during normal operation and maintenance, or during teardowns. There are four of these coffins, two each cast into the north-south poured-concrete shield walls. Each coffin consists of a double-walled, lead-filled cylinder 4 ft 8 in. long, with an inside diameter of 9 in., and a total wall thickness of 3-3/4 in., of which 2 in. is poured lead. Plugs fitting over the top of each coffin offer 3 in. of lead shielding in the upward direction.

It was necessary to install the coffins before the concrete pouring was done. The welded angle-iron sawhorses constructed for this purpose can be seen in Fig. 23.

Figures 23 and 24 show the general pattern of welded reinforcing rod set into place prior to pouring the side shielding. The vertical rods are welded to the ends of rods projecting upward through the poured foundation, and, in general, are arranged on approximately 9-in. centers. Figure 24 also shows the iron hooks welded into the sides of the mercury cabinet for the purpose of securing it firmly into the concrete.

Figure 25 is a photograph, taken from about the same position as Fig. 24, showing the wooden forming erected to retain the poured vertical slabs which form the side shielding. The especially strong reinforcing and buttressing of the forms were made necessary by the high density of the aggregate. The barytes aggregate mixture had a density of 203 lb/ft^3. A total of 468 cu ft of the mixture went into making the side shielding.

The finished outside dimensions of the shield are 11 x 15 x 9 ft high.

Top Shielding. The removable top shielding, as far as materials are concerned, was made to conform as closely as possible to the side shielding already described. It is made up of three kinds of removable pieces: shielding "boxes" immediately above the core region, laminated shielding pieces, and concrete blocks.

After assembly, the top shielding makes a reasonably level floor of the top surface of the reactor shield. The pieces are all dimensioned in such a way that vertical cracks or passageways through the shielding are as nearly as possible eliminated.

1. Shielding Boxes. The three top shielding boxes are placed directly over the core of the reactor and are designed to eliminate loss of shielding just around the reactor

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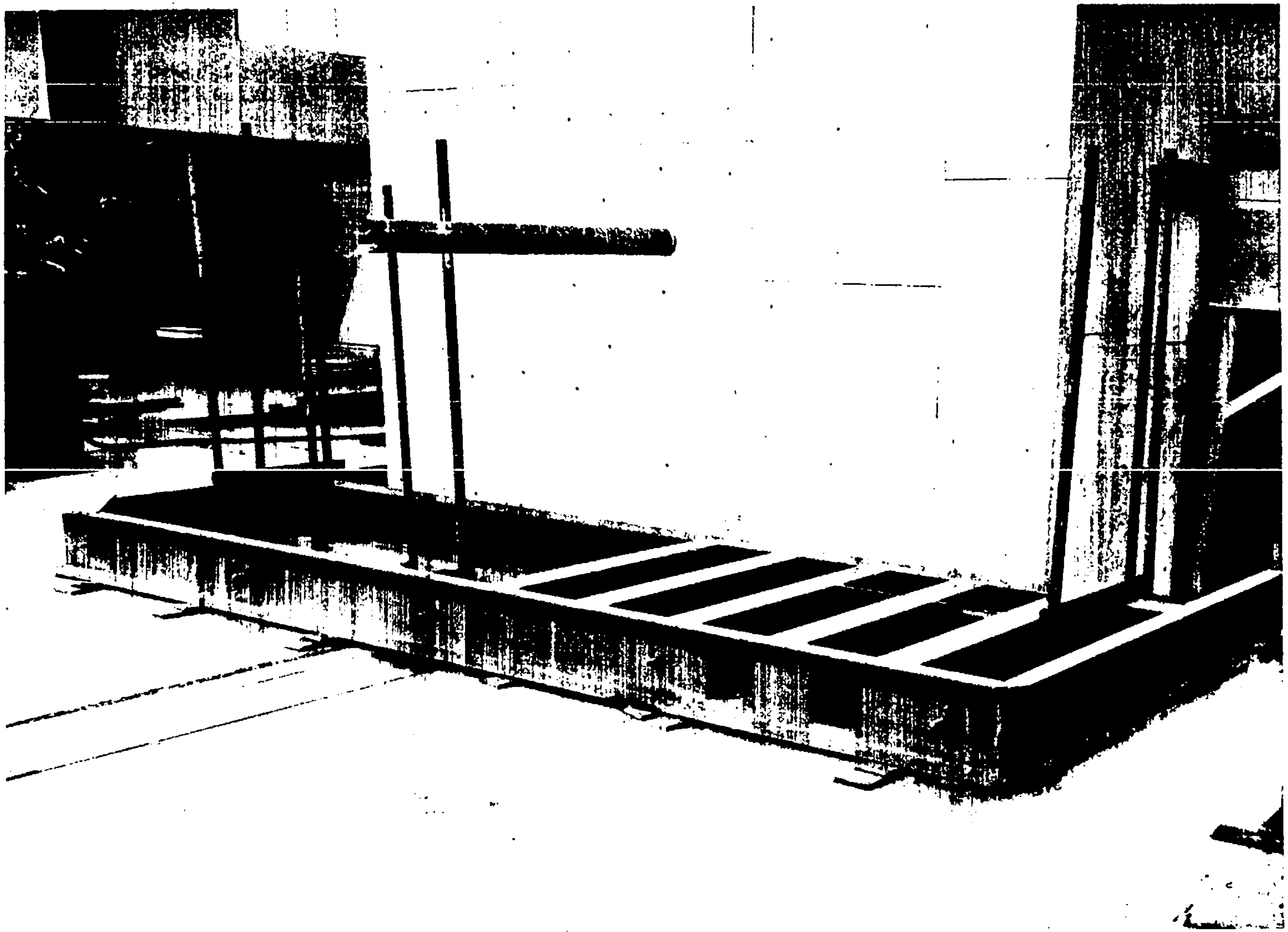

Fig. 22. I-beam support for the mercury cabinet.

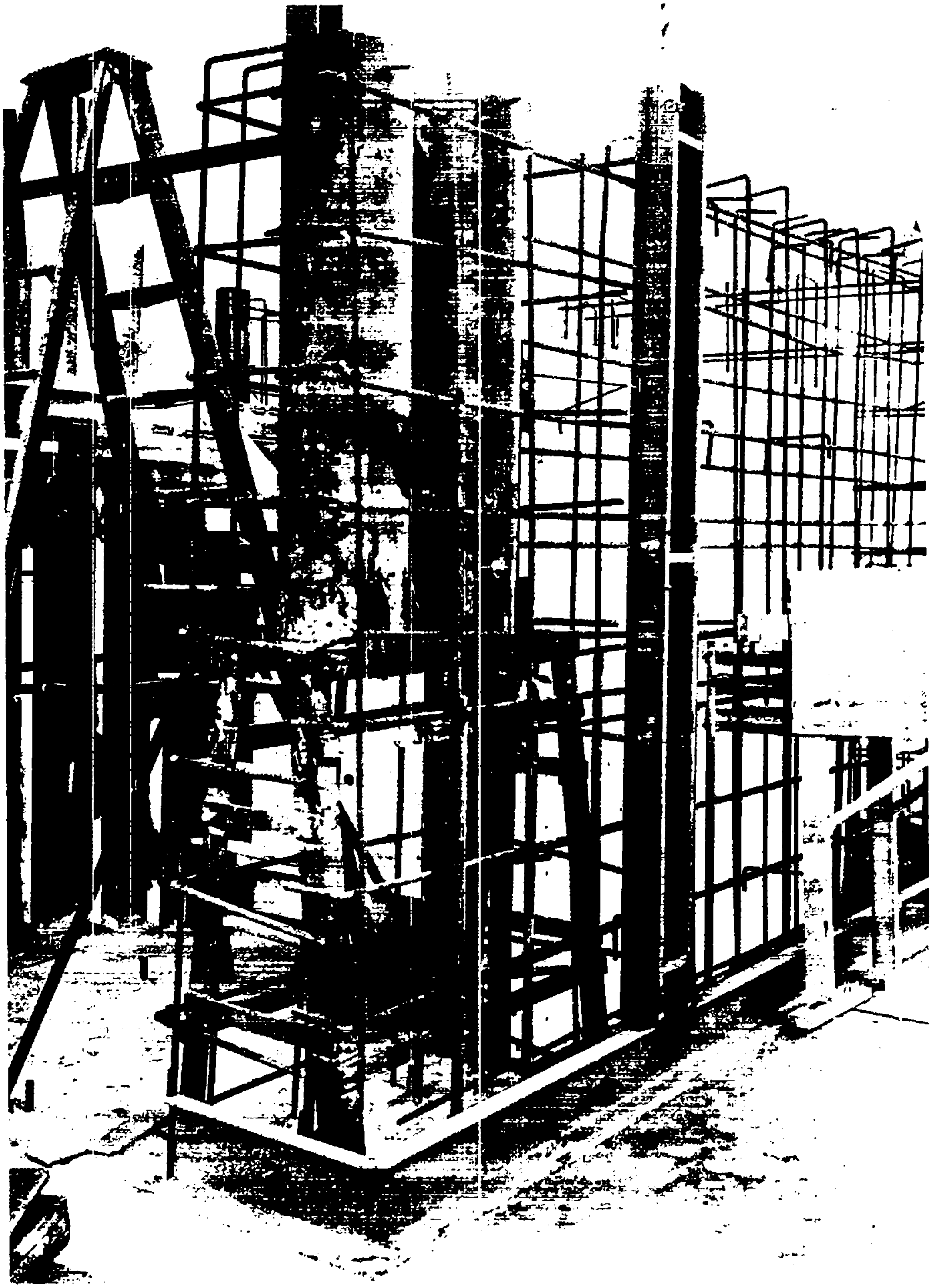

Fig. 23. Storage coffins and steel reinforcing.

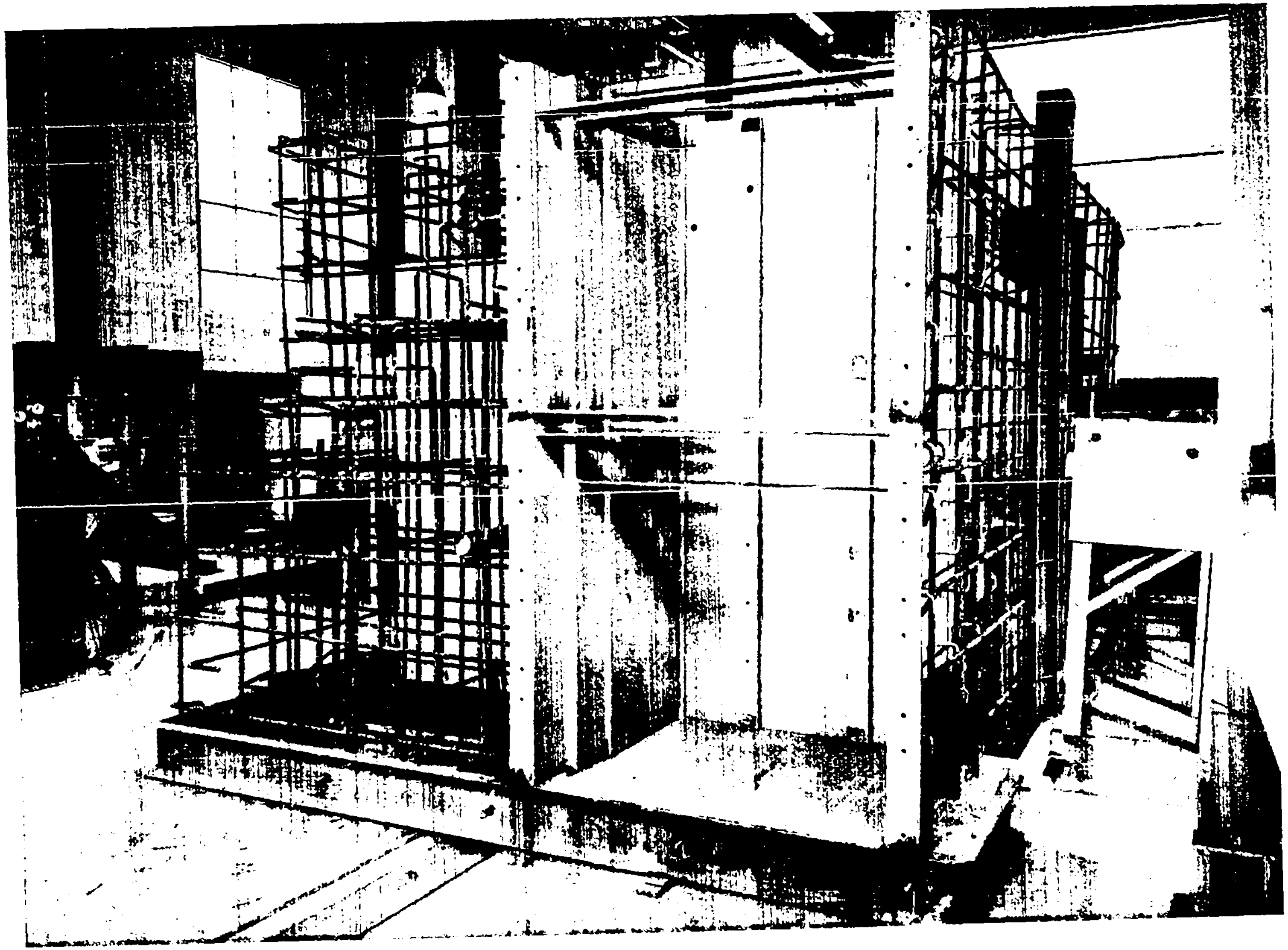

Fig. 24. Mercury cabinet and steel reinforcing.

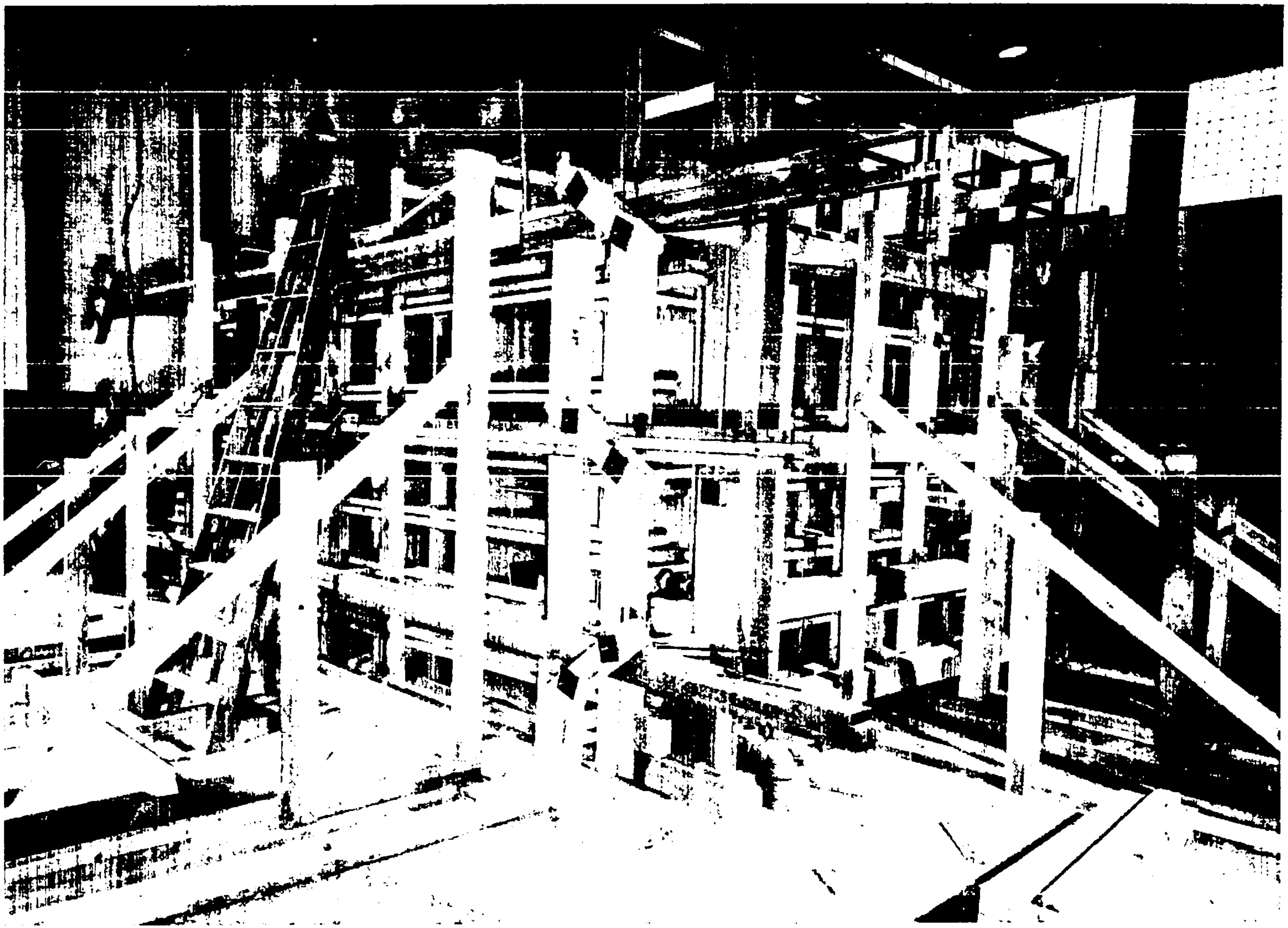

Fig. 25. Wooden forming for the side shielding.

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pot and to provide precision passageways for the control mechanism rods through the shielding. The two lower boxes fit snugly around the top part of the reactor pot, whereas the bottom of the uppermost box rests a few inches above the top of the pot. The boxes are staggered in size so that each of the two upper ones overlaps the one just underneath it.

Each box is a steel-walled affair filled with a mixture of lead shot and borated paraffin. After assembly, the uppermost box protrudes by a fraction of an inch above the level of the concrete blocks around it.

2. Laminated Shielding Pieces. The steel and Masonite and steel and boron-plastic removable pieces ("sandwiches") were arranged to rest on the top of the reflector cube and to nest into the vertical laminated shielding sections already described. In Fig. 2 the general arrangement of these pieces can be seen in their relation to the top shielding boxes.

3. Concrete Blocks. The arrangement of the removable concrete blocks can also be seen in Fig. 2. The mixture of barytes aggregate used in the side shielding was also used for pouring these eleven blocks. Each of them is provided with two ring eyes for convenient handling with the overhead crane.

Shield Plugs for Experimental Holes. Shielding plugs for the experimental holes (see Sec. 1.3.2) are required for easy access to reflector regions for irradiations. The plugs should provide shielding which is at least as good as the main structure and should also be quickly and easily removable. The diameter of the horizontal experimental holes ranges in 1/2-in. steps from 1-1/4 to 2-3/4 in. The innermost and smallest plug is made of steel to act as a primary gamma shield. This is followed by three separate plugs of boron-plastic. These plugs were made of strips of plastic cemented together with acetone solvent and secured at 6-in. intervals with bolts. After being cured for a week, the rough plug was fitted with steel end caps and turned to the finished dimensions. Coupling screws and tapped holes on each end plate allow each section to be handled independently of the others or joined together in one long plug. A 6-in. lead cylinder separate from the other plugs completes the shielding on the horizontal holes. All the plugs except those for the 1-S and 5-E holes are interchangeable.

The top experimental holes are shielded in a slightly different manner from the horizontal holes. In this case, the first two sizes of plugs are made of steel for a total length of 2 ft and the final plug of boron-plastic capped by 3 in. of lead. Neutron monitors described in Sec. 2.3 occupy five of the nine vertical holes, so that the shield plugs for these holes are channeled to provide room for their associated cables.

1.3.4 Thermal Column

The thermal column, made up of 4-1/4 x 4-1/4-in. reactor grade graphite stringers of

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various lengths, is stacked in the cavity left for it in the north face of the shield. Figure 26 gives the outside dimensions and shows the shape of the graphite structure as seen from the southeast direction. A 4 x 4 x 15-in. long bismuth block, mentioned in Sec. 1.3.2, paragraph 2, serves as a "window" in allowing fast neutrons to pass from the reactor core region into the thermal column. Thus, in Fig. 26, the bismuth block fits flush against the center of the 29-3/4 x 29-3/4-in. projection of graphite at the left.

The three small square holes seen in Fig. 26 pass completely through the column. They represent three transverse ports, incorporated into the thermal column design to permit access into the column for sample irradiation or to allow installation of special "through" pneumatic devices for special quick irradiations.

Main access to the column is through a door at the north face. Here are exposed the ends of seven stringers which can be removed by any desired amount up to the depth represented by the bismuth window. These experimental facilities will be described in more detail, with dimensions, in Sec. 4.4.

Thermal Column Shielding. The thermal column shielding is a 1-1/4-in. layer of boron-plastic on the top, two sides, and outside end of the graphite. This plastic layer is backed up by a layer of 0.040-in. cadmium. Most of the neutron leakage from the thermal column is absorbed by the boron contained in the plastic and consequently does not give rise to excessive gamma radiation. The cadmium layer serves to provide a small additional protection. The balance of the shielding on the top and sides is accomplished by the heavy aggregate concrete of the main structure. The outside end of the column is capped by a 6-in. wall of lead held in place by a 1-in. steel plate. In the center of the column face is a hinged lead door, 12 x 12 x 6 in., to provide access to the central removable graphite stringers. For added convenience, the lead door is fitted with a centrally removable 4-in.-square plug so that thermal neutron beams may be obtained while still retaining the benefits of maximum shielding.

1.4 Mercury Cooling System

The primary cooling agency of the reactor is the mercury circulating system which provides for heat transfer from the active core (or pot) to discharged water. This mercury system is entirely contained in welded steel and is provided with efficient gamma shielding. The operating volume of mercury is approximately 18 liters (245 kg) of which 0.75 liters (10 kg) is in the pot region, and the normal flow is about 9 liters per minute, providing a linear flow of 5 cm/sec in the active region.

Figure 27 shows a schematic diagram of the components of the circulating system. Starting from the supply tank, the mercury flows through the shielding to the pot, is mani-

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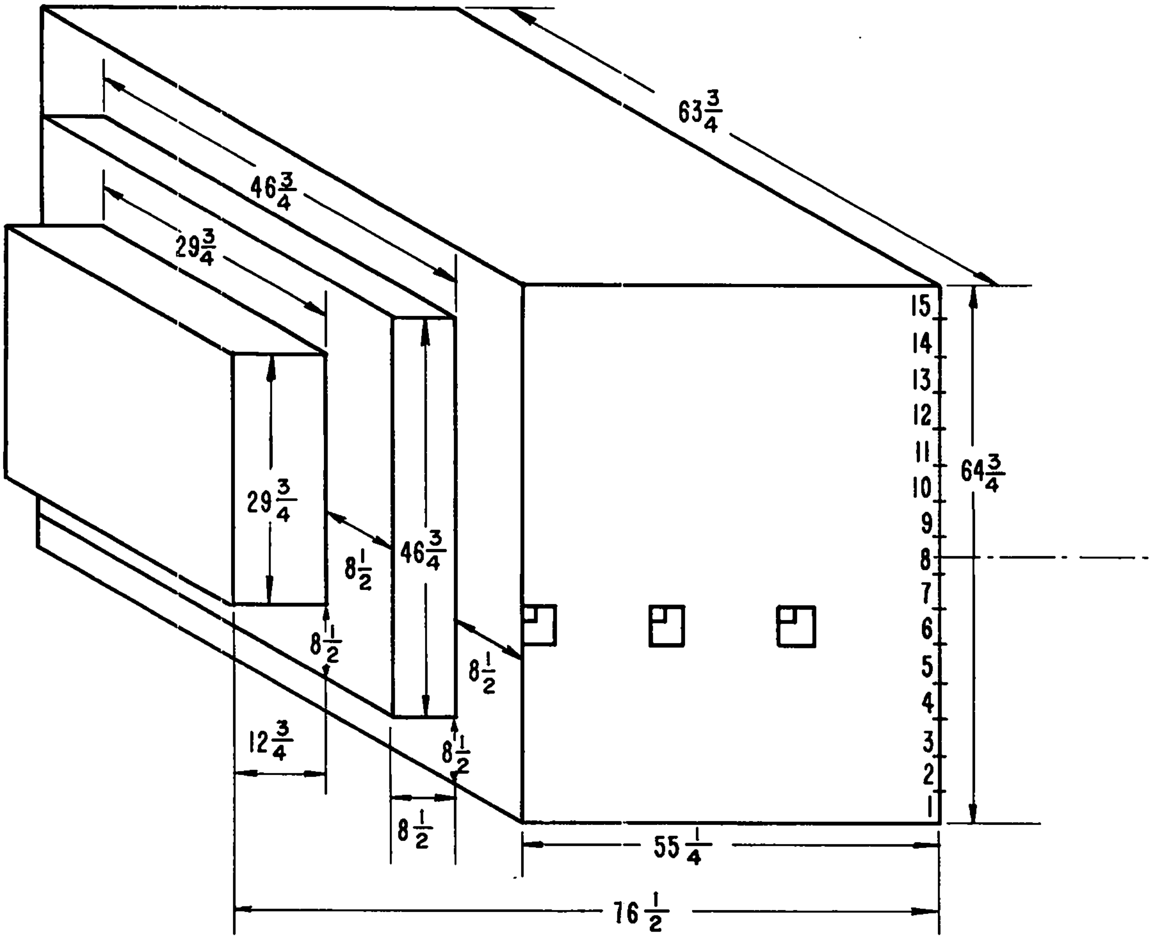

Fig. 26. Sketch of the thermal column graphite structure.

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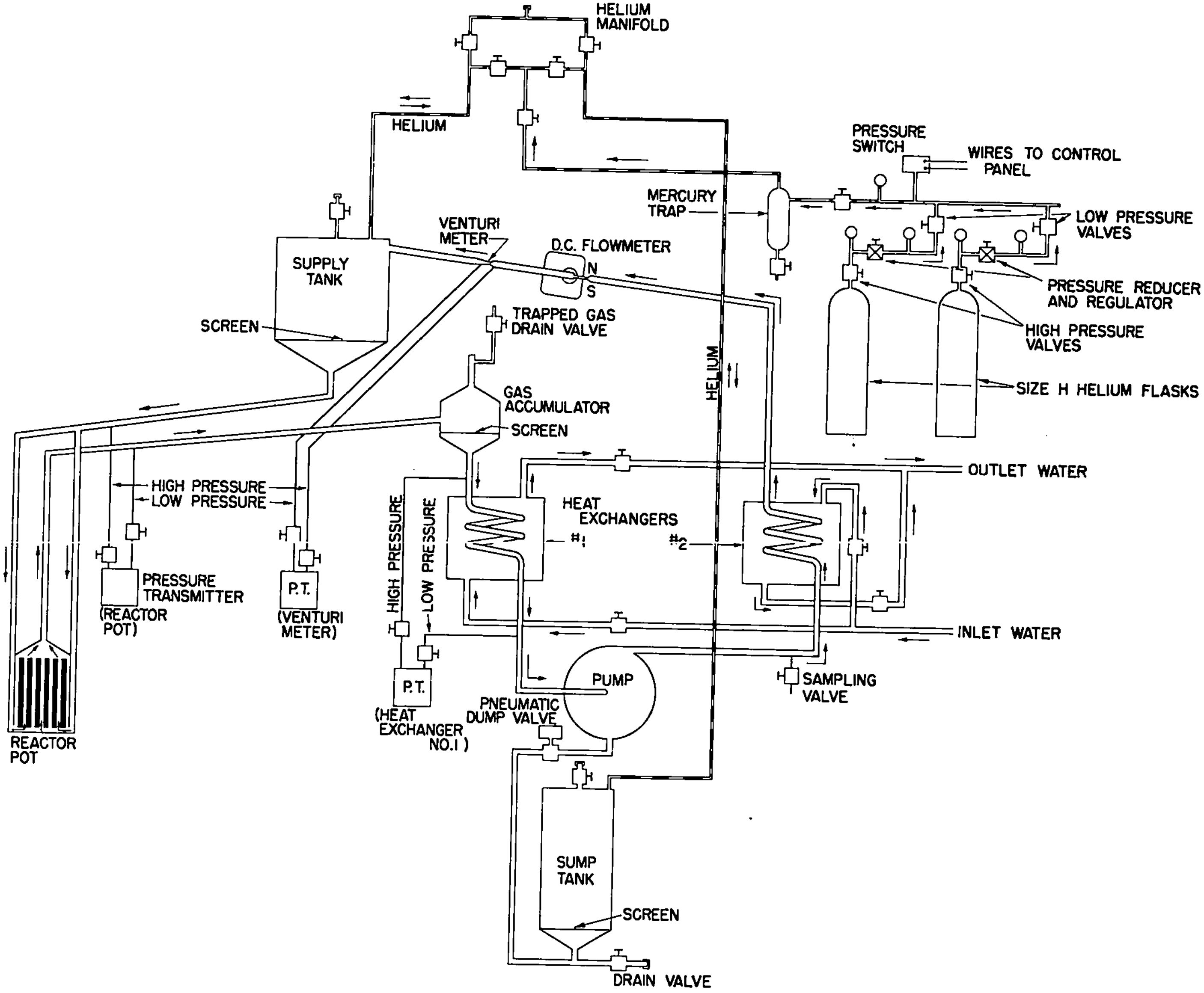

Fig. 27. Flowsheet for the mercury system.

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folded in a small region under the plutonium rods, and leaves through a centrally positioned pipe at the top of the pot. The hot mercury then returns to the cabinet, where it passes through a gas accumulator and enters the first heat exchanger to be cooled by water. It then passes through the pump and a second heat exchanger identical to the first one. The mercury leaves the heat exchanger No. 2 at essentially constant temperature and is metered for flow by a conventional venturi flow meter before returning to the supply tank. In addition to the pressure drop across the venturi flow meter, the pressure differential is measured across the pot at the points where it leaves and re-enters the mercury cabinet and across heat exchanger No. 1. These pressure drops serve the double purpose of providing a check on the operation of the venturi flow meter and indicating any changes in the flow characteristics of the system. The temperature of the mercury is monitored by thermocouples at six points in the system to give a check on the satisfactory operation of the component parts.

Provision is made to drain the mercury be means of a "dump" valve connecting a steel tank to the bottom of the circulating pump. Opening this valve allows the mercury to be transferred from the piping and apparatus in the cabinet to a shielded storage tank at the lower left of the cabinet so that maintenance or repair work on the system will not be complicated by the presence of radioactive mercury. This, however, does not drain the mercury from the region of the fuel rods.

The mercury system is maintained under a constant pressure of 50 psi of helium.

The main components comprising the mercury circulating system were built as a subassembly on a panel which was later bolted into the mercury cabinet. Figure 28 is a photograph of the panel with the parts numbered according to the following legend:

1. Top plate of cell
2. Exhaust hole shield
3. Supply tank
4. Gas accumulator and screen
5. Cooling air duct
6. Concrete shield
7. Steel and lead cell wall
8. Heat exchanger
9. Pump
10. Shielded sump tank
11. Venturi meter
12. Track for sampling device

The cabinet opening to the south is closed by a composite, sectionalized door that has staggered joints and is made up of 2 in. of lead, 1/2 in. of steel, and 12 in. of high-density concrete. The top of the cabinet is closed with a lead and steel top plate made up as a steel box with top and bottom of 1-in. and 3/4-in. steel, respectively, and filled with 4 in. of lead. Mercury piping to and from the reactor pot passes through small holes in the back of the cabinet and all other gas, air, water, and electrical lines are run through holes in the bottom of the cabinet with one exception--cooling air for the pump, which is provided by a

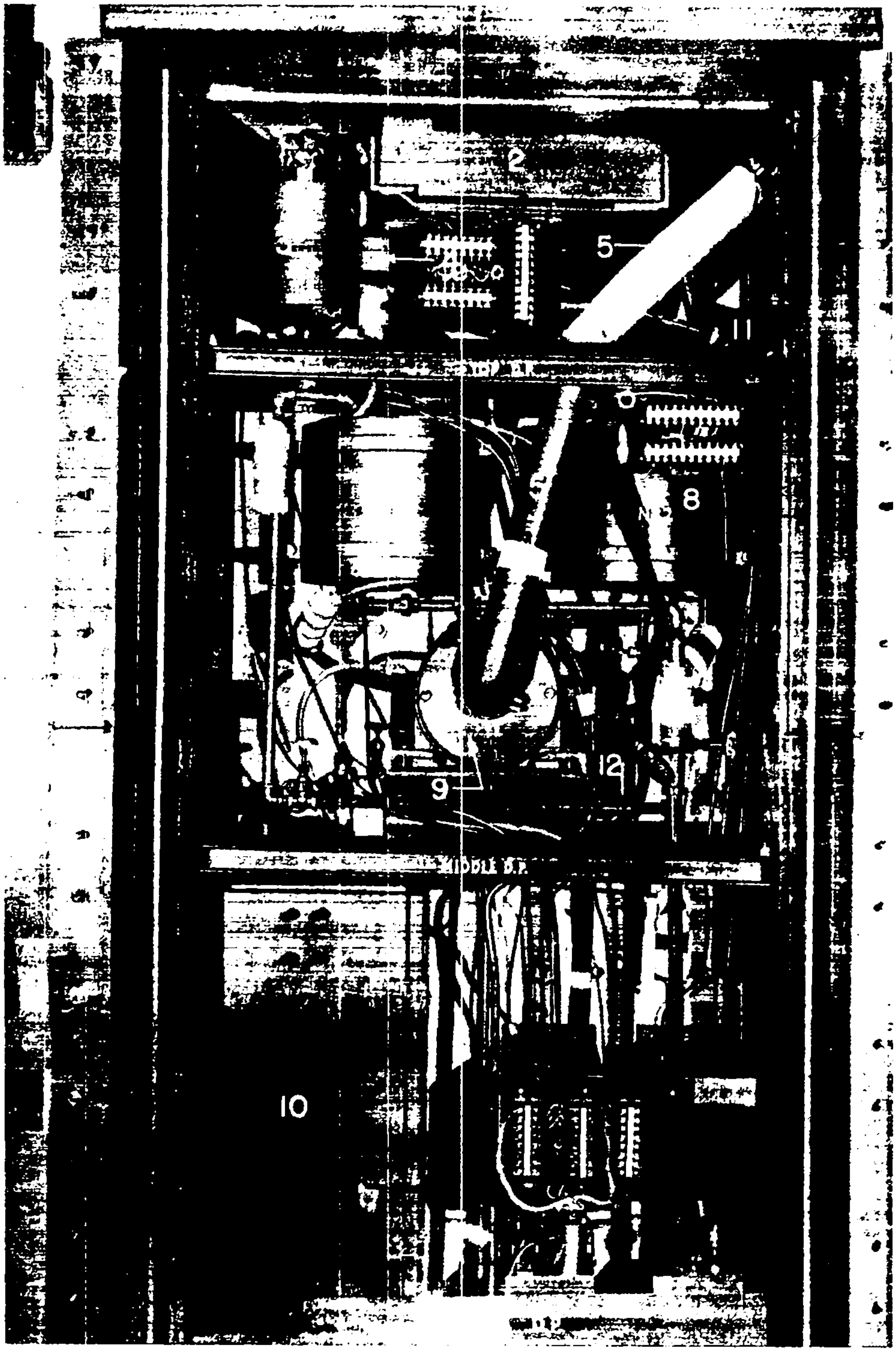

Fig. 28. Components of the cooling system.

blower located in a silencing box mounted on the east wall of the reactor near the top of the cabinet. This cooling air passes through a tube through the east wall of the cabinet and then, after passing through the pump, is discharged through a grill in the top plate. The discharge hole is shielded against gamma-ray leakage by a heavy lead and steel shield underneath the opening. The cooling-air entrance tube is shielded against leakage by having bends in its passage through the concrete wall.

A detailed description of the components of the mercury system is given to assist in effecting maintenances and repair.

1.4.1 Supply Tank

The supply tank serves as an expansion tank, reservoir, and filling point for the mercury system. The tank proper is 8 in. in ID by 10-1/4 in. in height, made of mild steel, and has a volume of 6.8 liters of which approximately 4.5 liters is filled with mercury. Located on the panel at the upper left corner, the tank discharges mercury thru a 16-mesh stainless-steel screen directly into the pipe line leading to the reactor pot. Four electrodes penetrate the top of the tank through porcelain insulators provided with steel gaskets and extend to various depths. The central electrode passes through the filter screen to the bottom of the tank; the second and third level electrodes define the limits of normal operating volume, about three-fourths of the tank capacity. The lower of these should always make contact, whereas the upper shows contact only under static conditions and goes out when the mercury flows. The last electrode makes contact with the inlet mercury stream to give indication of mercury flow. This last contact is incorporated in the interlock circuit described elsewhere.

1.4.2 Gas Accumulator and Screen

The return pipe from the reactor pot discharges into a chamber where entrapped gas in the mercury system may accumulate and be bled off. The accumulator is made of mild steel 6 in. in diameter by 3 in. deep and is provided with a 16-mesh stainless-steel screen at the bottom to prevent foreign particles from being backwashed into the pot during filling or dumping operations. The presence of accumulated gas is indicated by an electrode in a small cavity located on top of the chamber; a 1/8-in. steel tube capped by a needle valve permits relief of the excess gas.

1.4.3 Heat Exchangers

The heat exchangers used are helical coils of 7/8-in.-ID steel tubing sweated into a machined copper cylinder and cooled by discharged water. The copper body of the heat exchangers is made up of three concentric close-fitting cylinders. The central cylinder was

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cast from oxygen-free high-conductivity copper, machined externally with a round bottom thread having a 1.333-in. pitch and a width and depth of 1.010 in. This thread was designed to receive the steel tubing for the mercury. The inner surface of this cylinder was threaded with a round bottom thread with a 1-in. pitch, 3/4 in. deep by 1/2 in. wide, to carry the cooling water. After the steel tubing was tinned, it was wound into its grooves and the inner and outer copper cylinders were pressed onto the machined cylinder. The entire unit was then heated to the melting point of solder and the interstices between copper and steel tubing filled with solder. This design provides for about 1/2 in. of copper wall between water and mercury tubing. The overall size of each exchanger is 14 in. diameter by 12 in. high. The mercury path is 31 ft, providing a total surface of 7.16 ft^2 (6.7×10^3 cm^2). The water path is 24 ft long with a surface of 4.55 ft^2 (4.2×10^3 cm^2).

The two heat exchangers are operated in series with the electromagnetic mercury pump between them. The cooling water flows in the opposite directions to the mercury for maximum cooling.

1.4.4 Pump and Blower

The mercury is circulated by an eddy-current pump, selected because it meets the stringent requirements of no moving parts in the mercury stream and no packing glands. Another form of electromagnetic pump considered was the high-amperage direct-current magnetic-field type used elsewhere to pump liquid metals. The performance of this latter type, however, proved to be very sensitive to surface conditions of the pipe when used with mercury. The eddy-current pump in use is relatively inefficient but has proved stable in operation over a long test period.

The eddy-current pump as designed for the Fast Reactor mercury system uses a 5 hp (220/440 volt) three-phase stator of conventional type modified only in that the windings are insulated with silicone bonded glass.

This stator surrounds a thin cylindrical shell of mercury-contained stainless steel. The inner cavity of this cylinder is filled with washer-like laminations of transformer steel, stacked on a steel pipe that serves as the mercury inlet tube. The rotating magnetic field from the three-phase stator induces a current in the mercury and forces the mercury to follow the magnetic field. The pumping action is derived by continuing the mercury chamber into a bell-shaped space for expansion and discharge through a tangential tube. Since the rotating forces are set up in the mercury itself, the mercury system could be made entirely of welded metal. The pump is so constructed that the stator can be removed by slipping it off the core assembly. Figure 29 is a drawing of the pump. Figure 30 is a photograph of the parts.

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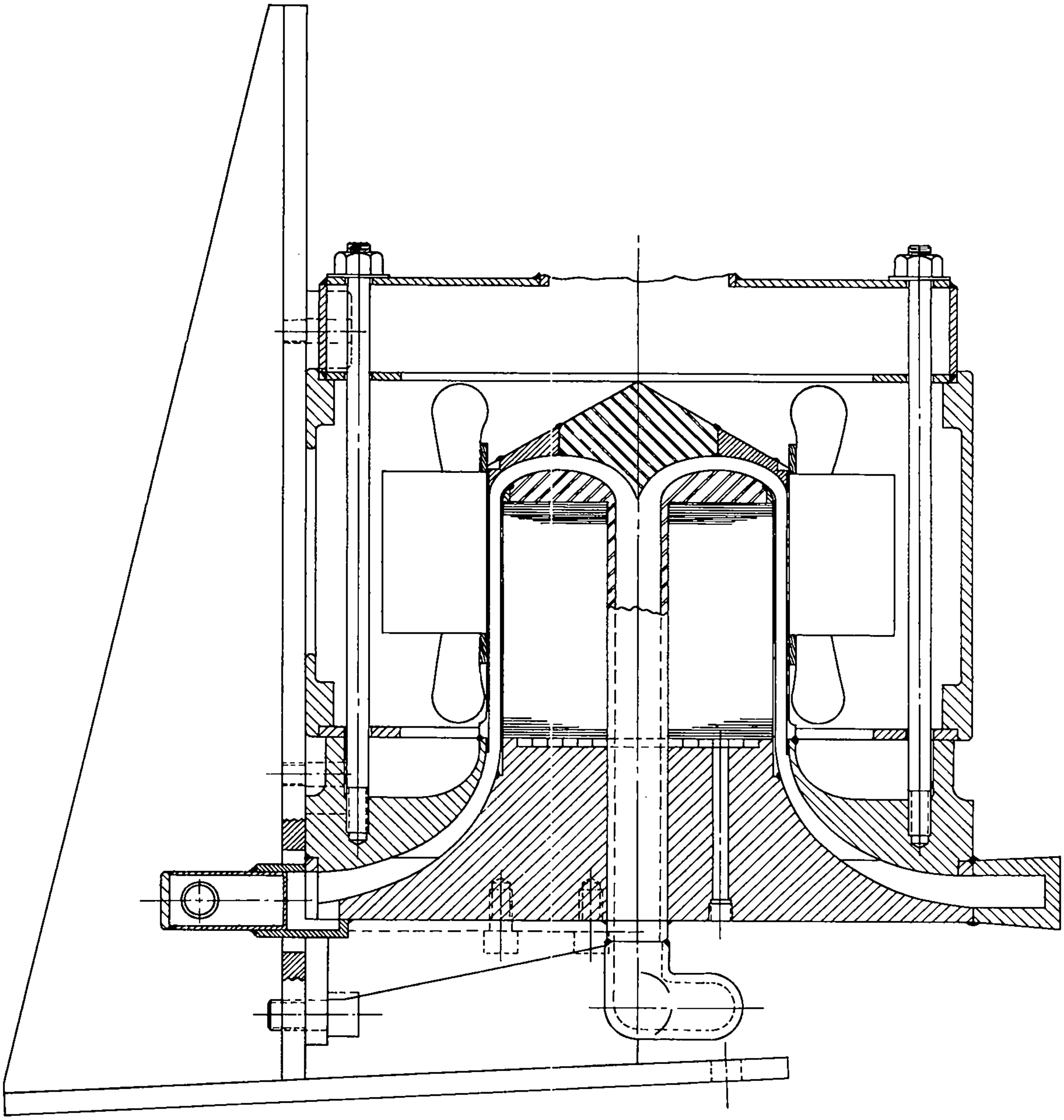

Fig. 29. Diagram of the mercury pump.

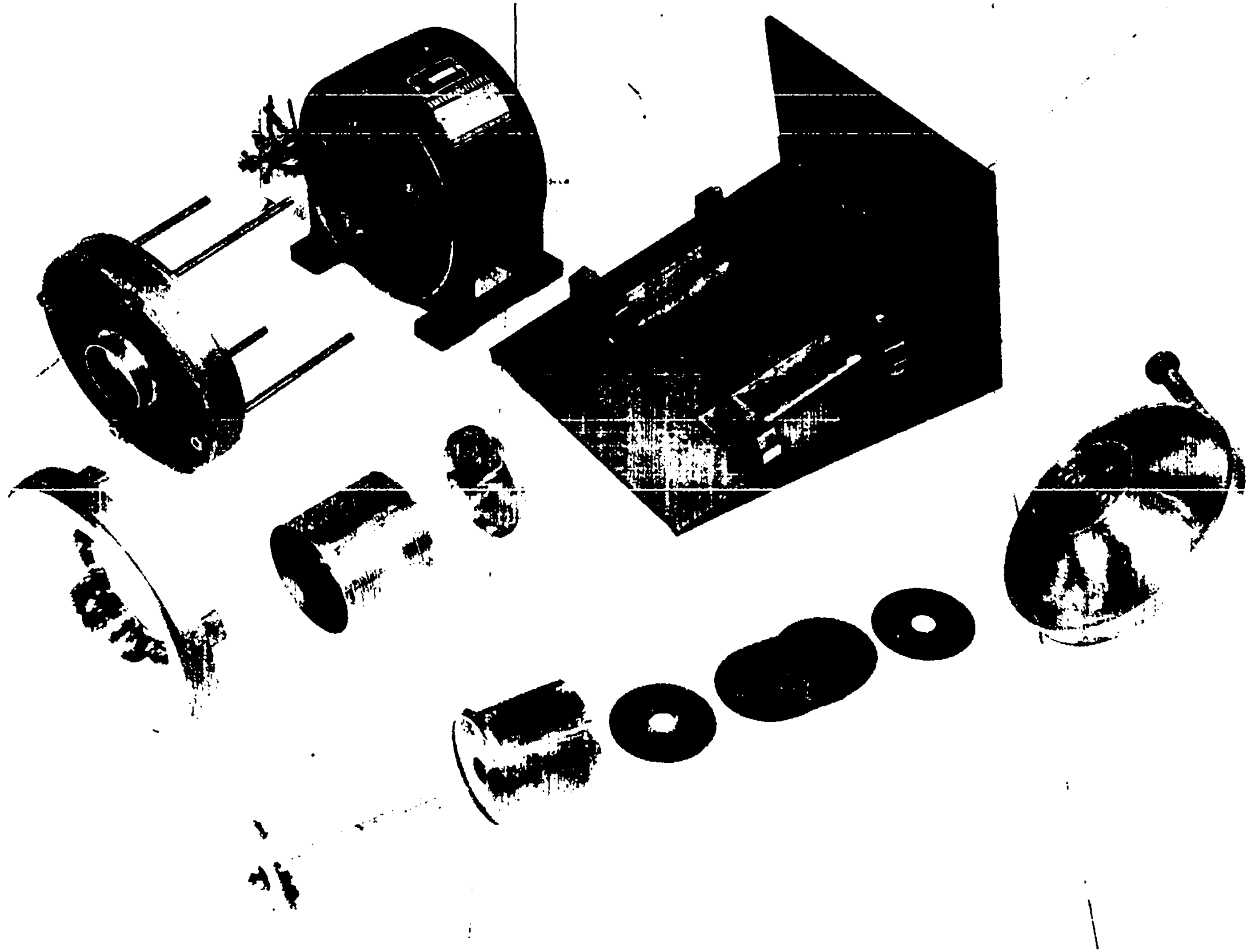

Fig. 30. Photograph of the mercury pump components.

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Cooling air for the pump stator is supplied by an electric blower mounted in a silencing box on the outside of the reactor. The power to the pump is interlocked with the blower to prevent accidental overheating of the stator windings. The temperature of the stator windings should not exceed 125°C for continuous operation.

Satisfactory operation of the circulating system is obtained with a pump current of about 11 amp per phase. This results in a mercury flow of 9.1 liters per minute at a total pressure drop of about 40 cm Hg. The efficiency of the pump under these conditions is 2 per cent, the principal loss being approximately 2.5-kw heat supplied to the mercury by the heating effects of the eddy-currents. This heating is approximately 10 per cent of that from the reactor proper and is removed by the second heat exchanger.

1.4.5 Flowmeter

Requirements. It was decided to use a venturi tube to measure the mercury flow since it would offer low resistance, have a stable calibration, and could easily be welded into the system. For operational convenience it is desirable to telemeter the venturi pressure differential to the control panel. Commercially available pneumatic pressure transmitting equipment (Moore Company of Philadelphia) proved satisfactory. The equipment most suitable had a pressure range of 0 to 2 psi.

For design purposes, the normal flow of the mercury was estimated at six liters per minute from power requirements and pump and heat exchanger performance. The venturi tube was designed to produce 0.8 lb pressure drop for this flow at a temperature of 20°C.

Design. The venturi was designed from the principles contained in the ASME Fluid Meter Report and the dimensions calculated from the formulas given.

Starting with Bernoulli's equation,

$$Z_1 + \frac{P_1}{W_1} + \frac{V_1^2 r_1^2}{2g} = Z_2 + \frac{P_2}{W_2} + \frac{V_2^2 r_2^2}{2g},$$

where

Z = elevation head in ft

P/W = pressure head

$V^2/2g$ = velocity head

r = tube radius

P is in lb/in.^{2}

W, the specific weight, is in lb/ft^3

V is the velocity of ft/sec. and

g is the acceleration of gravity

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The theoretical volume rate of flow through a restriction is

$$Q_t = a_2 \left[\frac{2gh}{1 - \beta^4} \right]^{1/2}$$

where

h = head loss

$\beta = r_1/r_2$ = ratio of the reduced diameter to the tube diameter

a_2 = cross sectional area of the constriction.

Including a friction factor C,

$$Q_c = CQ_t$$

which can be determined experimentally. For venturi tubes at high Reynolds number, then, with

$C = \sim 0.98$

$Q = 6$ liters per minute

$p = 0.8$ lb

$d_1 = 0.870$ in.

the equation was solved for d_2, the venturi throat diameter:

$d_2 = 0.462$ in.

The other dimensions, from ASME specifications, are upstream cone 21° total angle, downstream cone 6°, and throat length approximately equal to its diameter of 1/2 in.

Construction and Mounting. The venturi was bored and turned from a plain steel bar. The final angle on the cones was obtained by lapping. Polishing of the throat and cones was done with emery cloth held in a small slotted dural bar, spun with an electric drill. The throat diameter was left at 0.460 in. instead of 0.462 in., as the results were close enough for the Moore equipment.

The tap holes are 1/8 in. in diameter with a 1/32-in. radius cut on the inside edge to avoid burrs. The upstream tap is located 1 in. from the start of the cone, and the low pressure tap in the middle of the throat. Connections were made to the taps by welding 1/4-in. steel tubing over the holes.

Connection of the venturi to the pipe system by welding is strong and leak proof. The

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end sections of the venturi were made about 0.002 in. larger than the internal diameter of the tubing selected to slide over them. The tubing was then bored for a close-press fit, the end of the bore-cut forming a shoulder to meet the venturi, thus minimizing flow disturbance. Welding was done under helium gas to preserve the finish on the throat and cones. The ends of the tubing and the shoulder of the venturi were beveled to take the weld and presented no problem in welding. Figure 31 is a drawing of the venturi tube.

Calibration. Calibration consisted of determining the value of the discharge coefficient, C, for various Reynolds numbers. Since $C = Q_t/Q_c$, it was determined by measuring the flow under stable conditions of head-loss across the venturi. Water was used for the calibration since mercury is difficult to handle and the calibration is theoretically transferable to other fluids. Stable flow was obtained from a "constant head" water supply, consisting of two 55-gallon tanks elevated 24 ft, supplied through float valves, and controlled with a gate valve.

The head-loss across the venturi was measured with a 1/4-in. glass tube and scale manometer. Volume rate of flow was measured by observing the time required to fill known volumes. Temperatures were measured with a mercury thermometer. The constants of the venturi give the following equations.

$$Q_t = 49.4\ (\Delta h)^{1/2} = 112.6\ (\Delta p)^{1/2}\ \mathrm{cm}^3/\mathrm{sec},$$

$$Re = 1.09\ \frac{Q\rho}{\mu},$$

in which ρ is the density of the fluid in g/cm^3 and μ is the absolute viscosity in poises.

Values of the discharge coefficient and percentage of pressure-drop regained in the discharge cone were determined with water for several different Reynolds numbers as a preliminary calibration. The final calibration was done with a thin plate orifice meter in the actual mercury circuit, in series with the venturi, and using the Moore air equipment. The orifice meter was calibrated with water to ±1/2 per cent as described above. The venturi discharge coefficient data scattered ±1.5 per cent, probably because of temperature drift in the transmitters, friction, and slack in the pressure gauges. This accuracy is thought to be sufficient.

The head regained in the discharge cone was about 85 per cent when the venturi was first checked on water. Subsequently, using mercury it was found to be about 70 per cent; the reduction was probably caused by roughness from rust, pickling, and welding.

The graph in Fig. 32 shows the variation of discharge coefficient with Reynolds number.

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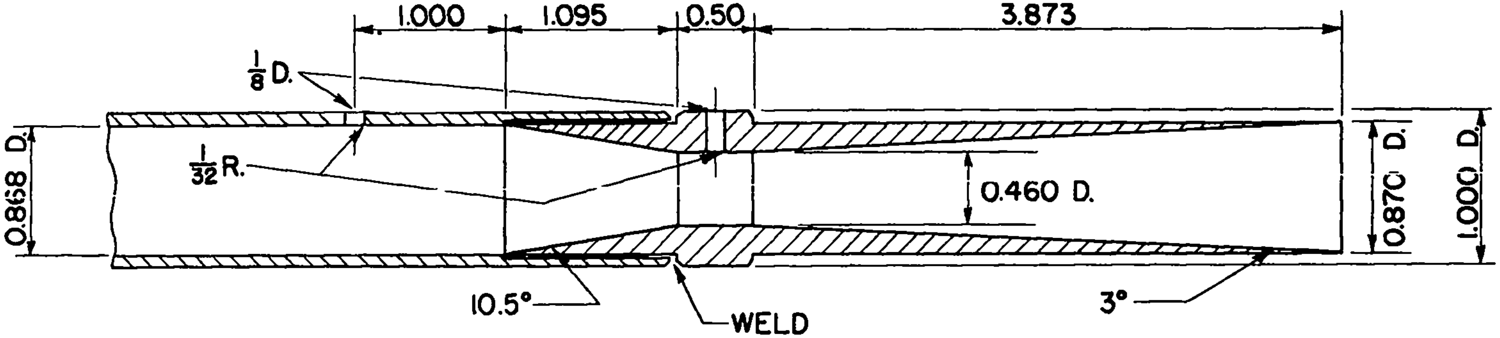

Fig. 31. Mercury flow venturi.

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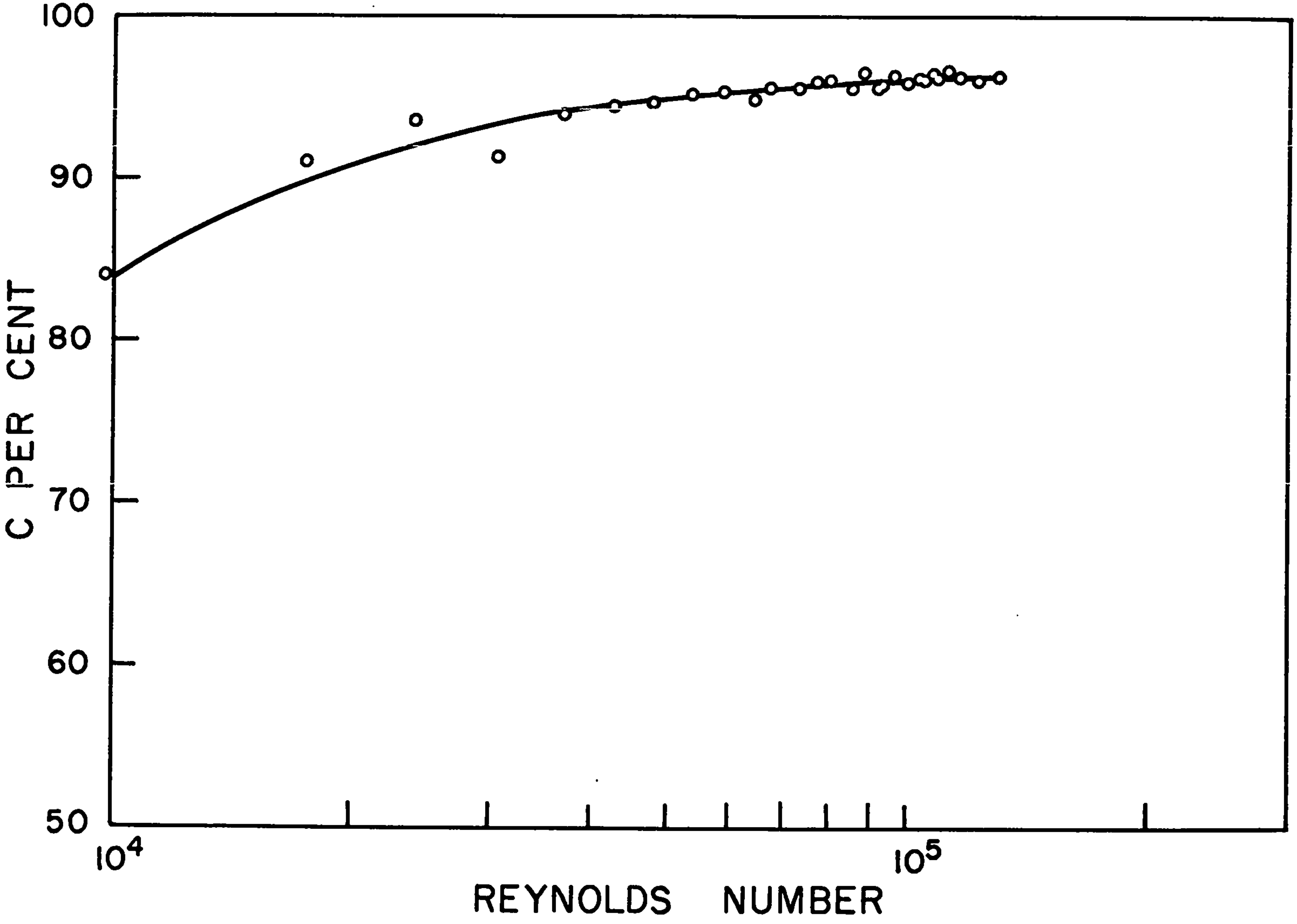

Fig. 32. Venturi calibration.

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The normal operating range is above 6 liters per minute flow, or Reynolds numbers above 100,000, where the curve is nearly flat and the points scatter less than 1.0 per cent.

The temperature of the mercury through the venturi is normally between 20 and 30°C. A check calculation at 20°C and at 50°C showed insignificant variations in calibration. Therefore a calibration scale was made to mount on the Moore pressure gauge, indicating the drop through the venturi, using the relation,

$$Q = 6.75\ C\ (\Delta p)^{1/2} \text{ liters per minute,}$$

or

$$\Delta p = 0.0219\ Q^2/C^2,\ \text{lb/in.}^2$$

where Q was given values in half-liter steps between 0 and 10 liters per minute, and C determined from curves of Reynolds number vs flow and C vs Reynolds number.

It was interesting to note that the actual performance of the venturi was very close to its design specifications. A flow of 6 liters per minute produced a pressure drop of 0.85 lbs/in.^{2} with a throat diameter of 0.460 in.

1.4.6 Auxiliary Equipment

Dump Valve. The dump valve separates the mercury circulating system from the sump tank and, when opened, allows the mercury to drain out of the circulating system and into the sump tank where it is behind extra gamma-ray shielding. This allows the circulating system to be worked on without unnecessary exposure to radiation. It also allows parts of the circulating system to be opened, or removed, without loss of mercury. The valve is about 15-1/2 in. high and has a maximum diameter of 6 in. It has about the same rating as that of a conventional 1/2-in. ips globe valve. The sylphon bellows and the parts welded thereto are of stainless steel. To ensure a good seal at the plunger, it was necessary to make the valve seat out of teflon. The valve is held closed by a spring and is opened by a pneumatic operator which is a slightly modified commercial unit manufactured by the Foxboro Company.

Sump Tank. The sump tank serves as a separately shielded reservoir that can contain all of the mercury in the circulating system should some work on the system require that the mercury be drained. The mercury can be returned to the circulating system by blowing it out of the sump tank by means of helium pressure. The mercury in the sump tank can be drained out of a valve at the lowest point. The sump tank is made of the same size tubing as used for the supply tank and is of the same general type of construction except that it is considerably longer. This gives it a volume of about 18.7 liters as compared to the 6.8 for the supply tank. The tank has a screen across the bottom and a set of three level-indicating electrodes like those for the supply tank. Approximately 1 liter of mercury is contained

[redacted]

between the two lower electrodes. The sump tank, being in a lower corner of the cabinet, has only two sides and the top that are exposed and need shielding. The two sides (front and right) are shielded with steel-encased lead doors that have about 3 in. of lead and 1/4 in. of steel. The common joint is staggered and so is the joint between the side and top shields. The top shield is made of two 1-in. plates of lead that can be slipped into position separately. The drain valve handle extends through the shield as does the discharge line.

Drip Pans. Three steel pans extend across the cabinet near the top, middle, and bottom. These pans serve to catch any mercury or water that might leak above them, and have electrodes that give an indication on the instrument panel in the control room whenever any water or mercury collects in the pans. The two higher drip pans, which would not satisfactorily hold all of the mercury in the system, are connected to the lower pan which has a large volume.

Mercury Sampling Valve. It is desirable to make periodic checks of the mercury in order to detect corrosion or break-through of the steel system. A 1/8-in. stainless-steel needle valve is located on the mercury pipe leading from the pump to the second head exchanger. Samples of mercury can be withdrawn by this valve through the concrete shield by removing a shield plug and sliding a container in on a guide track.

Helium Pressure. Helium pressure of 50 psi is maintained on the supply tank and on the sump tank. This helium is delivered from tanks on the wall of the room to a set of manifold valves at the top of the mercury panel. By proper selection of valves the mercury may be forced from the sump tank into the system by helium pressure. In normal operation the sump tank and supply tanks are connected together to the helium source. The presence of the helium pressure provides an inert atmosphere over the mercury, a static pressure to the closed system, and a method for moving the mercury volume from the sump tank to the system.

1. 5 Water Supply System

Four to five gallons per minute of water are required to cool the reactor. The water supply must meet the following requirements:

1. Pressure must be constant to 10 per cent and not exceed 60 psi. The 1/4-in.-OD aluminum tubes cooling the tamper are inaccessible for servicing, and leaks in this area would be dangerous. Therefore a high pressure limit is necessary.

2. The water must be free from particles which might clog the system. The reflector cooling tubes have an inner diameter of 1/8 in. with many 90° bends, and even small particles of rust, lime, and sediment could stop the line. The heat exchanger tubing is less

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subject to stoppage, having an inner diameter of 0.687 in.

3. The temperature of the water should be below 30°C and preferably below 20°C. It is desirable to operate the water below boiling, and hence with a lower input temperature more power can be dissipated.

Water for the reactor is supplied from the municipal system through a 4-in. pipe at a pressure of 200 psi. The high pressure results from the Omega location in a canyon about 300 to 400 feet below the town level.

This pressure is too high for safe operation; consequently high quality reducing valves (Mueller 4-in. and 2-in. and a Mason-Neilan 3/4-in.) and over-pressure relief valves are used (see water system flowsheet, Fig. 33). Before entering the Omega Site buildings the water passes through a strainer, the pressure is reduced to 80 psi, and the pipe size reduced from 4 to 2 in. An automatic relief valve of large capacity set at 100 psi is located about 200 ft from the first reducer and inside the utility basement. The pressure is reduced from 80 to 45 psi in the basement. A second relief valve, set at 60 psi is in the 45 psi section. From the basement a 3/4-in. pipe carries the water about 100 ft to the reactor control room. Here the water is strained and the pressure reduced to 25 psi before entering two filters. Strainers precede the reducing valves to protect them from sediment in the valve seats, which causes them to "creep."

Even with this system of reducers the flow fluctuates about 20 per cent, since other utilities precede the reactor on the line. (An independent supply from the 2-in. 80-psi main was installed later.)

Two filters connected in parallel precede the flow meters and control valves. These use a fine mesh screen and paper filter to remove particles such as clay and rust. The filters, each of 10 gallon per minute capacity, are commercially available from the Filtrine Company, Brooklyn, N. Y. In spite of the capacity rating of four to five times the normal flow, it is necessary to change the filter paper about twice a week. Sediment on the paper restricts the flow below usable limits. Pressure gauges across the filters give an early indication of this; thus the paper can be changed when convenient during the next 3 or 4 hr, and, if necessary, one filter at a time without shutting off the water.

The present piping from the filters to the reactor is 3/4-in. galvanized iron. A fine-mesh strainer placed just before the tamper and exchangers is used to prevent lime or rust flakes from entering the tubing. (Copper water-service tubing was installed later to avoid the scale formation.)

A flow-control valve for each line is located on the control panel within reach of the operator. Two rotameters, one for the heat exchangers, one for the reflector cooling plates, are on the panel in view of the operator so that flow can be set as desired.

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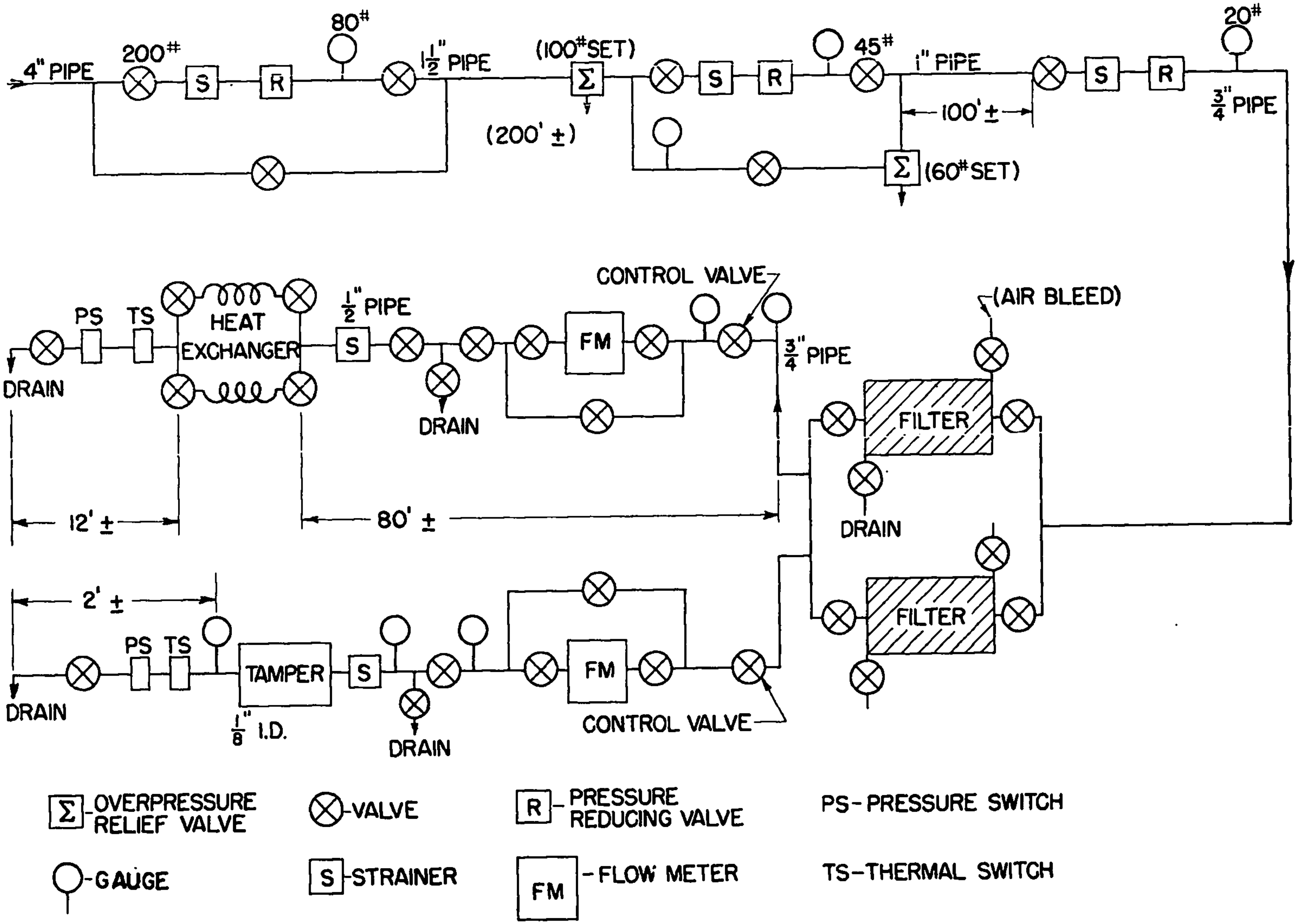

Fig. 33. Flowsheet for the water cooling system.

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On each line pressure gauges in the operator's view permit easier flow settings because of their rapid response and allow occasional checks on the pressure conditions.

Pressure and thermal switches are installed in the lines leaving the heat exchangers and the reflector to operate an over-temperature and no-flow alarm.

The heat-exchanger water and reflector water drain into a 4-in. pipe which discharges into the wash near the reactor building.

1.6 Helium Supply System

A flow of 0.3 cfm of 99.8 per cent pure dry helium is circulated around the safety block, through the reflector, around the control rods, through the control housing, and exhausted above the roof. It serves two purposes: removal of possible free fission fragments, and protection of the unplated uranium block and reflector from corrosion.

Four 220-cu ft capacity steel helium bottles are secured in a wall rack and connected to a manifold serving the helium line. The manifold is designed to meet the following requirements:

1. To furnish at least a week's supply.
2. To permit the change of empty bottles while operating from other bottles.
3. To have pressure regulators arranged so that one may be replaced while operating from the others.

Figure 34 shows the manifold equipment and arrangement used. Pressure reducing valves (Model VTS-87, Victor Welding Equipment Co., San Francisco, California) are connected directly to the bottles, reducing the pressure from a maximum of 2500 psi for a full bottle to about 7 to 10 psi. The reducers are placed immediately after the bottles to avoid high pressure on the manifold and its fittings. Spring-loaded relief valves on the low pressure side of the reducers protect the system from overpressure. Two-turn "pigtails" of 5/16-in. copper tubing connect the reducers to four 5/16-in. Kerotest sylphon valves which are attached to a "header" of 1/4-in. brass pipe. A tee in the center of the header leads to the flow control valve, a 1/4-in. Hoke, sylphon, needle valve, which is connected by a flare fitting to 1/4-in. copper tubing.

In operation, the output pressure of each reducing valve is set at a slightly different value from the others, for instance, 7, 8, 9, 10 psi. This results in the gas being used through the reducer with the highest setting until the pressure of that bottle falls below the pressure setting of the next lower reducer, and thus bottles are used successively. Empty bottles can be replaced, while operating from others, by closing the appropriate valve leading to the header and disconnecting the reducer from the bottle, the 5/16-in. pigtail being strong enough to support the reducer during the change.

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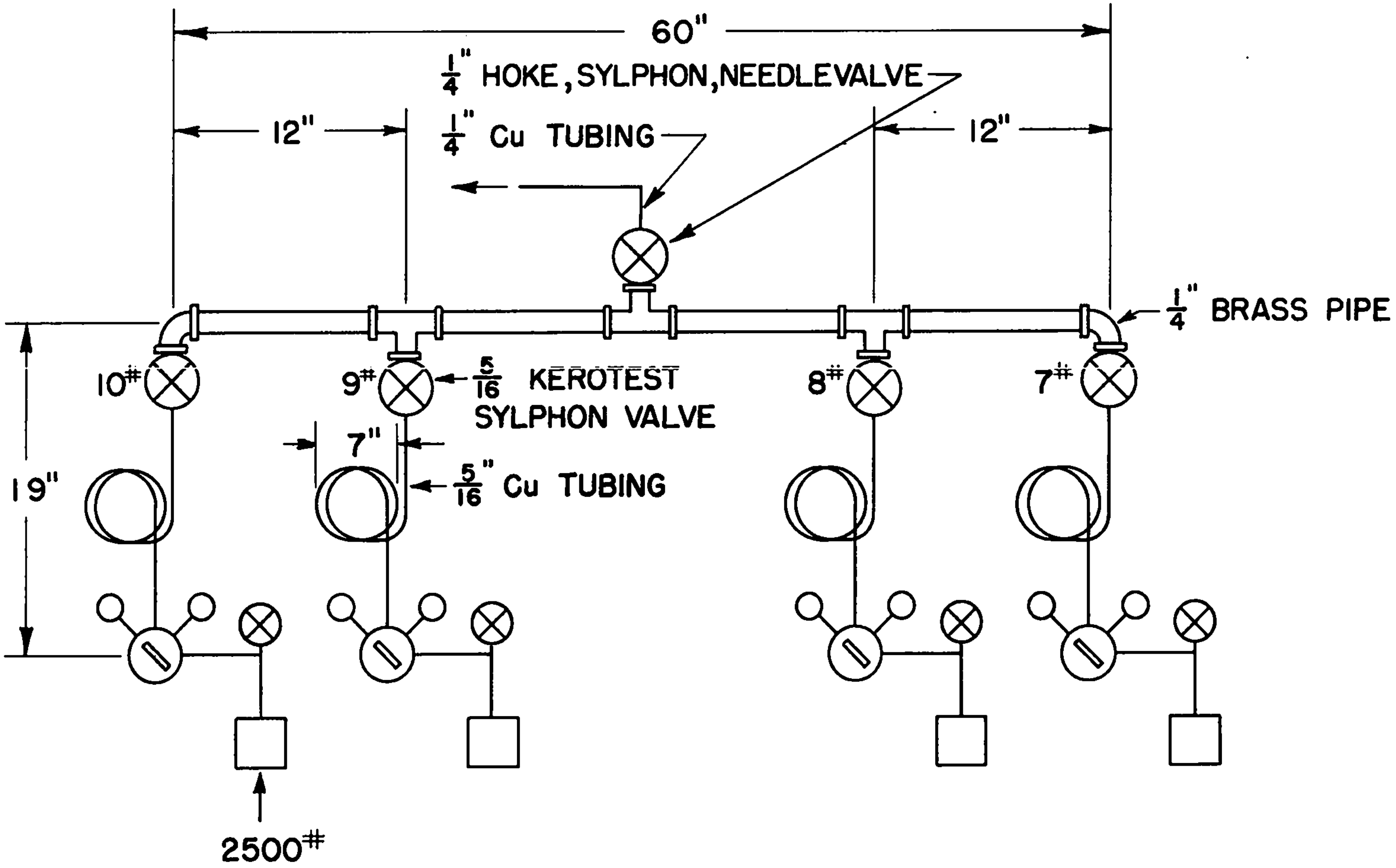

Fig. 34. Helium supply manifold.

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The flow of helium is measured with a rotameter connected in the line following the control valve; it is a Fischer Porter Company Flowrator Meter Alarm, inductance type, range 0.1 to 1.0 cfm. It operates a high-low flow alarm light on the reactor control panel, being sensitive to 0.1 cfm change about the normal operating flow of 0.3 cfm. Figure 35 shows the flowrator alarm circuit.

Following the flowrator is a liquid nitrogen trap to remove water vapor and hydrocarbons from the helium. The trap consists of a Pyrex thimble with a centrally located stainless-steel tube fastened to a lucite disk. The thimble is submerged in liquid nitrogen contained in a 4-liter Dewar flask, the lucite disk being a removable lid. Helium flows down the stainless-steel tube and up along the inner wall of the glass tube. Connections are made with 1/4-in. flare fittings. Atmospheric water vapor condenses on the top of the trap and on the exit tube. To avoid water deterioration, lucite is used for the lid and the metal fittings are of stainless steel. The Dewar is filled through a 1-in. hole drilled in the lucite, closed with a lucite stopper. Compressed air is used to transfer liquid nitrogen directly from the shipping containers to the Dewar. The trap uses about 3 liters of nitrogen in 24 hr (8 hr of operation and 16 hr without gas passage), and thus one filling a day is sufficient. Two traps are connected in parallel so that one may be removed while operating with the other. Figure 36 is a drawing of the trap.

It has been found in the Laboratory what water vapor in a helium atmosphere reacts with uranium above 50°C more rapidly than in air. Analysis of the helium from four different cylinders (Bureau of Mines 99.8 per cent pure) showed water vapor and hydrocarbons in appreciable amounts. A chemical analysis of one bottle gave 9 mg water per cubic foot of air, which consumed about half a uranium cylinder, 5-1/2 x 0.687 in., being heat-cycled between 30° to 250°C twice an hour for 3 weeks. Other bottles have been tested by passing the helium through a liquid air trap and weighing the condensate, giving 1.5 mg per cubic foot and 0.2 g per cubic foot. The reflector, and probably the safety block, operate at approximately 100°C; thus drying of the helium is indicated.

As a further precaution and indication of the condition of the unplated safety block, the helium is passed over a heated unplated uranium rod, after leaving the trap and before entering the reactor. The rod is mounted on a Lavite stand inside a Pyrex bell jar, which is clamped to a brass plate and sealed there with a synthetic rubber O-ring. A nichrome heating element of no. 28 wire threaded through a two-hole porcelain insulating rod 1/4 in. in diameter and 4 in. long is inserted in the uranium rod, leaving the rod in view. A current of 6 amp, 6 V alternating current, heats the rod to 175°C, which is measured with an I/C thermocouple and a millivoltmeter pyrometer. Electrical leads are carried through the

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brass plate with Kovar-glass seals. The rod is heated when the reactor operates. Connection between the bell jar and the copper tubing is made with a "housekeeper seal," the copper end of the seal being a standard 5/16-in. flare size.

Figure 37 is a schematic drawing of the complete helium supply and flow system.

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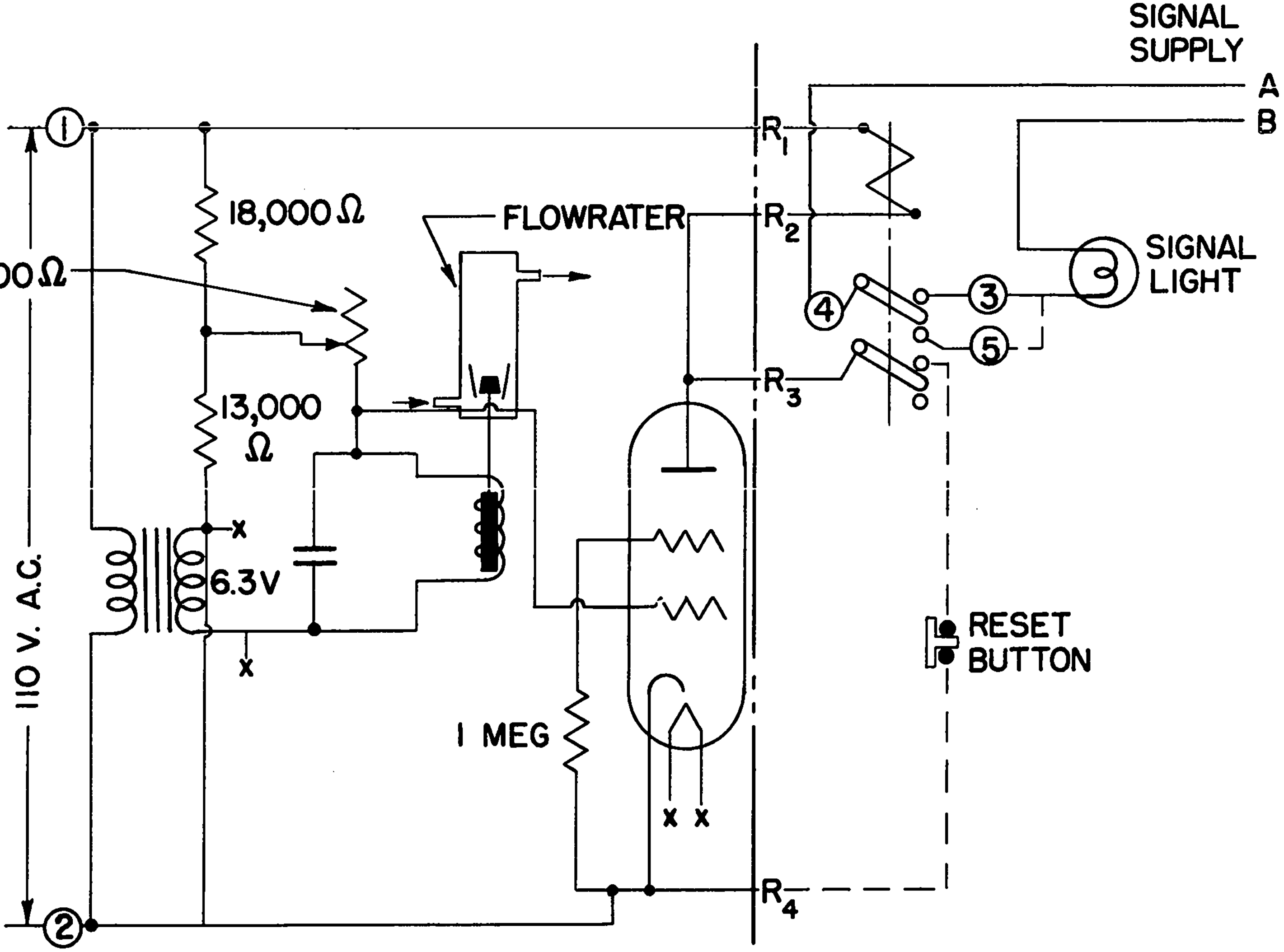

Fig. 35. Flowrator alarm circuit.

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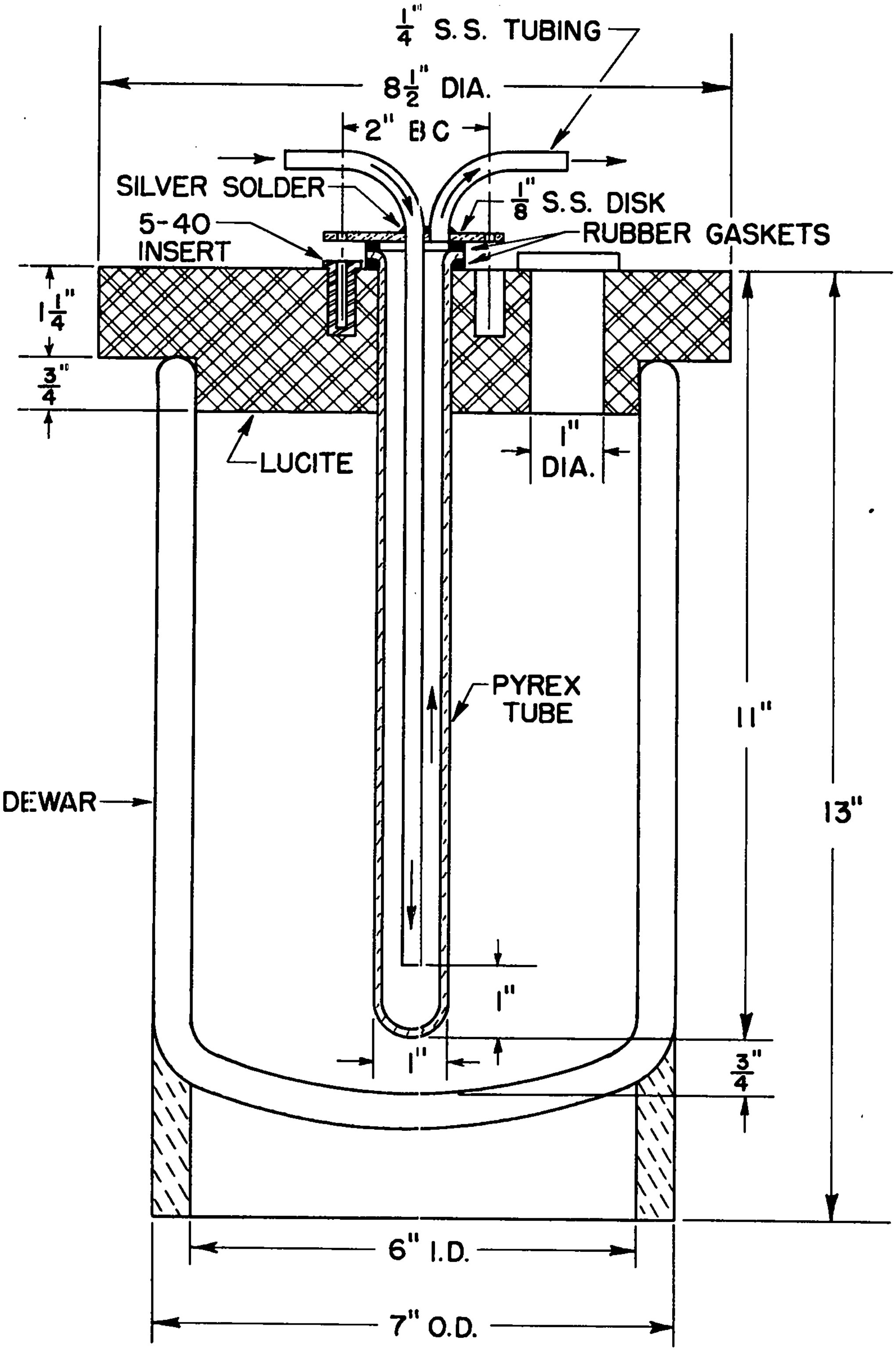

Fig. 36. Helium cold trap.

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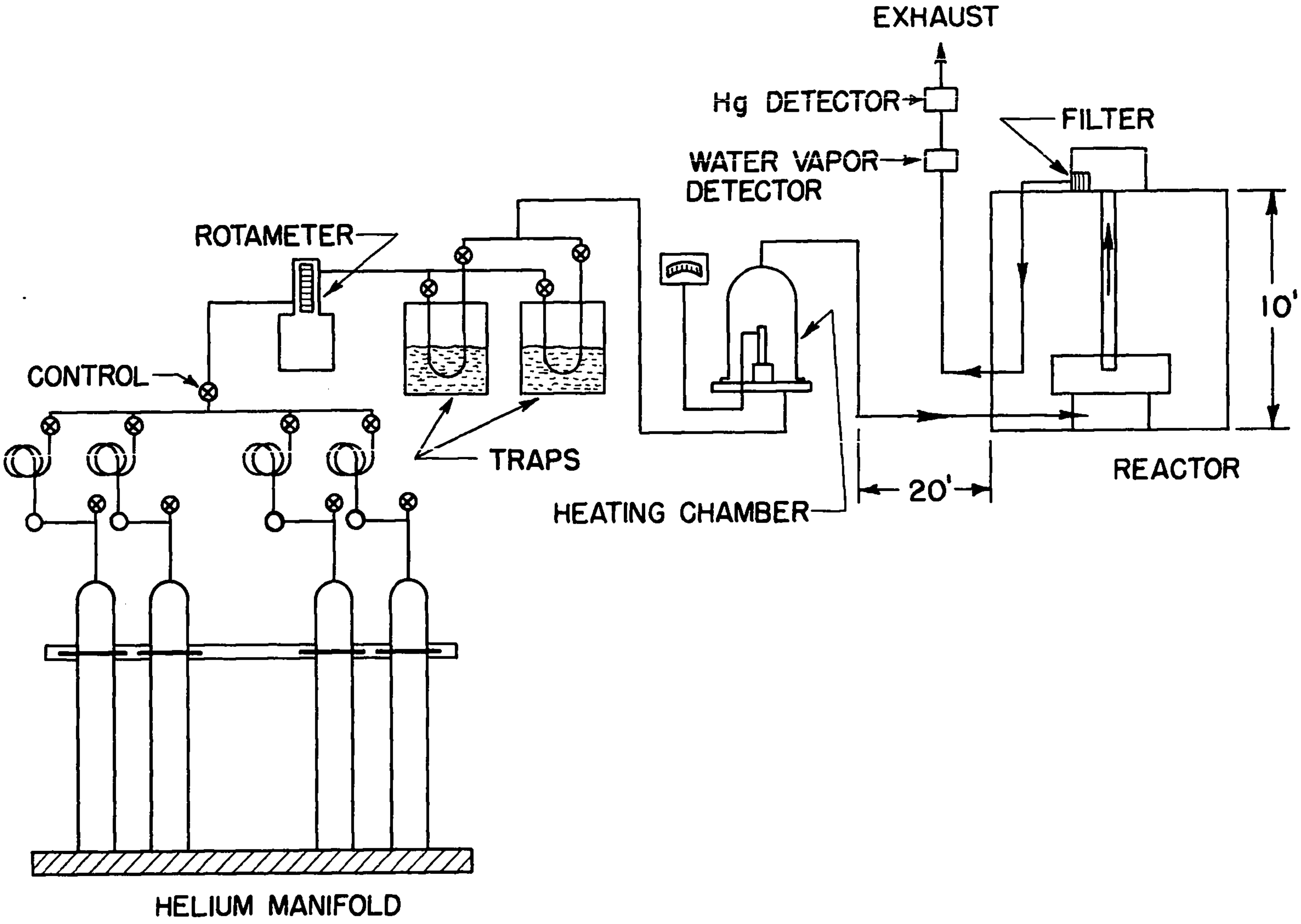

Fig. 37. Helium system.

Chapter 2

CONTROL AND SAFETY MECHANISMS

2.1 Principles of Reactor Control

The principles of control of a chain reacting system have been adequately described in other writings, but a few general remarks are in order here.

An assembly of fissionable material is said to be critical in a given geometry when the fission process sustains itself without contribution from neutrons arising from nonfission sources. This is conventionally defined as stating the reproduction factor, k, to be unity, or excess reactivity, $\delta k = (k-1)$, to be zero. The quantity k is here understood to be the ratio of neutrons produced to neutrons lost by all captures or escapes, and is a measure of the quality termed "reactivity." For values of $k>1$, the neutron population will increase exponentially, without limit; for $k<1$ the population will be stable at a value proportional to $s/1-k$ where s is the number of neutrons per second arising from the source (spontaneous fission in the fuel rods).

The neutron growth may be controlled by varying k in any of a number of methods. The conventional method used in existing thermal reactors is to vary the number of nonproductive absorptions occurring in the system by the introduction of poisons such as cadmium or boron. In the Fast Reactor, control is achieved principally by variation of the neutron leakage from the system by moving portions of the neutron reflecting blanket. This, then, may be described as positive control, since reactivity is added to bring the system to a critical condition, as opposed to the negative method of removing poison control rods of the conventional system. This leakage form of control is desirable in the case of the Fast Reactor since at the neutron energies utilized in the reactor, there are no large absorption cross sections such as exist at thermal energies. In fact, under the operating conditions of the Fast Reactor, B^{10} has one of the few absorption cross sections large enough to act as a poison in the region of the reflector. This fact was utilized in increasing the effectiveness of the shim rods which will be described in this chapter.

In measuring reactivity changes it has been convenient to adopt a unit arbitrarily termed a "dollar," with subdivisions of "cents." This unit is based on the expression (sometimes called the "in-hour formula") relating reactor behavior to reactivity changes.

$$\delta k = \frac{(1 - \gamma f)t_p}{T + t_p} + \gamma f \sum_i \frac{a_i \ t_i}{T + t_i}$$

[redacted]

where

t_p = mean life of prompt neutrons
t_i = mean life of delayed neutrons of group i
a_i = relative abundance of neutrons of group i
T = period of neutron growth in reactor
f = total fraction of neutrons which are delayed
γ = factor to measure the greater effectiveness of delayed neutrons relative to prompt neutrons in producing fission in the assembly

For practical purposes of control, the first term can be neglected if the reactor period is greater than 1 sec. The expression can then be written

$$\frac{\delta k}{\gamma f} = \sum_i \frac{a_i \, t_i}{T + t_i}$$

By definition, then, the excess reactivity which is equal to the effective fraction of delayed neutrons is 1 dollar, or reactivity in cents = 100 $\frac{\delta k}{\gamma f}$. The fractions in each class of delayed neutrons and the corresponding decay periods are measured by separate experiments and this expression enables a simple conversion of reactor periods, T, into reactivity units of cents.

This unit has the feature of being essentially independent of the type reactor or fuel used. One dollar above critical represents the point at which mechanical safety controls are not adequate to stop the reaction.

Operation of a reactor in starting, then, involves the addition of reactivity until an excess of 20 to 30 cents is reached. Under these conditions the neutron level will increase exponentially until the excess reactivity is removed either by motion of the control elements or by heating effects in the active region. In the Fast Reactor, the control elements are, in the order of addition:

1. Safety block. A large block of uranium reflector immediately below the active region.
2. Shim rods. Two rods made of half uranium and half B^{10}. B^{10} poison is removed and replaced by uranium.
3. Control rods. Two light weight uranium rods which are continuously and accurately positioned.

Shutdown operation involves the dropping, by free fall, of the safety block and shim rods, which causes the neutron intensity to fall abruptly to about 10 per cent of the steady state, and to decay in a few minutes to background levels.

The basic principles of the Fast Reactor safety-control system are similar to those of other existing reactors in these respects:

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1. The fundamental force for motion of the control elements is gravity.
2. Electrical power is used to constrain the control elements against motion, so that the controls will shut down in the event of the failure of a power main.
3. Multiplicity of control elements and control circuits insures against any chance failure of one of the elements.

The following sections will describe in detail the control mechanisms, safety circuits, and monitors which are incorporated in the operation of the Fast Reactor.

2.2 Control Mechanisms and Circuits

2.2.1 Safety Block

The safety block is a mass of normal uranium roughly the shape of a cone frustrum (Fig. 14) with a base diameter of 6-3/4 in., a top diameter of 4-1/4 in., a height of 4 in., and a weight of 32.7 kg. In its full-up (most reactive) position, the top surface of the block is 1/4 in. from the bottom of the pot; in its down (least reactive) position, this same face is 3-1/4 in. from the bottom of the pot. Threaded into the bottom of the block is a 1-1/4-in.-diameter hardened steel actuating shaft, guided by a splined steel bearing. Splining of the shaft allows relief between the shaft and its bearing, thereby preventing possible binding from an accumulation of dirt or other foreign matter.

The safety block is actuated by a 1/4-hp electric motor driving a rack and pinion through a 1760:1 gear reductor and a magnetic clutch. The magnetic clutch consists of two discs, with the facing clutch surfaces perpendicular to the drive shaft, as seen in Fig. 38. Power to the 230-V d-c winding of the clutch is supplied by a full-wave mercury-vapor rectifier and reaches the winding via two slip rings on the driving part of the clutch.

The bottom of the actuating shaft threaded into the safety block rests on, but is not attached to, the top of the rack. A "scram" signal from the reactor disengages the clutch by removing the d-c voltage to its winding; spring loading of the rack enables it to be pulled down rapidly when the clutch is disengaged, and, accordingly, free fall of the safety block is accomplished. A pneumatic dashpot acts, at about 1 in. from the bottom of its travel, to cushion the stopping of the rack and with it the safety block.

2.2.2 Shim Rods

The two shim rods are removed vertically in the reflector, near the fuel assembly, to produce a differential change in reactivity. The upper half of each rod contains B^{10}, the lower half is filled with normal uranium, and the separate sections are sealed together into a welded steel can. As seen in Fig. 39, each can is fitted at the top with a clevis joint into which is threaded a 1/2-in. steel rod.

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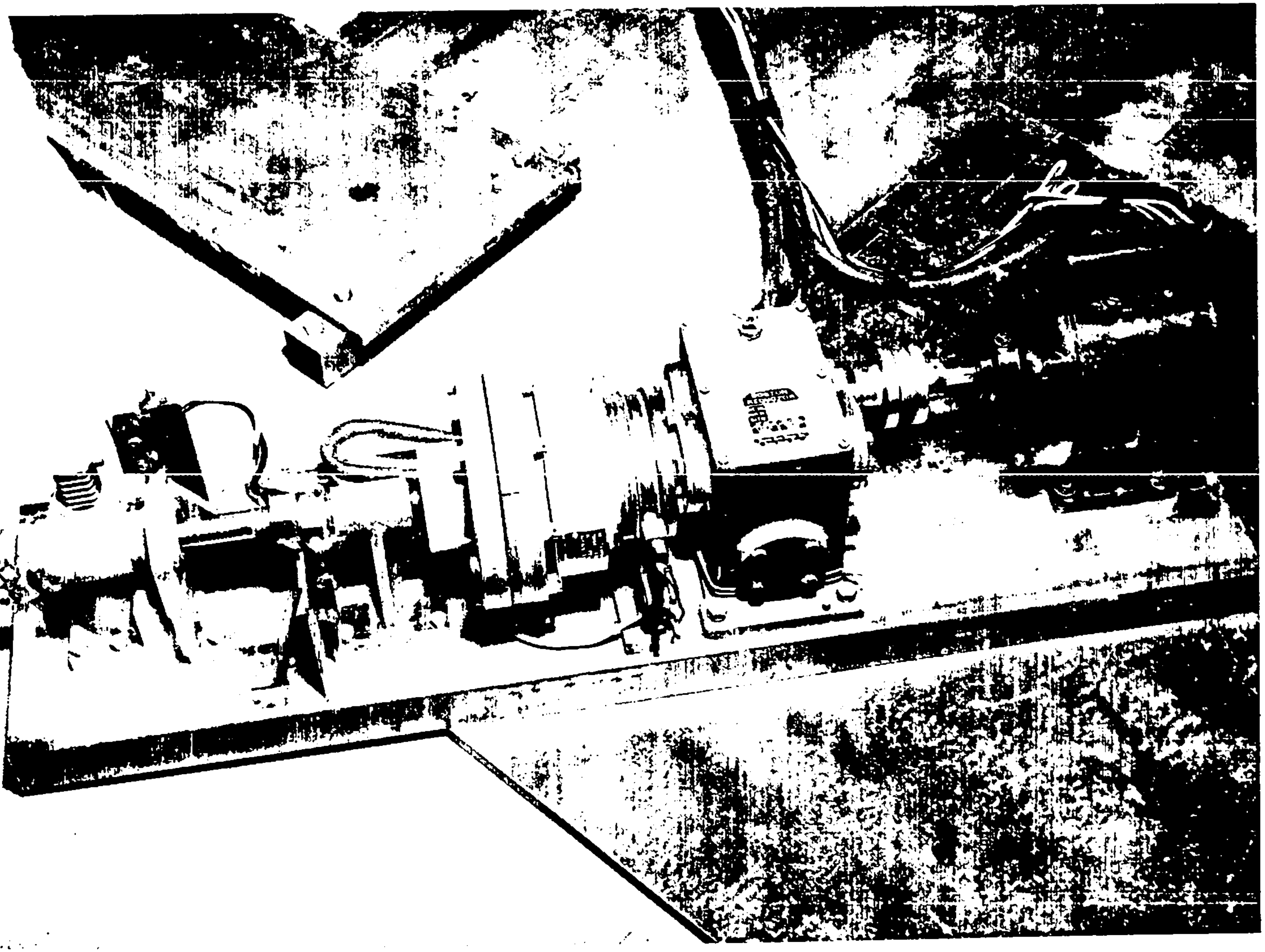

Fig. 38. Safety block actuating mechanism.

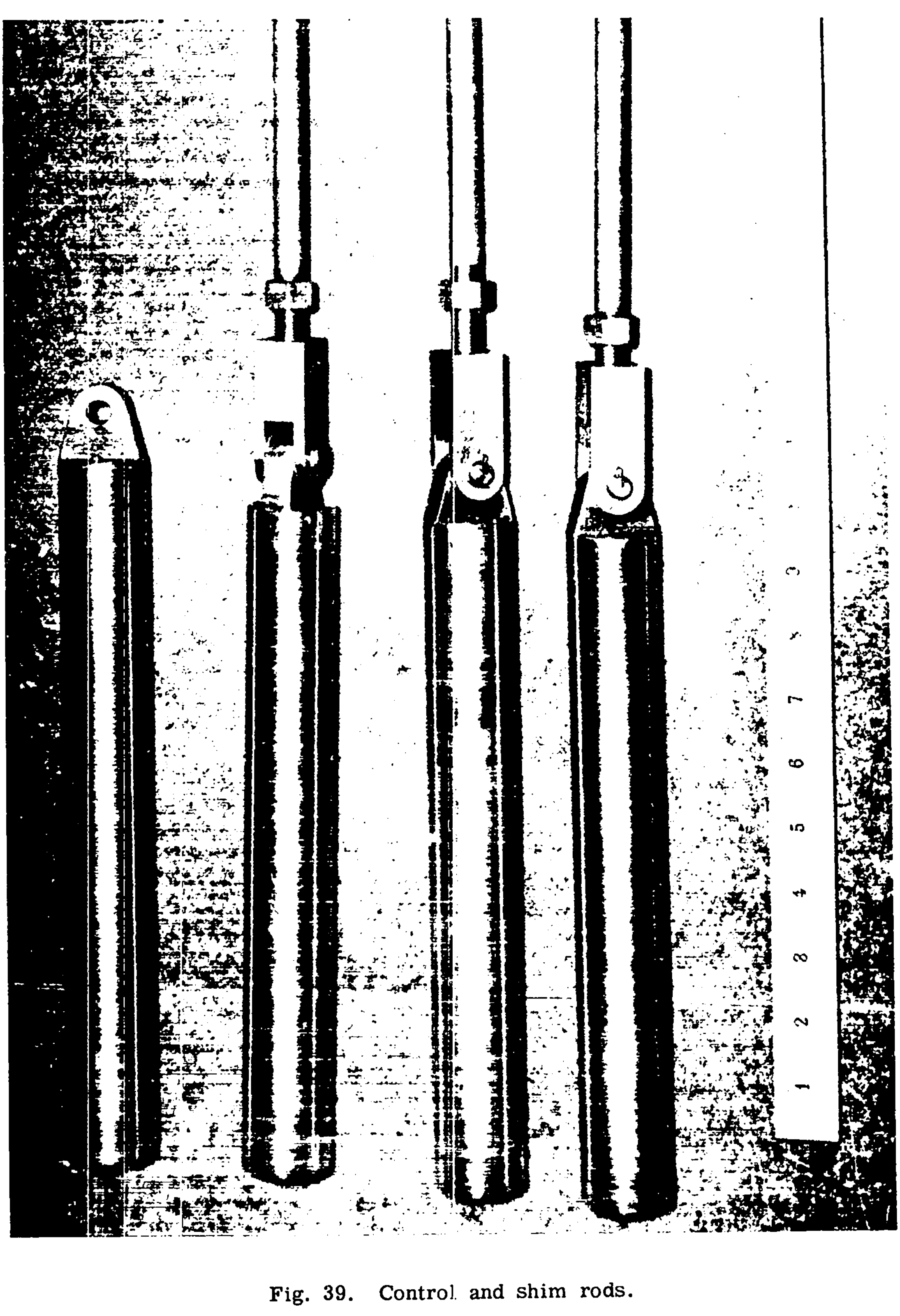

Fig. 39. Control and shim rods.

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In their least reactive position the centers of gravity of the uranium sections are approximately 10-1/4 in. below the center of reactivity of the pot, and the center of the B^{10}-filled section is opposite the center of reactivity; in the full-up position, the centers of gravity of the uranium sections are approximately 1/4 in. below the center of reactivity.

Identical mechanisms, each powered by a 1/6-hp electric motor, operate the shim rods. Each motor connects to a rack and pinion through a 900:1 gear reductor and a friction clutch. The 1/2-in. steel rods, from which the shim rods proper are suspended, pass freely through holes in the bottom of the racks. A solenoid-actuated latch must engage a notch machined into this 1/2-in. steel rod in order for the rack to raise its rod; when the reactor is "scrammed," the solenoid latches are released and the shim rods are dropped, by gravity, concurrently with the safety block. Pneumatic dashpots, located outside the shielding and just below the mechanisms, cushion the last inch of the fall of the shim rods.

Adjustment of the amount of shimming effected by each rod can be made by moving a top limit switch and mechanical stop. At its top position, the limit switch and mechanical stop permit a rod movement of 10 in. It is possible, in a matter of minutes, to locate the limit switch and mechanical stop to allow movement of either shim rod by any integral number of inches up to 10. As will be discussed later, the proper amount of shimming to be accomplished here is determined by the amount of excess reactivity to be allowed in the control rods.

When a rack has neared the end of its travel, it strikes its limit switch, and power to its motor is interrupted. The override of the system carries the rack against the mechanical stop provided for it; additional override of the motor and gear reductor is permitted by slippage of the friction clutch. Such an arrangement assures accurate positioning of a shim rod each time it is raised into position.

2.2.3 Control Rods

The two control rods also move into and out of the reactive region. Each rod comprises a uranium cylinder sealed into a welded steel can and is suspended, like the shim rods, from a 1/2-in. steel rod. In its least reactive position the center of gravity of a control rod is approximately 10-1/4 in. below the center of reactivity; in its full-up position its center of gravity is about 1/4 in. below the center of reactivity.

Motion of the control rods is accomplished remotely from the control panel by means of selsyns. The receiver selsyns, at the reactor end of the system, each drive a rack and pinion through a 60:1 gear reductor. The 1/2-in. supporting rods are each threaded into one of these racks. The pinion size is such that one-sixth of a revolution of the pinion moves its rod 1.00 in., or one revolution of the transmitter selsyn moves the rod 0.10 in. Each rack actuates upper and lower limit switches which are connected into the sequence and control circuit (Figs. 40 and 41).

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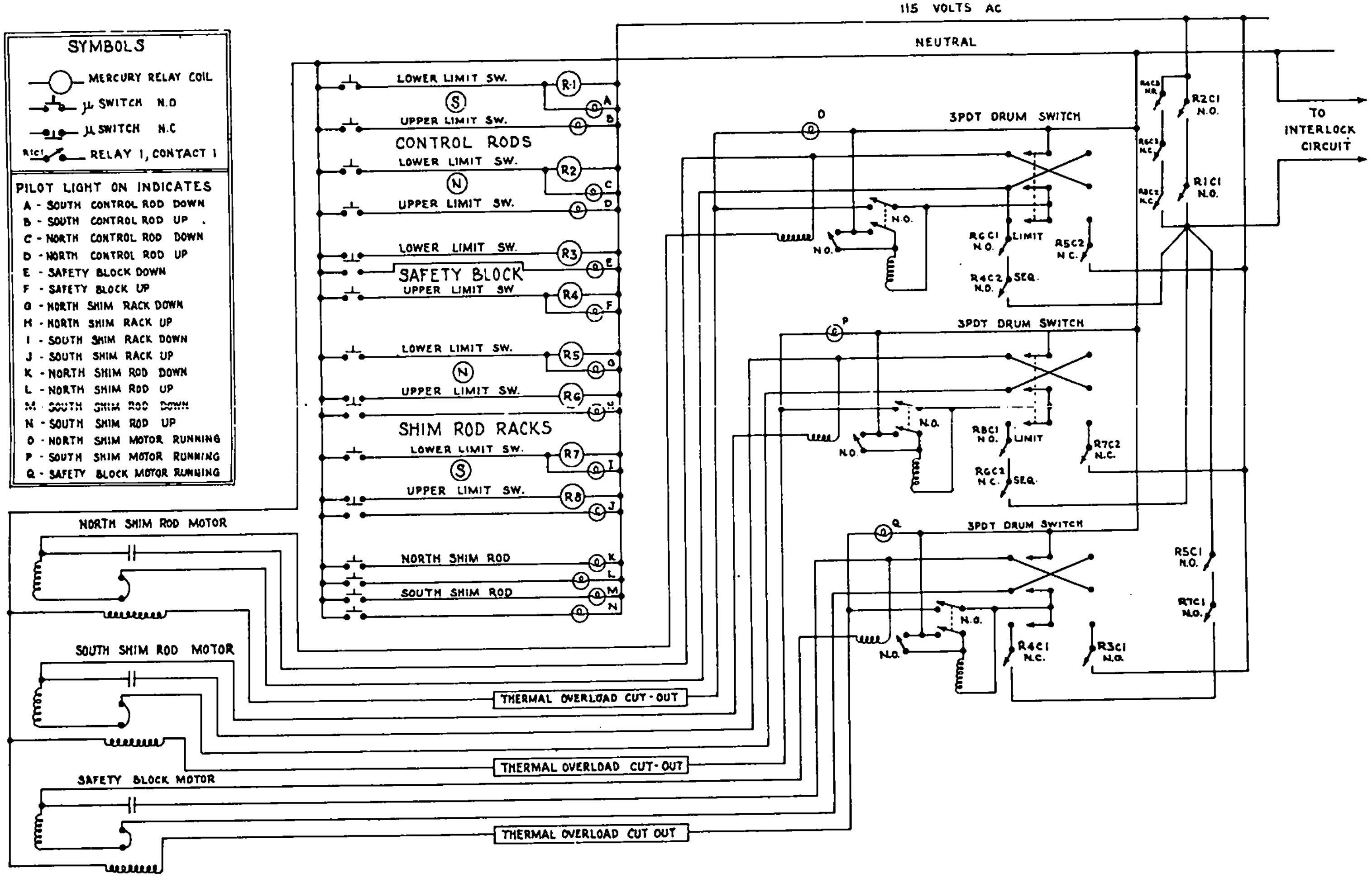

Fig. 40. Sequence circuit diagram.

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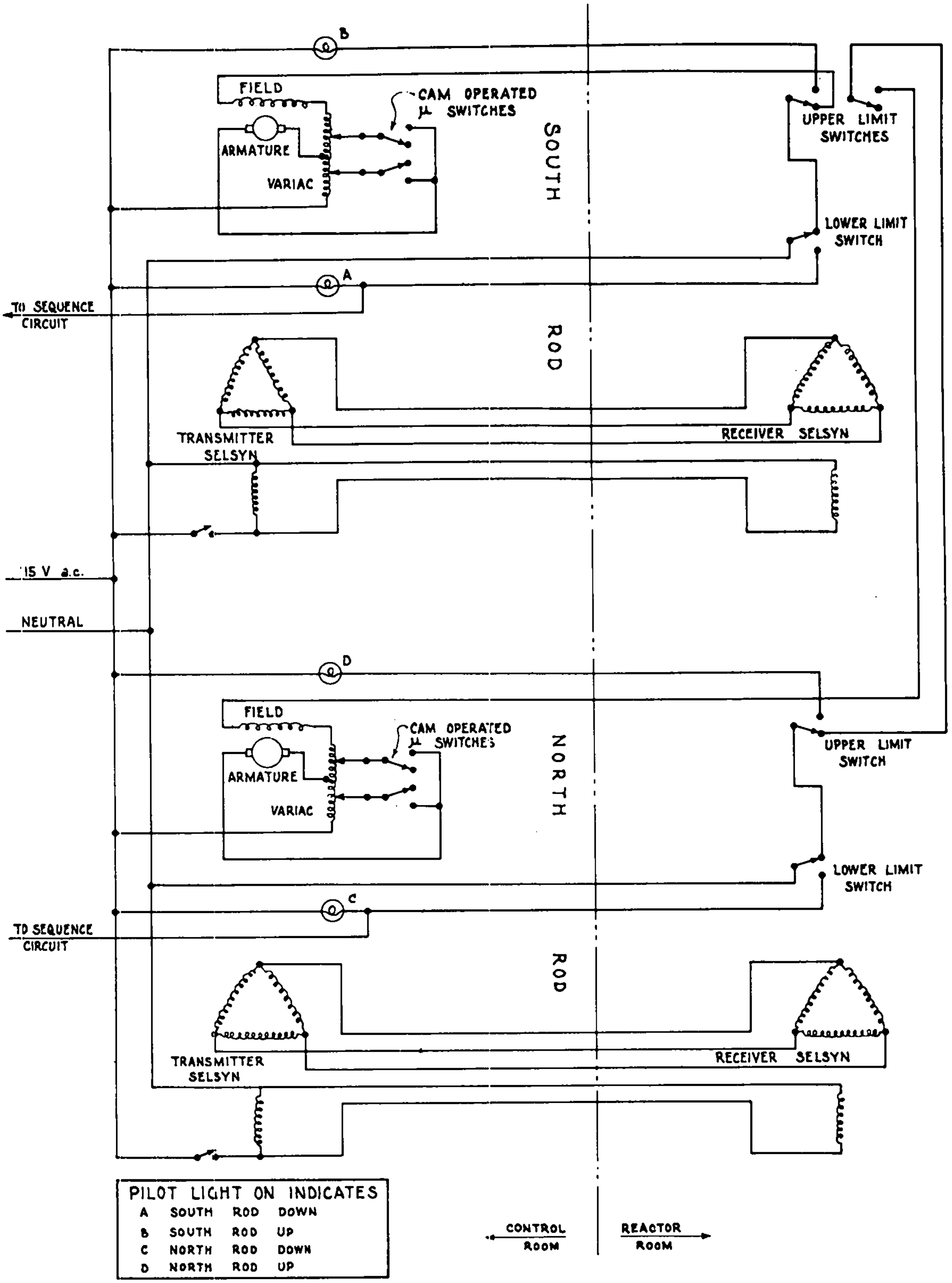

Fig. 41. Control circuit diagram.

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In the control room the transmitter selsyns may be turned by a small hand crank, or alternatively they can be engaged to a small electric motor through a manually operated cone clutch. The speed and direction of rotation of the motor is controlled by a Variac to which a second brush has been added. The Variac shaft has been spring loaded so that the brushes return to a "no-run" position when the Variac control knob is released.

Position indication of each control rod is furnished by a direct-drive revolution counter coupled to the transmitter selsyn. The coupling ratio is 1:1, so that digits on the farthest right-hand wheel represent hundredths of an inch moved, those on the second wheel tenths of an inch, and those on the third wheel inches.

2.2.4 Sequence and Control Circuits

To reduce the possibility of an operator's adding reactivity at a dangerous rate, the five elements which add reactivity (safety block, shim rods, control rods) have been sequenced. The sequence and control circuits require the following order of operations to start up the reactor:

1. Safety block positioned up.
2. First shim rod positioned up.
3. Second shim rod positioned up.
4. First control rod in its most reactive position before the motor drive on the second control rod is operative.

Furthermore, this sequence circuit (Fig. 40) is connected into an interlock circuit (Fig. 42), which requires that each of several safety interlocks must be closed before power to operate the safety block is supplied. Should either of the control rods be moved off its lower limit before the safety block or the shim rods are up, power to the safety block magnetic clutch and shim rod solenoids is interrupted. The sequence circuit does allow motion of both the control rods simultaneously, but this motion must be done manually and as a consequence cannot be done at a rapid rate.

2.3 Monitor and Associated Safety Devices

Although the control of a reactor is generally invested in the hands of an operator who is responsible for the normal operation of the machine, it is necessary to provide additional features for safeguarding against operator negligence or equipment failure. These controls (safeties) must be designed to shut down the reactor in the event of unusual or undesirable conditions such as:

1. Failure of power main.
2. Excessive reactor power level.

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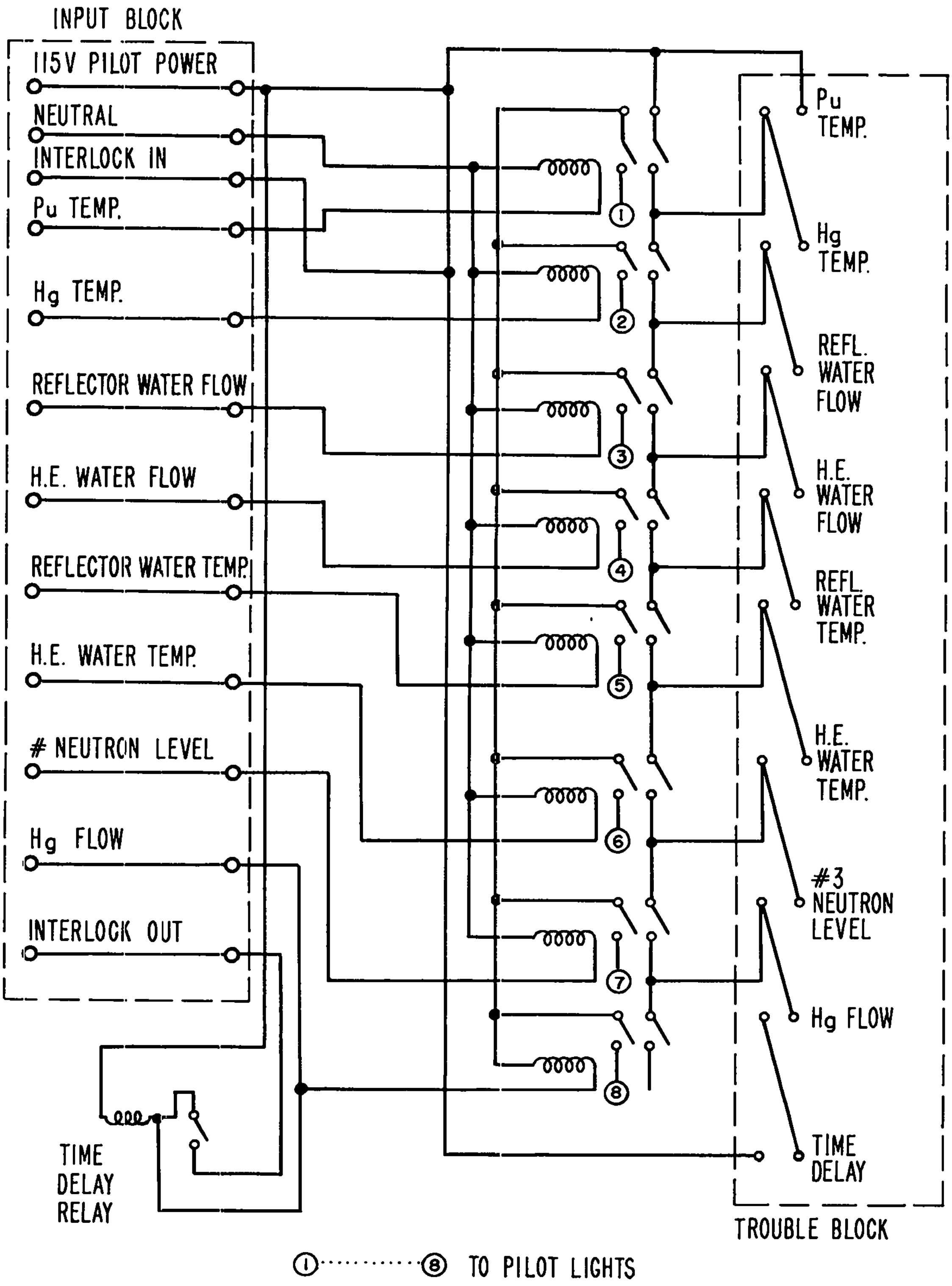

Fig. 42. Interlock circuit diagram.

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3. Excessive rates of power increase.
4. Failure of integral parts of the system.

The safeties should have a high degree of reliability, so that reasonable confidence may be placed in their operation. In this connection the safety circuits must shut down the reactor if they themselves are nullified by component failure.

2.3.1 Interlock Circuit

Figure 42 is a schematic diagram of the reactor interlock circuit. If one of the several interlocked items actuates the circuit, then the safety block, shim rods, and control rods will immediately drop, thereby shutting down the reactor.

2.3.2 Monitor and Safety Circuits

Neutron Levels. Figure 43 is a schematic diagram of the operating galvanometer circuit. This circuit allows the reactor to be operated at some arbitrarily chosen power level. The neutron level circuit, shown schematically in Fig. 44, is connected to the interlock circuit; it normally is adjusted to trip on power levels some 20 to 30 per cent above the maximum expected normal power level.

The log level circuit of Fig. 45 permits a display of the operating power level on a strip recorder for levels covering several decade factors. The derivative log level circuit, also in Fig. 45, yields a signal proportional to the rate of change of the power level. This signal is reproduced on a microammeter on the control panel as an aid to the operator in changing the power level, and, as with the neutron level circuit, it is connected with the interlock circuit so that a dangerously fast rate of increase in the power level will cause a reactor scram.

Temperature Monitoring Devices. Temperatures are measured or monitored of the following cycles and locations in the Fast Reactor:

1. Central plutonium rod (one location).
2. Mercury coolant cycle (six locations).
3. Uranium reflector (one location).
4. Water cooling cycles
   - (a) Mercury heat exchangers, water cycle (six locations);
   - (b) Reflector cooling plates (two locations).
5. Mercury pump stator
   - (a) Temperature measurement (one location);
   - (b) High temperature alarm device (four points in the stator).

The following discussion presents brief descriptions of the monitors.

1. Central Plutonium Rod (one location). A hole about 2 in. deep was drilled in a standard plutonium rod, and the rod canned in a steel jacket using methods identical to the

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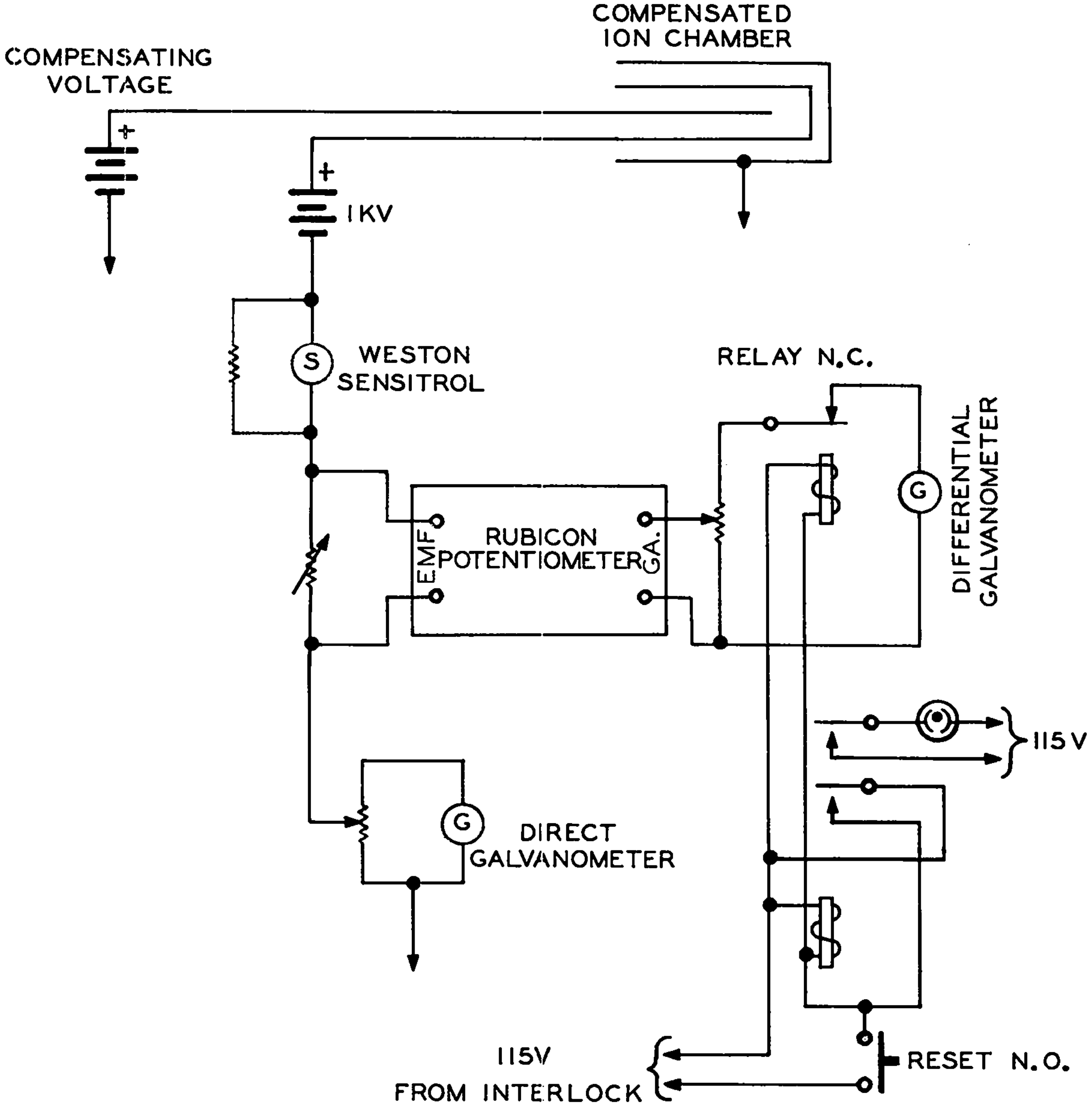

Fig. 43. Galvanometer circuit diagram.

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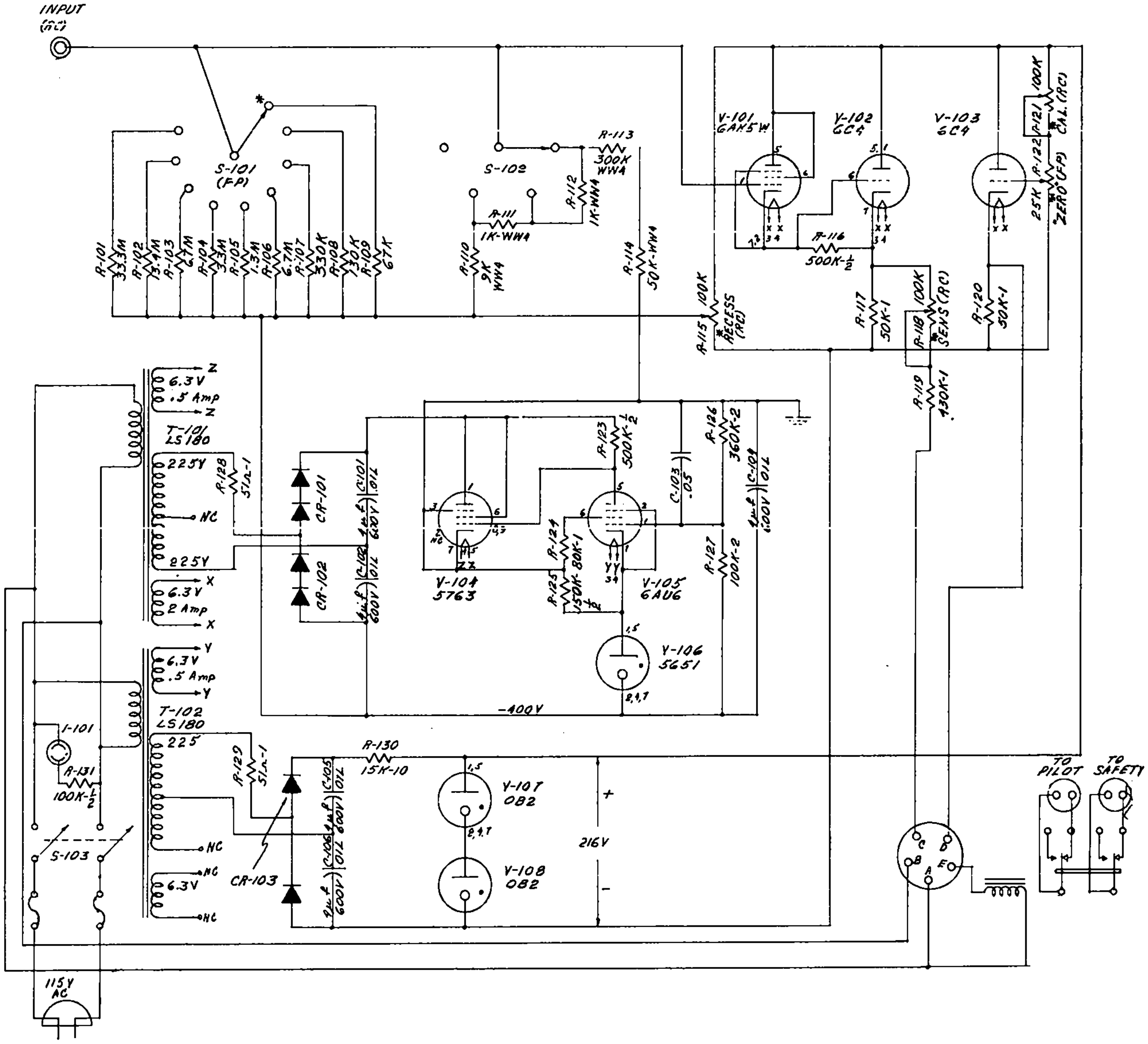

Fig. 44. Linear neutron level circuit diagram.

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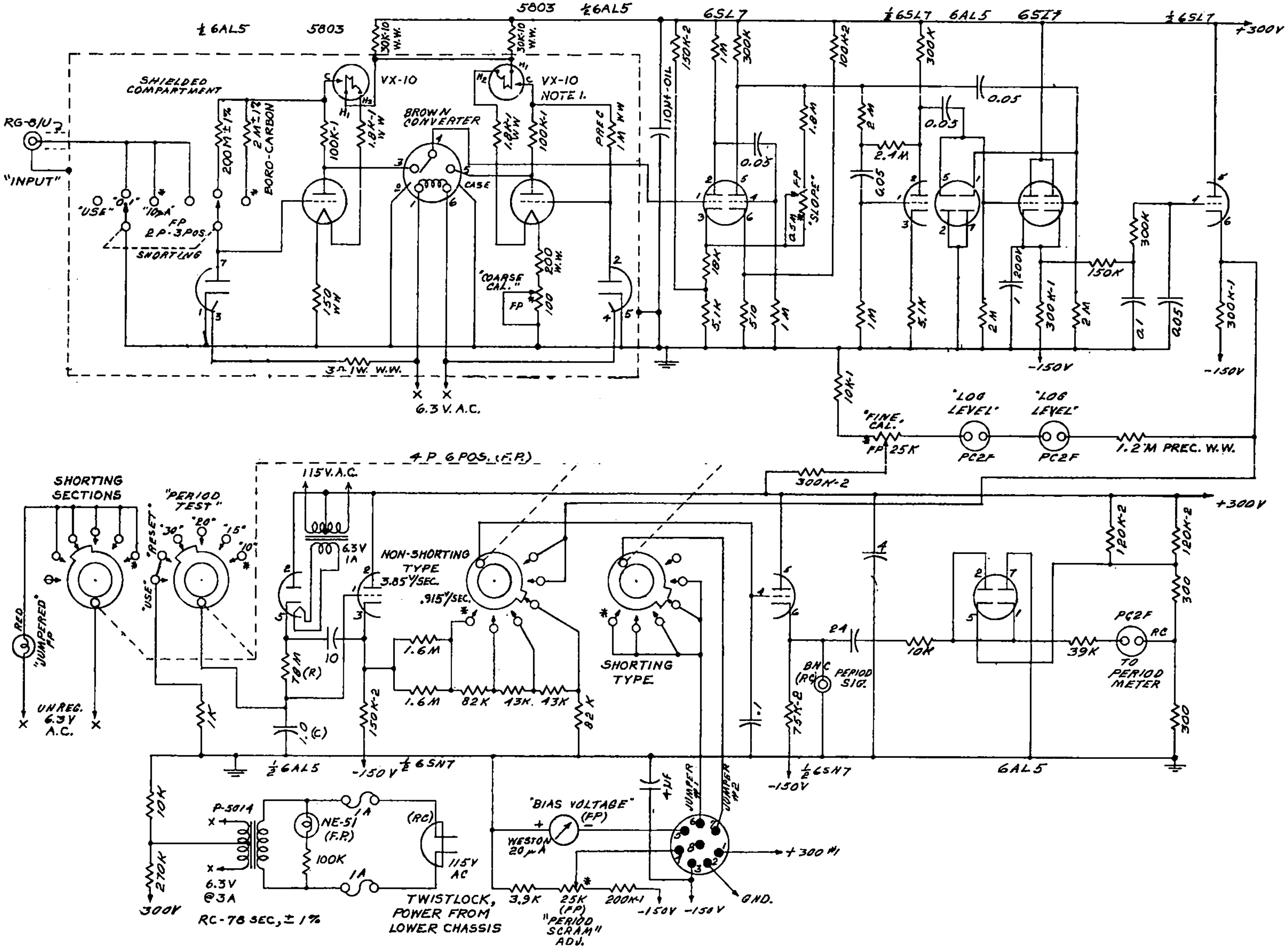

Fig. 45. Log neutron level and derivative log level circuit diagram.

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standard rod methods described in Sec. 1.3.1 with the exception that a steel tube 0.125 in. OD, 0.090 in. ID, and closed at the bottom extended into this hole. This steel tube was welded to the top steel cap of the canned plutonium rod. The steel tube is about 80 in. long and leaves the reactor core region through the exit mercury pipe (see Fig. 10). A specially designed thermocouple can be inserted into this well for monitoring the temperature of the central plutonium rod. This type of construction allows easy and frequent removal of the thermocouple for recalibration or replacement, and yet is small, which causes little restriction to the mercury flow and little reduction in the amount of plutonium in the central rod.

The thermocouple which extends down this well is made of steel tubing 0.060 in. OD and 0.030 in. ID through which a glass-insulated Constantan wire 0.025 in. OD is drawn and spot-welded at the end. The response of this couple deviates from the standard Fe-Constantan couple by 5 per cent at 100°C and by 4.3 per cent at 300°C. Since it is used with standard potentiometer recorders, this correction, which does not exceed 6°C, can be applied readily from a curve.

Figure 46 is a drawing of the thermocouple assembly for the central plutonium rod and for the exit mercury temperature.

The temperature of the central plutonium rod is recorded and indicated on a Leeds and Northrup Speedomax Model G (single point, indicating-recording automatic-standardizing; 0 to 300° range, Fe-C couples, high-low control switches, chart speed 3 in. per hour, potentiometer pyrometer). A standard Leeds and Northrup fitting consisting of a cam mounted on the slide wire shaft opens a switch at a preset temperature. These switches operate through a relay to the reactor interlock safety circuit. The Speedomax is set to open at 200°C.

2. Mercury Coolant Cycle. The mercury temperatures at the following locations are monitored and recorded: (a) Into reactor, (b) Out of reactor, (c) Into heat exchanger No. 1, (d) Out of heat exchanger No. 1, (e) Into heat exchanger No. 2, and (f) Out of heat exchanger No. 2.

Locations a, c, d, e, and f are measured by standard Fe-Constantan couples, No. 24 gauge, glass-braid insulated. The couples are silver-soldered to the exterior pipe walls and insulated with a sheath of glass wool 1 in. thick and 6 in. long and covered with heavy paper. This type of mounting was used to avoid the possibility of leaks and flow restrictions caused by the introduction of wells into the pipes. Tests demonstrated that this mounting gave temperatures about 1 per cent lower than a couple directly in the stream at 120°C and about 0.2 per cent lower than a couple in a well fitting in a pipe. These locations are recorded on a Leeds and Northrup Micromax Model S (12-point indicating-recording, 0 to 300°C range, chart speed 3 in. per hour, self-standardizing, potentiometer-pyrometer, Fe-C couples).

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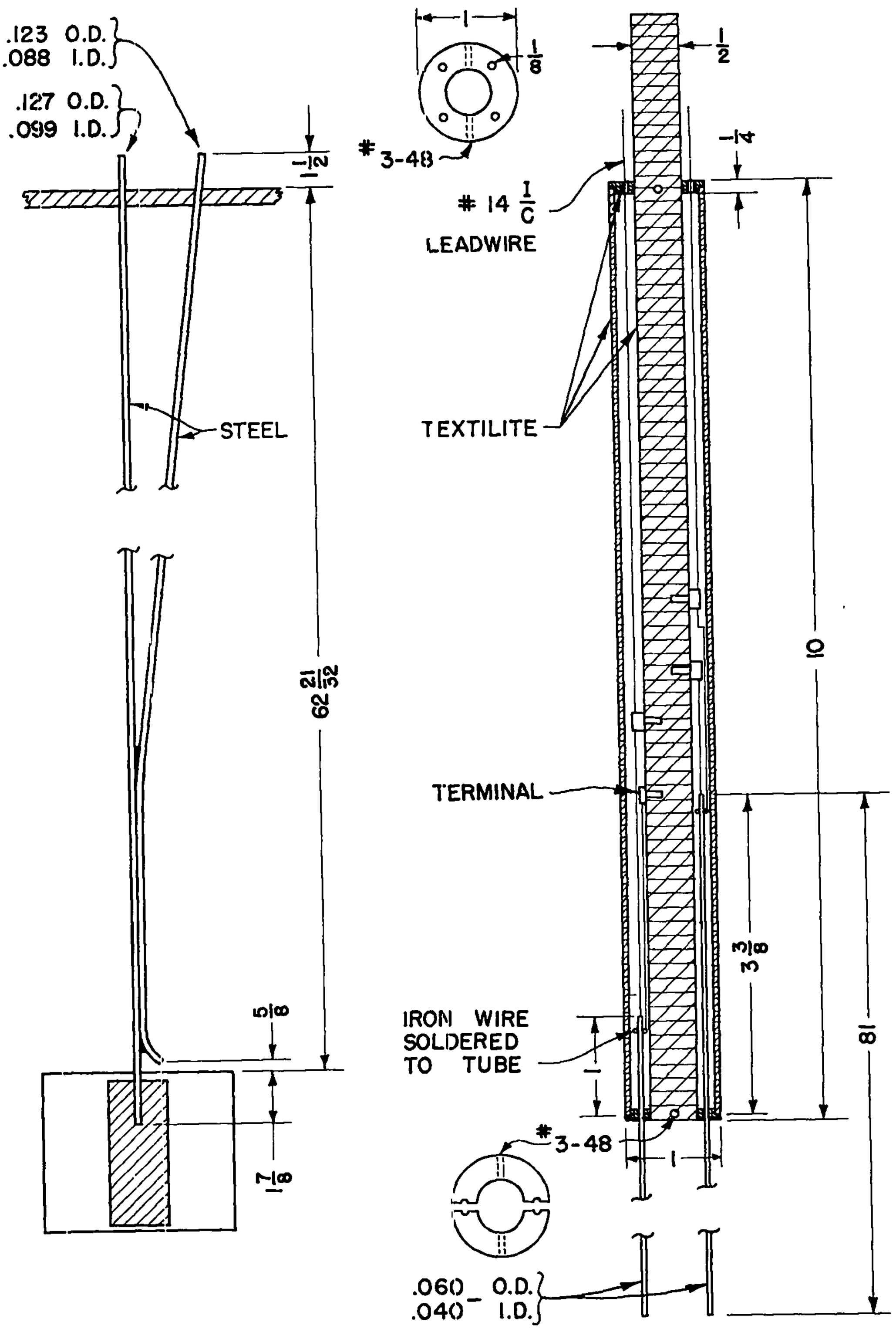

Fig. 46. Wells and upper assembly for core thermocouples.

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Location b is measured by a steel-Constantan thermocouple identical to the central plutonium rod thermocouple. A steel tube well 0.125 in. OD, 0.090 in. ID, and closed at the bottom extends down the mercury exit pipe into the mercury region above the plutonium rods and the thermocouple is inserted into this well.

The temperature of the exit mercury is recorded on a Leeds and Northrup Speedomax Model G identical to the one used for recording the plutonium temperature. This is also connected to the interlock circuit and is set to operate at 200°C.

3. Uranium Reflector. Two detectors are used to monitor the temperature of one location of the uranium blanket. A hole extends through the top shielding into the uranium block which surrounds the reactor pot. This hole is located 6 in. from the center of the pot with the bottom about 1/2 in. up from the center of the plutonium rods. The hole in the uranium is 1/2 in. in diameter. In an aluminum can in this hole are located an Fe-Constantan thermocouple and a resistance thermometer assembled as shown in Fig. 47. The thermocouple is recorded on the 12-point Micromax and is not interlocked. The resistance thermometer is a Weston aircraft type Model 727, the coil of which was removed from the standard fitting and placed in the aluminum can. The temperature elements are attached to a radiation shielding plug which carries the lead wire and closes the port. The resistance thermometer dial is located on the control panel and is not interlocked. Calibration of the resistance thermometer showed a 5 per cent elevation in indicated temperature in the operating range.

4. Water Cooling Cycles.

(a) Mercury Heat Exchangers (four locations). The water temperatures of the mercury heat exchangers are monitored at the following locations: (1) Main intake, (2) Out of heat exchanger No. 1, (3) Out of heat exchanger No. 2, and (4) Out of heat exchanger No. 1 plus heat exchanger No. 2.

All are detected by Fe-Constantan thermocouples fastened on the exterior pipes as described in the mercury temperature section and all are recorded on the 12-point Micromax. Since the intake water to each heat exchanger and to the reflector plates is from the main supply, only the main supply water intake temperature is monitored.

In addition to the recording of the water temperatures, a thermal switch (Fenwall Company) is installed in the 1/2-in. pipe T in the exit water line from the combined heat exchanger No. 1 and No. 2 water. It is connected to the interlock circuit through a relay and will open at 85 ± 0.5°C.

(b) Reflector Cooling Plates. The intake reflector water temperature is recorded on the 12-point Micromax mentioned above. An Fe-Constantan thermocouple is located in the exit water manifold, held against the bottom of a copper well by a plastic plug secured

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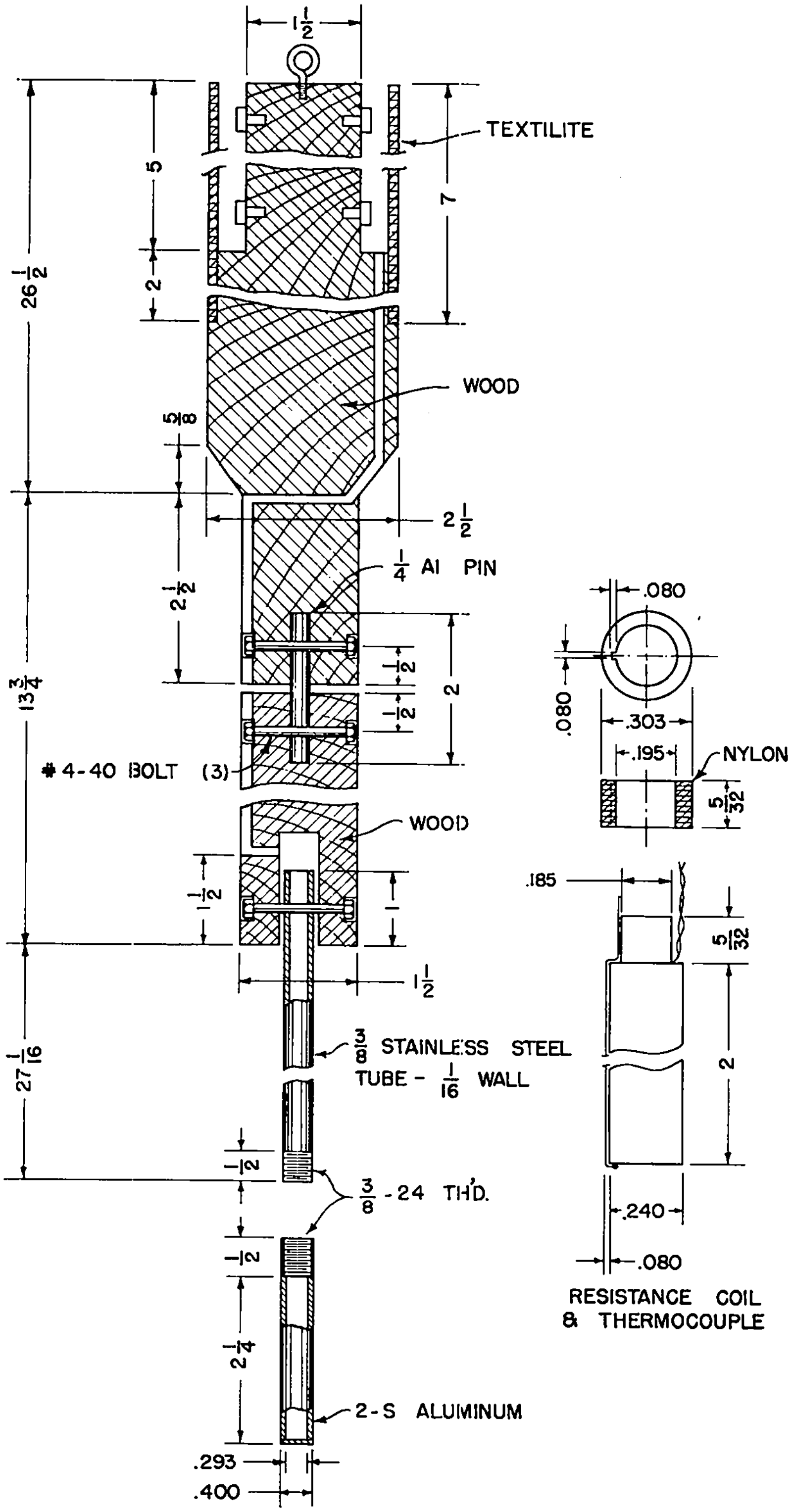

Fig. 47. Reflector resistance thermometer and thermocouple.

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with a screw cap. This temperature is recorded on the 12-point Micromax and is not interlocked. A Fenwall thermal switch set to operate at 85°C is also located in the exit water and is interlocked with the safety circuit through a relay.

5. Mercury Pump Stator. The temperature of the mercury pump stator is continuously monitored and recorded on the 12-point Micromax by an Fe-Constantan thermocouple inserted 2 in. in the stator winding. A thermopile, having four junctions in the stator and four in the input side of the forced air cooling system, is used to actuate a Sensitrol Relay alarm system for protection against excessive temperatures. This is connected to the main mercury panel light but is not interlocked with the safety circuit. It is set to close for a temperature difference of about 80°C.

The circuit for the 12 thermocouples to the Micromax recorder is through a zone box which permits the use of copper wire for the long leads through small conduit. The resistance of the zone box circuit is larger than for a plain Fe-Constantan leadwire circuit by the resistance of the copper wire (<1 ohm). The convenience of using compact multiconductor copper cables made the zone box advantageous, particularly if the leads are to be shielded. It should be mentioned that the cold junction is located at the automatic-cold-junction compensating coil in the Micromax. The temperature of the zone box has no effect, but the temperatures of the junctions must be very nearly the same, since the copper circuit is an "intermediate metal" whose emf's with the iron and Constantan must be self-cancelling. Tests have shown this circuit and recorder to be accurate within ±2°C over the range of the recorder, 0 to 300°C.

The zone box is supported by angle irons 4 in. from the wall and 3 ft from the floor. The concrete wall in back of the box is faced with 1-in. plywood 4 ft square to modify the cold-wall temperatures.

Flow Indicators

1. Mercury Flow. As described in Sec. 1.4.5, the mercury flow is measured by the pressure drop across a venturi tube. It is indicated on the control panel on a pressure dial which reads from 0 to 10 liters per minute mercury flow. The flow is also interlocked with the safety circuit by means of a probe inserted in the mercury flow path return to the supply tank. An interruption in the flow will remove the ground connection (mercury) to the probe and cause the interlock circuit to open. A control-panel trouble light is also connected with this probe.

In addition to the indication of the pressure difference across the venturi, the pressure differences across the reactor pot and heat exchanger No. 1 are also monitored and indicated in the same manner as in the case of the flowmeter. The dials are mounted on the wall of the control room. Any change in flow resistance in these two parts of the mercury

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system during long time operation will be evidenced by a pressure change.

2. Water Flow

(a) Heat Exchangers. The heat-exchanger water flow is indicated by a commercial rotameter (Fischer and Porter Co.) of range 0 to 4.5 gallons per minute. It is installed directly in the pipe line and mounted on the control panel where the water control valve is also located.

A pressure switch is located in the water line leaving the heat exchangers to serve as a monitor against restrictions or stoppage of flow. The switch (Detroit Company) consists of a sylphon bellows operating a variable position microswitch with a range from 10 in. vacuum to 15 lb pressure, minimum differential 1-1/2 lb, maximum differential 3-1/2 lb. A valve is located in the discharge line after the pressure switch to raise the pressure within the operating range of the instrument. With the differential set at the minimum, the pressure level at 8 lb (3-gpm flow) and the switch indicator at 3-1/2 lb, a flow of 1.8 gallons per minute will close the switch, and a decrease to 1 gallon per minute will open the switch. This operating range of 0.8 gallon per minute can be shifted up and down the flow range. The switch is interlocked with the safety circuit, indicated by a trouble light on the control panel, and set to open at about 2 gallons per minute.

(b) Reflector Cooling Water. The water flow through the reflector cooling tubes is measured by a rotameter of 0- to 1.7-gallon per minute range, installed directly in the pipe line and mounted on the control panel.

The system and equipment for the safety-circuit interlock is similar to that described above for the heat-exchanger water. The only difference is that the Detroit pressure switch used has a smaller range and is more sensitive. This is necessary since the pressure drops from 18 to 2-1/4 psi through the reflector cooling tubes, with a flow of 0.9 gallon per minute, and the pressure variation with flow is proportionately less. The switch used is a Model MC-2, range 3 in. vacuum to 3-1/2 lb pressure, minimum differential 6 oz, maximum differential 1 lb.

3. Helium Flow. The flow of helium is measured by a Fischer-Porter Roto-Sight alarm of range 0.1 to 10 cfm. This is mounted in the reactor room in the helium supply system but operates a trouble light on the control panel. Normal operation is set for 0.3-cfm flow.

Special Mercury and Helium Monitors. A small section of the control panel contains warning lights which indicate special items connected with the mercury coolant system as listed in Table 2. The lights are "on" for operation. Any light not on will cause a trouble light, labeled Mercury Panel, to go off, thereby calling the attention of the operator to the smaller mercury-panel lights.

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TABLE 2. MERCURY WARNING LIGHT SYSTEM

Monitor	Method of monitoring	Interlock	Trouble light
3 mercury level indicators in supply tank	Spark plugs with electrodes	No	Yes
3 mercury level indicators in sump tank	Spark plugs with electrodes	No	Yes
Mercury flow	Spark plugs with electrodes	Yes	Yes
3 drip indicators	Spark plugs with electrodes	No	Yes
Gas presence indicator	Spark plugs with electrodes (light to go off if gas collects)	No	Yes
Helium pressure gauge for mercury system supply	Pressure switch (to open at 45 psi)	No	Yes
3 phase currents on pump	Meters	Yes	Yes
Pump stator temperature	Thermocouples (Sensitrol)	No	Yes
Pump blower		With pump	Yes

Summary of Measurements. Table 3 gives a summary of measurements described in this chapter.

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TABLE 3. SUMMARY OF MEASUREMENTS

I. Temperature Measurements

Subject	Location	Type	Recorder	Interlock	Trouble light
Mercury	Into heat exchanger No. 1	Thermocouple	Micromax on control panel	No	No
Mercury	Out of heat exchanger No. 1	Thermocouple	Micromax on control panel	No	No
Mercury	Into heat exchanger No. 2	Thermocouple	Micromax on control panel	No	No
Mercury	Out of heat exchanger No. 2	Thermocouple	Micromax on control panel	No	No
Water	Mains	Thermocouple	Micromax on control panel	No	No
Water	Out of heat exchanger No. 1	Thermocouple	Micromax on control panel	No	No
Water	Out of heat exchanger No. 2	Thermocouple	Micromax on control panel	No	No
Water	Out of heat exchangers Nos. 1, 2	Thermocouple	Micromax on control panel	No	Yes
Water	Out of reflector	Thermocouple	Micromax on control panel	No	Yes
Reflector	Reflector	Thermocouple	Micromax on control panel	No	No
Pump stator	Pump	Thermocouple	Micromax on control panel	No	Yes
Fuel	Central rod	Thermocouple	Speedomax on wall, Micromax	Yes	Yes
Mercury	Out of core	Thermocouple	Speedomax on wall, Micromax	Yes	Yes
Reflector	Reflector	Resistance thermometer	Micromax	No	No

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II. Neutron Measurements

Detector type	Location	Circuits	Interlock	Trouble light
U^{235} fission ion chamber	Reflector	Level safety No. 1	Yes	Yes
U^{235} fission ion chamber	Reflector	Level safety No. 2	Yes	Yes
U^{235} fission ion chamber	Reflector	Galvanometer	Yes	Yes
U^{235} fission ion chamber	Reflector	Rate safety	Yes	Yes
U^{235} fission counter	Reflector	Scale of 1000	No	No

III. Flow Measurements

Subject	Detector	Interlock	Trouble light
Reflector water	Rotometer	Yes	Yes
Heat exchanger water	Flowmeter	Yes	Yes
Mercury	Probe in supply tank	Yes	Yes
Mercury	Venturi	No	No
Mercury	Pressure difference across heat exchanger No. 1 (Moore pressure dials)	No	No

IV. Mercury System, Exclusive of Flows and Mercury Temperature

Subject	Interlock	Trouble light
Pump currents, 3-phase	Yes	Yes
Supply tank, 3 levels	Yes	Yes
Sump tank, 3 levels	No	Yes
Pump stator temperature	No	Yes
Pump blower	With pump	Yes
3 drip indicators	No	Yes
Gas presence indicator	No	Yes
Water overflow, reflector	No	Yes
Water overflow, heat exchanger	No	Yes
Helium pressure	No	Yes
Time Meter	No	No

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Chapter 3

OPERATIONAL CHARACTERISTICS

This chapter will discuss the general operation and behavior of the reactor at power, including the effects of the control parts, the adequacy of the shielding, the operation of the cooling system, and some of the experiments which have been done in order to predict better the long-time power operation.

3.1 Arrangement of the Fissionable Material

Figure 48 is a diagram of the cage with the plutonium and uranium as arranged in the reactor. In the course of critical assembly experiments it was found that only 22 rods of plutonium and 33 rods of uranium are necessary for criticality if all of the plutonium is assembled in the center position and mercury is present in the cage. It was decided, however, to put in the maximum possible amount of plutonium in order to reduce the specific power and hence the operating temperature of the plutonium rods and to flatten the neutron distribution as much as possible. Thus, the reactor contains the 35 rods of plutonium (15.9 kg) and 20 rods of uranium arranged as shown in Fig. 48.

3.2 Calibration of Control Parts

The mechanism and general theory of reactor control has been discussed in Sec. 2.1, and the physical descriptions of the control parts are given in Sec. 2.2. The performance and methods of calibration of the parts are given here.

Calibrations were done in two ways. For the massive pieces, the safety block and shim rods, the calibrations were done in terms of multiplication measurements. The control rods were calibrated by means of period measurements, and the in-hour equation

$$\frac{\delta k}{\gamma f} = \sum_i \frac{a_i \; t_i}{T + t_i} \quad .$$

With the reactor critical at 1 watt, a control rod is moved in a given amount and the resulting period of reactivity change can be measured by observing the time for the power to increase by a factor of ten. Thus, the value of the control rods in cents as a function of rod position can be found. With the reactor very close to critical, a counting rate of a neutron counter is observed. The control rods are then lowered a given amount in cents and the counting rate again observed. This is repeated for several values of reactivity reduction in order to obtain a correlation factor between cents and counting rate. The observed net neutron multiplication, M, of an assembly can be written

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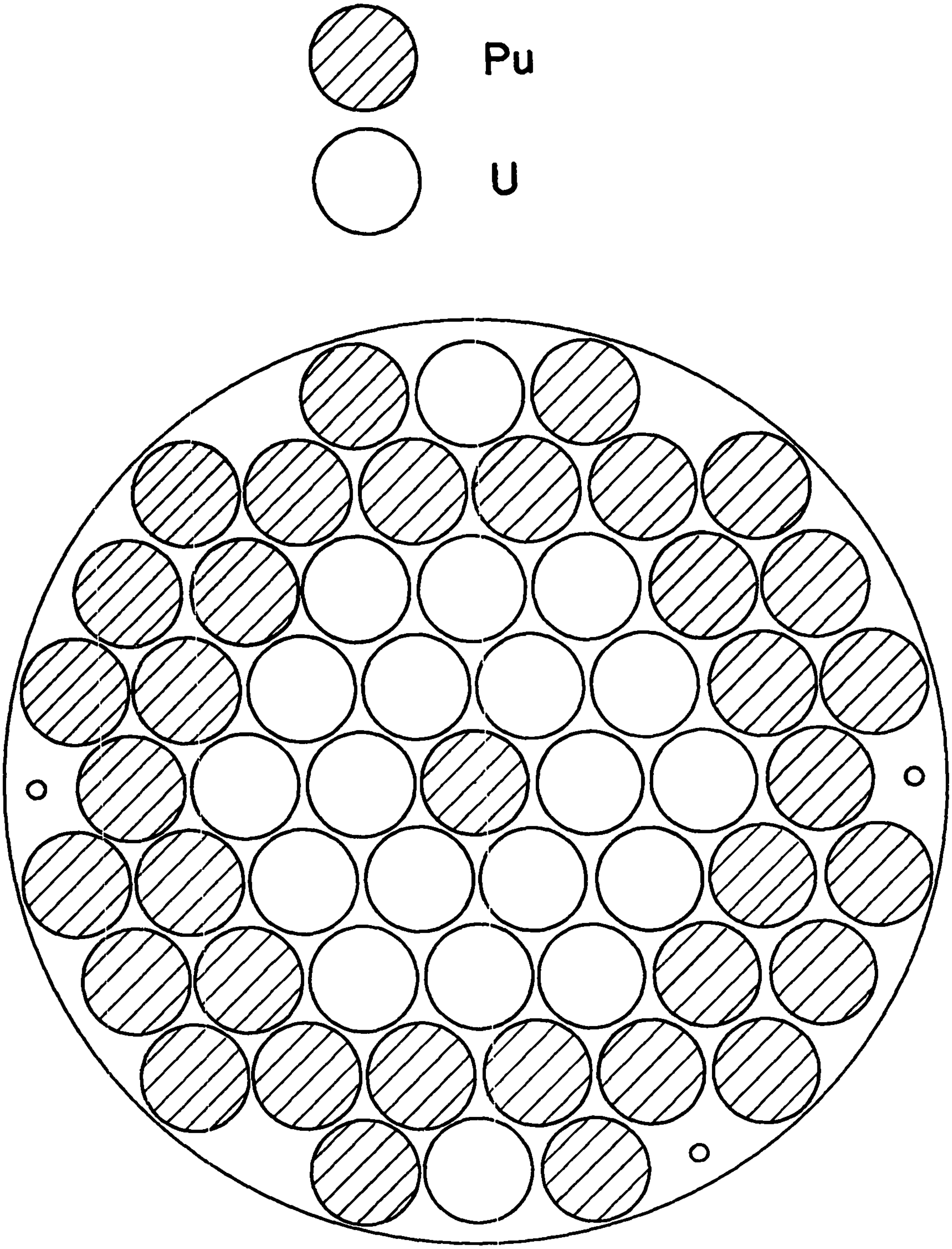

Fig. 48. Reactor fuel loading (peripheral).

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$$\frac{1}{M} = C(1-k)$$

where C is a constant. For a change in k the multiplication changes

$$\frac{1}{M_1} - \frac{1}{M_2} = C\left[(1-k_1) - (1-k_2)\right]$$

$$\frac{1}{M_1} - \frac{1}{M_2} = C(k_2-k_1) = \frac{C}{CPM_1} - \frac{C'}{CPM_2}$$

where C' is a constant relating the counting rate (CPM) to the observed multiplication, or

$$\frac{C'}{C}\left(\frac{1}{CPM_1} - \frac{1}{CPM_2}\right) = \Delta k = (\Delta \text{¢})\ \gamma f$$

or

$$\frac{C'}{C(\gamma f)}\left(\frac{1}{CPM_1} - \frac{1}{CPM_2}\right) = \Delta \text{¢}$$

The combined constant $(C'/C\gamma f)$ can thus be determined by two settings of the control rod.

This relation can then be used to determine the reactivity value in dollars and cents of a larger control part by measuring the counting rates with the reactor just critical and the part in position and below critical with the part out of position. The safety block and shim rods were calibrated in this fashion. During a critical assembly when absolute multiplications are being measured, it is also possible to measure the value in 1/M of a control part, but one then has to calculate the relation between the external or net multiplication, M, and the k of the reactor (cf. LA-335).

3.2.1 Safety Block

Results of calibrations given above yield a reactivity value for the safety block equal to \$5.30. In addition, the position of the block after a signal to drop was measured by photographing the block with a Fastax camera. A Brush high-speed pen recorder connected to an external neutron counter was used to measure the fractional power change with time. It was found that a relatively long time, of the order of 0.15 sec, elapses between the signal and the beginning of the free fall of the block.

3.2.2 Shim Rods

The two shim rods, each comprising a rod of uranium and a rod of B^{10} (Sec. 2.2.2), were calibrated in the same manner as the safety block. The uranium section controls about \$1.60

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and the B^{10} section about $1.50. The total control of the two shim rods is about $6.20. The action of the B^{10} is to absorb neutrons in a nonproductive process, thereby reducing the reactivity. In this region of the reflector it is interesting to note that B^{10} is one of the few elements which exhibits this effect, the effect of other materials being to increase the reactivity. The gain in control by use of this material results in a considerable safety factor.

3.2.3 Control Rods

The two control rods, sectioned with aluminum and steel in order to reduce and make linear their reactivity control, were calibrated by means of period measurements. The calibration curve is shown in Fig. 49.

For power operation up to 1 kw the critical setting is obtained with the safety block in position, the two shim rods each up 6 in., one control rod at about 4 in., and the other at 0 in. For higher powers, where the temperature reduces the reactivity, it is necessary to have more of the control rod in, and for 40-kw operation one control rod and part of the other must be used.

When bringing the reactor to power, a control-rod position of about 3 in. above the cold critical position produces a period of about 25 sec.

The excess k available in terms of dollars at low power is about $1.60; at 40 kw about $0.60, with the temperature coefficient using up approximately $1.00. In terms of k the values are 0.4 and 0.15 per cent, respectively. Additional excess k is available, however, if the shim rods are manually changed so that they will travel their total 10 in. If this additional excess k is considered, the values for the above two power conditions are $4.00 and $3.00, respectively.

3.3 Physical Measurements Relating to Reactor Operation

Some of the measurements made in order to predict and understand the reactor behavior at both zero and high power are discussed in this section.

3.3.1 Temperature Coefficient

The reactivity change of the reactor as a function of temperature has been measured under the following conditions:

(a) At 1-watt power before the shielding was present, the temperature changes being produced by the external room temperature.

(b) At 100 watts with the shielding on and mercury present but not circulating, the temperature changes being produced by the internal fission heating.

(c) At operating powers where the coefficient can more properly be called a power coefficient of reactivity.

In condition (a) the reactor was loaded with 34 plutonium rods. One thermocouple was

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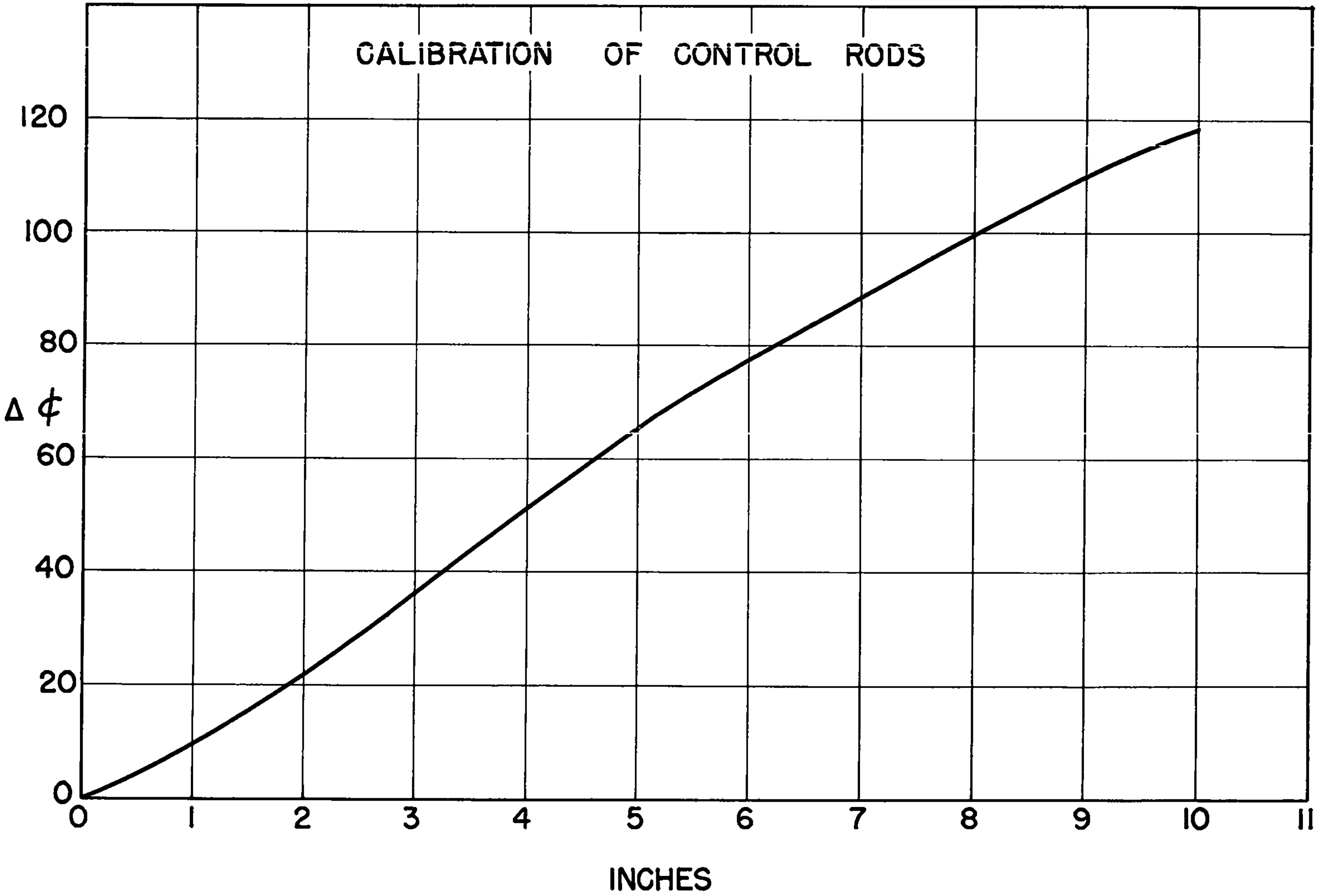

Fig. 49. Control rod calibration curve.

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attached to the central plutonium rod and one was inserted in the mercury which surrounded the rods. The temperature was changed by opening the doors of the reactor room and allowing the entire reactor (without shielding) to cool. A temperature difference of 10°C was observed. Changes in reactivity were observed by changes of the reactor period for a given control-rod setting and by changes in criticality settings of a rod. The over-all period change was from 176 to 72 sec, equivalent to a coefficient of -1.1¢/°C.

In condition (b) the reactor was loaded with 35 plutonium rods with mercury present and was operated at 100 watts. The plutonium temperatures increased during 1/2 hr operation by 5.7°C and the mercury by 4.4°C. A reflector temperature rise was not detected. The reactor was kept critical during the run by an increase of control-rod position amounting to a decrease in reactivity of 2.8¢. The plutonium coefficient can be roughly estimated from these measurements to be -0.3¢/°C, the mercury (including the steel pot, cage, and uranium rods) -0.2¢/°C, and from the measurements in (a), the reflector about -0.5¢/°C.

Condition (c) represents the normal operating condition of the reactor. During operation at high powers (~20 kw) about 2 hr are required for the plutonium, mercury, and reflector temperatures to arrive at equilibrium conditions. Because of the large temperature gradient through the reflector, it is difficult to assign a true average temperature to the reflector. Table 4 lists, however, the observed temperatures of the three most important components of the temperature coefficient at different powers. For operation conditions it is more meaningful to consider power coefficients rather than temperature coefficients. The average of the mercury temperatures between the temperatures into and out of the reactor pot was taken to be the average of the mercury, steel cage, reactor pot, and uranium slugs. These temperature-coefficient components are referred to as the "mercury" temperature coefficient. Using the values obtained in condition (b), the over-all temperature coefficient was calculated as shown in Table 4. The agreement is fairly good considering that the temperatures are averages.

TABLE 4. TEMPERATURE AND POWER COEFFICIENTS

Calculated power, kw	Pu, °C	Hg, °C, Av.	Reflector, °C	Δ¢ (observed)	Δ¢, kw	Δ¢ (calculated*)
Pot + reflector						
0.05	32	28	27	0.0	0.0	0.0
12.0	77.5	49.5	51	-26.3	-2.2	-29.8
23.4	119.5	70	76	-57.0	-2.4	-59.1
32.9	154	88	97	-82.0	-2.5	-83.6

*Calculated using -0.3¢/°C, -0.2¢/°C, -0.5¢/°C for Pu, Hg, and reflector, respectively.

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3.3.2 Determination of γf

In the quantity γf, f is the fraction of delayed neutrons and γ represents the relative effectiveness of the delayed neutrons in causing fission compared to the prompt neutrons. The average energy of the delayed neutrons (~0.5 Mev) is smaller than the average energy of the prompt neutrons (~1 to 2 Mev) and hence the effectiveness of the delayed neutrons compared to the prompt neutrons may be different. The determination of this quantity is important in relating the change in k of any reactor to the resulting period of the rise or fall of the neutron level.

The determination of γf was done in the following way.

With the reactor just critical (k = 1), the safety block which controls about 6 x γf was dropped. The neutron level, initially at a value of N_1, drops to N_2 from which value the level decays with the delayed neutron periods. Thus, the level N_2 is a source composed of the delayed neutrons initially present in level N_1 which are promptly multiplying

$$N_2 = \frac{N_1 \gamma f}{1-kp} = \frac{N_1 \gamma f}{1-k(1-\gamma f)}$$

or

$$\gamma f = \frac{N_2 (1-k)}{N_1 - kN_2}$$

where (1-k) is the δk of the safety block. N_1 is observed initially by a counter in terms of counts per unit time. At time t_1 after the block is dropped, a count was started and continued until time t_2 (about 3 min). The total counts in the interval t_1 to t_2 can be found by the following relation:

$$\frac{dN}{dt} = N_2 \left[a_1 e^{-\alpha_1 t_1} + a_2 e^{-\alpha_2 t_2} + a_3 e^{-\alpha_3 t_3} + a_4 e^{-\alpha_4 t_4} + \alpha_5 e^{-\alpha_5 t_5} \right]$$

ΔN = counts in interval t_1 to t_2

$$\Delta N = \int \frac{dN}{dt}\, dt = N_2 \left[\frac{a_1}{\alpha_1} e^{-\alpha_1 (t_2 - t_1)} \quad \frac{a_2}{\alpha_2} e^{-\alpha_2 (t_2 - t_1)} \right]$$

Hence by evaluating the bracketed quantity M,

$$N_2 = \frac{\Delta N}{M}$$

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The value of (1-k) for the block is known from multiplication measurements discussed in Sec. 3.2. γf in the measurements made was 0.0025, and using the value of $f = 0.0023$ (cf. LA-539), γ becomes 1.1.

3.3.3 Phase Change

Because plutonium metal can exist in five phases (see Table 5), depending upon the temperature, it is desirable to use a stabilized phase in reactor operation where the temperatures may vary over wide ranges.

TABLE 5. PROPERTIES OF UNSTABILIZED PLUTONIUM PHASES

Phase	α		β		γ		δ		ϵ
Transition		116°C		200°C		300°C		490°C (410°C stable form)	
Density, g/cm^3	19.8		17.8		16.8		15.8		16.4
Thermal conductivity	-		-		-		0.020 (stable)		-
Specific heat	-		-		-		0.03 (stable)		-
Linear coeff. of expansion x 10^6	54.5		35.0		36.0		-21 (5 stable)		4
Malleability	Brittle		Ductile		Soft		Very soft		-

It is seen that unstabilized plutonium metal would be a very unsatisfactory and dangerous material to use for reactors unless the temperatures were limited to the alpha phase because of the density change and consequent reactivity change. The alpha phase is also difficult to fabricate. Consequently, the stable delta phase is used in the reactor with the temperature limited to 200°C, which is far below the transition of delta phase to epsilon phase.

In order to ensure, however, that the safety control of the reactor is adequate to account for an unexpected and probably impossible temperature rise and consequent transition to the epsilon and more reactive phase, a rod of alpha-phase material of the same mass as the standard delta-phase rod was put in various positions in the reactor cage and its effect upon the over-all reactivity determined. Table 6 lists the data for the alpha-phase material and the predicted effects for the epsilon-phase transition.

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TABLE 6. REACTIVITY EFFECTS OF α-PHASE PLUTONIUM
(Control = \$10.00)

Position	Measured Δ¢ for rod changing to α-phase	Predicted Δ¢ for 35 rods changing to α-phase	Predicted Δ¢ for rod changing to ϵ-phase	Predicted Δ¢ for 35 rods changing to ϵ-phase
Center	30¢	\$8.80	8¢	\$1.80
Edge	20¢		5¢	

Report LAMS-733, "Effect of Temperature and Reactivity Changes in Operation of the Los Alamos Plutonium Reactor," discusses the possibility of phase changes in more detail than is given here.

3.3.4 Effects of Radiation

Plutonium. It has been reported that blistering occurs in normal uranium rods when one atom in 3000 has fissioned. For the reactor this amounts to 1.3×10^{22} total atoms fissioned. To produce this number of fissions at the rate of 1.1×10^{17} fissions per kw-hour requires 1.2×10^{5} kw-hours. Present operation is about 10^{3} kw-hours per month, or a total time of 10 years is required to produce rod blistering if plutonium shows the same behavior as normal uranium. In order to check the behavior of plutonium with respect to radiation, a standard plutonium rod was irradiated at the Argonne National Laboratory in CP-3 in a flux of 2×10^{11} neutrons per sec per cm^{2} per 300 kw at a temperature of 60°C for a total of 2.7×10^{5} kw-hours, receiving an nvt equal to 4.5×10^{17}. This nv, mostly thermal, will produce fissions in an energy region where the cross section could be roughly estimated as 500 barns compared to 2 barns for the reactor spectrum. Since the rod is black for thermal neutrons only, the outer 0.15 cm is effective in producing fissions. The effective mass of the rod is therefore about 175 g instead of 450 g. The total number fissions which occurred in the rod was thus

$$(4.6 \times 10^{17}) \times 500 \times \frac{0.6}{239} \times 175 = 1 \times 10^{20} .$$

At the operation level of the Fast Reactor, one rod has $\frac{1.1 \times 10^{17}}{35} = 3.1 \times 10^{15}$ fissions per kw-hour. Consequently a total time of $10^{20}/0.31 \times 10^{16} = 3 \times 10^{4}$ kw-hours will be required to produce this many fissions. Thus, 30 months of normal operation of the Fast Reactor will be required before one rod has had fissioned the same number of atoms which the test rod had at Argonne. No structural or dimensional changes were observed for the test rod.

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Boron-Plastic. The boron-plastic which is used in the laminated shielding receives a flux of about 1 x 10^{11} neutrons per cm^2 per kwh. Tests made in the Water Boiler and at Argonne showed that after about 10^{17} total nvt, disintegration of the plastic began to take place. Thus 10^5 to 10^6 kw-hours or about 10 years of operation should be possible before the plastic begins to disintegrate.

3.4 Shielding

Neutron measurements were made in various parts of the reactor shield utilizing fission foils of U^{235}, U^{238}, and Np^{237}, and activation foils of Au and In. An attempt was made, by analyzing the counting rates produced in the threshold detectors, to infer spectral changes in various parts of the shield as well as to measure the neutron intensity attenuation. The results of these experiments have been presented in some detail in an internal Laboratory report. Here only the attenuation data is presented (Fig. 50).

The attenuation in neutron flux in one laminated section of steel and boron-plastic appears to be, from Fig. 50, about a factor of 20. If one assumes an attenuation factor of 10 in 7 in. of concrete, then it can be estimated that a total attenuation of 10^{12} is suffered by neutrons in the entire reactor shield. After the reactor attained power operation, it was possible to confirm that this estimate was very nearly correct.

It is interesting to note in Fig. 50 that the thermal neutron content of the spectrum gets rather high in the neighborhood of the laminated Masonite section of the shield, as exhibited by the abrupt appearance of a large cadmium ratio. No evidence of thermal neutrons could be found nearer the core region, however.

3.5 Mercury System

3.5.1 Mercury Pump

The mercury volume output of the pump depends upon the current in the stator winding and that, in turn, depends upon the maximum temperature to be allowed in the winding. The manufacturer's rating for the stator is 125°C for continuous operation, and 175°C for short periods. Therefore operation is limited to temperatures of 125°C or below.

The pump power is supplied in the form of low current and high voltage, and therefore the pump stator is connected in the series or 440-V connection. The relation of pump current to the phase voltage required to produce it is shown in Table 7.

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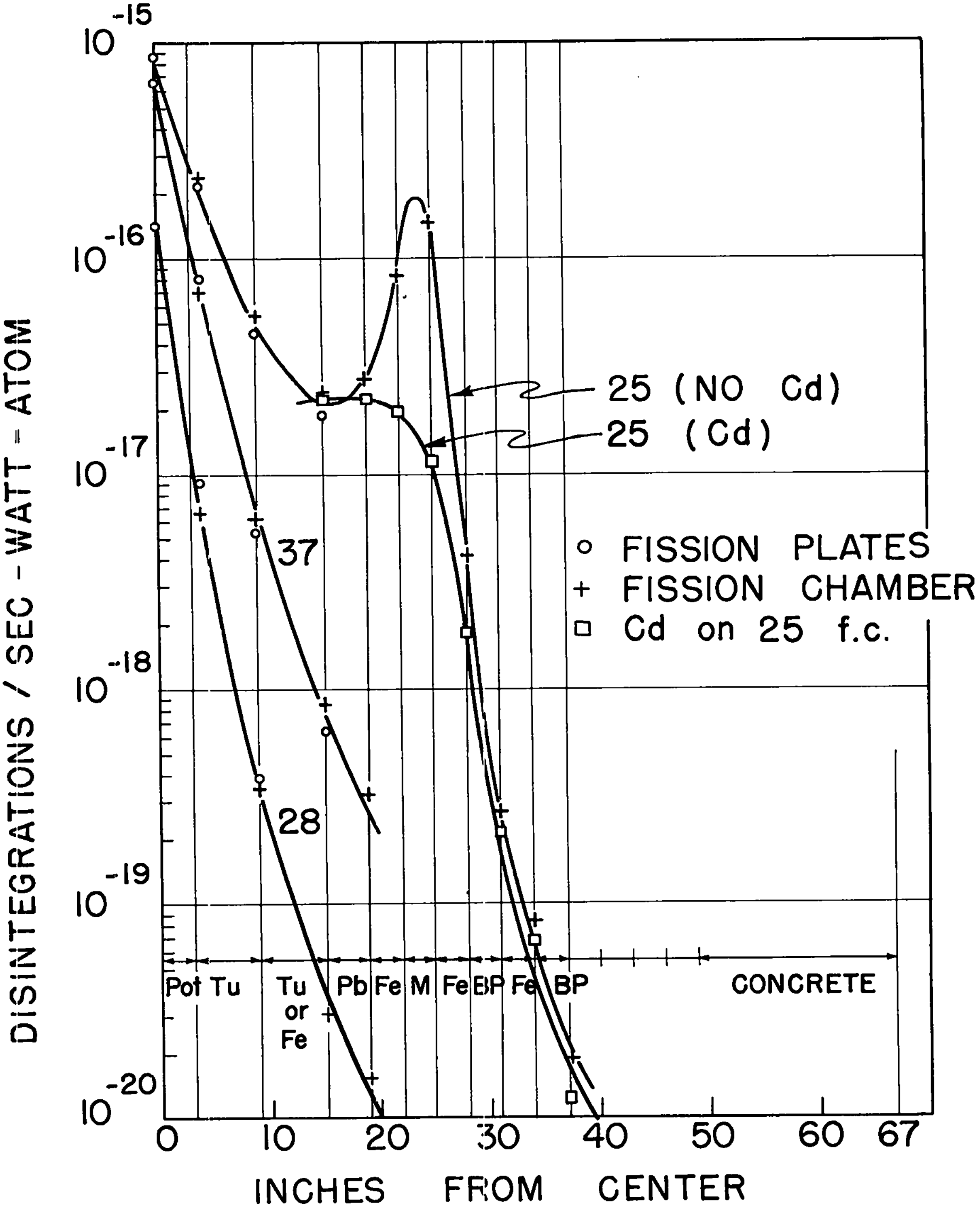

Fig. 50. Neutron attenuation in the shield.

[redacted]

TABLE 7. PHASE VOLTAGE VS MERCURY PUMP CURRENT

Pump current, amp	Phase voltage, V
2.0	50
4.0	99
6.0	147
8.0	196
10.0	243
11.0	266
12.0	289
13.0	315

It has been found that a pump current of about 11 amp produces a mercury flow of 9.1 liters per minute and does not overheat the pump even when the pump is handling mercury above 100°C.

The static, or closed discharge, pressure of the pump varies with current, as shown in Table 8.

TABLE 8. STATIC PRESSURE VS MERCURY PUMP CURRENT

Pump current, amp	Static pressure, cm Hg
1.0	0.00
2.0	0.95
3.0	3.2
4.0	6.0
5.0	9.5
6.0	14.0
7.0	20.3
8.0	28.9
9.0	35.6
10.0	45.7
11.0	58.4
12.0	65.4
13.0	77.8
13.5	87.6

The discharge head against which the pump operates is between 35 and 45 cm of mercury. Some of the pressure drops that can be measured, or estimated closely, are given in Table 9.

TABLE 9. PRESSURE DROP IN COOLING-SYSTEM COMPONENTS

Component	Pressure drop, cm Hg
Reactor pot	9.4
Heat exchanger No. 1	10.2
Heat exchanger No. 2	10.2
Supply tank	2.5
Venturi (loss)	1.0
	33.3

This list leaves the d-c flowmeter, the two screens, and the tubing and fittings as factors not included. Prior tests with the pump alone had shown that the discharge pressure, when the pump was operating at 11 amp, did not vary greatly when the flow was changed by throttling with a valve. These data, which are shown in Table 10, were taken on the pump before some alterations were made on the discharge nozzle, but are thought to be sufficiently accurate for our purpose.

TABLE 10. MERCURY PUMP DISCHARGE HEAD VS FLOW RATE AT 11 AMP

Discharge head, cm Hg	Flow rate, liters/min
47.0	5.75
48.2	4.6
48.9	3.5
48.2	2.7
49.2	1.9

The high pressure drop in the measuring system did not allow the flow to go as high as 9.1 liters per minute, but it is thought from the above data that the discharge pressure would still be about 45 cm at that flow. We thus have an estimated minimum of about 35 cm and a maximum of 45 cm. For further work we have assumed that the discharge pressure was 40 cm.

The efficiency of a pump of this type is very low compared to the conventional motor-driven centrifugal pumps, but this disadvantage is considered to be more than offset by the

[redacted]

absence of moving parts and other desirable features of the construction. The efficiency would doubtlessly depend upon the fluid being handled, and mercury is probably poor because of its relatively high density and electrical resistivity. Based on the 40-cm head and 9.1-liter per minute discharge, the efficiency at 11 amp is 2 per cent. By far the greater part of the energy loss appears in the mercury as heating caused by the eddy-currents. The heat in the mercury amounts to about 2.7 kw at 11 amp, but this is easily removed by the heat exchanger that follows the pump. This heat amounts to less than 10 per cent of the reactor power at the higher power outputs.

3.5.2 Heat Exchangers

The details of construction of the heat exchangers, which are identical, have been discussed elsewhere. Their important physical data are as follows:

Mercury Side	
Diameter of passage	0.870 in.
Cross-sectional area of passage	0.596 $in.^2$
Length of passage	31.4 in.
Surface area of passage	1031.6 $in.^2$
Velocity of mercury at 9.1 liters/min	15.55 in./sec
Pressure drop at 9.1 liters/min	1.97 psi
Water Side	
Cross-sectional area of passage	0.348 $in.^2$
Length of passage	23.9 ft
Surface area of passage	655.8 $in.^2$
Velocity of water at 1.5 gpm	16.6 in./sec

The total heat transfer coefficient for the heat exchangers is different for the two sides because of the different areas exposed to the fluid, and it varies with the flow of the fluids. The following figures in Table 11 are not considered to be the maximum obtainable with the heat exchangers, but only represent some typical data that have been taken. Increased water and mercury flow would increase the coefficient because of the increase in turbulency of flow.

[redacted]

[redacted]

TABLE 11. HEAT-EXCHANGER PERFORMANCE

Heat exchanger no.	Total kw	Transfer coefficient, Btu/hr/ft^2/^{o}F		Mercury flow, liters/min	Water flow, gpm
		Hg	Water		
1	10	107.0	168.1	9.10	3.0
2	10	105.6	166.1	9.10	3.0
1	17.73	86.0	135.2	5.29	2.5
2	17.73	92.9	131.5	5.29	2.5
1	18.83	106.9	168.1	6.52	2.5
2	18.83	88.2	138.8	6.52	2.5
1	20.0	118.4	186.2	9.10	3.0
2	20.0	96.4	151.7	9.10	3.0

3.6 Power Operation

3.6.1 Start-up

The operation of the reactor at any power requires that (a) the mercury, heat exchanger water, and reflector water are flowing; (b) the neutron level circuits are in operation; and (c) all temperatures are below values considered unsafe for power operation. As discussed in Chap. 2 these conditions are interlocked with the energizing voltage necessary for the operation of the control mechanisms. Further, the sequence circuit (see Sec. 2.2.4) requires that reactivity increases must be made in a certain order to ensure safe operation. Hence, the start-up of the reactor can only be made under safe conditions and operational procedures. With the safety block and shim rods in position, the reactor is brought to power by the control rods on periods which cannot be less than 10 sec owing to the rate safety circuit. It is shown in LAMS-733 that for the control speeds possible, that is, for the highest possible rate of k increase through control rod motion (about 1¢/sec), no dangerous condition can be realized.

The fission-chamber current indicated by the direct galvanometer responds linearly from about 0.5 watt to full power. The logarithmic-level amplifier responds from no power to full power, thereby allowing the initial neutron-level increase to be easily observed during start-up. No blind spot exists, therefore, in the start-up procedure.

3.6.2 Normal Operation

The reactor can operate continuously at powers up to 25 kw. Above this power it is operated for only a few hours consecutively because of the temperature of the reflector. Table 12 gives various equilibrium conditions of the reactor as a function of power. Because of the large heat capacity of the system, about 2 hr operation is required for temperature equilibrium to be established at 25 kw; less time is required at lower powers.

[redacted]

[redacted]

TABLE 12. NORMAL OPERATION CHARACTERISTICS

Operating power	50 w	10 kw	20 kw	30 kw
Calc. pot power	-	10.6	20.2	28.2
Calc. reflector power	-	1.4	3.2	4.7
Calc. total power	-	12.0	23.4	32.9
Pu temperature, °C	32	77.5	119.5	154
Mercury flow, liters/min	9.2	9.2	9.2	9.2
Mercury temperature into pot, °C	27	31.0	35	39.0
Mercury temperature out of pot, °C	29.5	68	105.5	137.5
Mercury temperature into heat exchanger No. 1, °C	27	63	99	134
Mercury temperature out of heat exchanger No. 1, °C	25.5	37.5	49.5	60.5
Water temperature in °C	24.5	24.5	24	24.5
Water temperature out of heat exchanger No. 1, °C	25.5	43.0	52	63.0
Water flow in heat exchanger, gpm	3.0	3.0	3.0	3.0
Mercury temperature into heat exchanger No. 2, °C	33.5	45.0	55.5	66.0
Mercury temperature out of heat exchanger No. 2, °C	27.5	31.5	35.5	39.5
Water temperature out of heat exchanger No. 2, °C	28.0	34.0	48	61.5
Water temperature out of heat exchanger No. 1 + No. 2, °C	27.5	38.0	50	63.0
Reflector temperature, °C	27	51.0	76	97
Reflector water flow, gpm	1.1	1.09	0.92	1.12
Reflector water temperature out, °C	26	29.5	37	40.5
S Control rod position, inches	2.85	4.65	7.15	9.54
Δ¢ of control rod necessary in excess of low power operation	0.00	-26.3	-57.0	-82
Δ¢ per kw		- 2.2	- 2.4	- 2.5

[redacted]

From the data in Table 12 the following information can be obtained. As an example, operation at 20 kw will be considered.

a. Power in reactor core

The power in the reactor pot is obtained by the heat and flow characteristics of the mercury. The flow through the pot is kept at 9.2 liters per minute and for 20 kw operation the mercury temperature rises 70.5°C. Thus, the power in watts being developed in the pot is:

$$P = \Delta T^{o}C \times \frac{\text{gm}}{\text{sec}} \times \frac{\text{calorie}}{{}^{o}C \text{ gm}} \times \frac{\text{watt-sec}}{\text{calorie}}$$

$$= 0.0311 \times 70.5 \times 9.2$$

$$= 20.2 \text{ kw}$$

b. Power from pump

The mercury temperature rise in going through the pump is 6°C, or the power added to the mercury from the pump is

$$0.0311 \times 6 \times 9.2 = 1.7 \text{ kw}$$

c. Power extracted from heat exchangers

$$P = \Delta T^{o}C \times \frac{\text{gal}}{\text{min}} \times 0.263$$

$$= 27 \times 3 \times 0.263$$

$$= 21.3 \text{ kw}$$

This can be compared with the sum of (a) and (b), 20.2 + 1.7 = 21.9 kw

d. Power in reflector

$$P = 0.263 \times \frac{\text{gal}}{\text{min}} \times \Delta T^{o}C \text{ kw.}$$

At 20 kw operating power the temperature rise of the reflector cooling water is 13^{o}, where the flow is 0.9 gallons per minute or the power being extracted from the reflector is 3.2 kw.

e. Over-all temperature coefficient

The temperature coefficient of the reactor has been discussed in Sec. 3.3.1. The over-all temperature coefficient in terms of Δ¢/kw is more meaningful for operation behavior and is about -2.5¢/kw.

[redacted]

3.6.3 Shut-down

As discussed previously, there are 12 safety interlocks which can cause the reactor to shut down. Of these, 11 will result in normal shut-down in which the rods and block will drop and the mercury will continue to circulate. This, of course, is the same condition as that when the reactor is normally shut off manually. If, however, the mercury flow should stop because of pump failure, stoppage, leakage, etc., the reactor will shut down, but without benefit of mercury circulation to provide shut-down cooling. These two conditions, shut-down with mercury circulation and shut-down without mercury circulation, are discussed here.

Normal Shut-down; Mercury Continues To Flow. Figure 51 shows several curves relating to normal shut-down. The fractional decrease of observed neutron intensity with time is shown, so that it may be compared with the calculated delayed neutron intensity. The delayed neutron curve was calculated using a k change at shut-down equal to \$10.00 (0.025 in k) and agrees very well with the observed fractional decrease of neutron intensity. The fission-product heating curve was calculated as described in LAMS-733. The sum of the delayed neutrons and fission product heating contributes to the shut-down power. The observed fractional decrease of the plutonium temperature after shut-down does not agree with the calculated sum because of the large heat capacity and slow cooling of the reflector and other parts.

Figure 52 shows normal shut-down temperatures of the plutonium and mercury. Normal shut-down operational procedures require that the mercury circulate about 1/2 hr before shutting the pump off.

Shut-down Without Continued Mercury Circulation. Figure 53 shows cooling curves of the mercury and plutonium without mercury circulation. These curves were obtained by shutting off the mercury pump and allowing the reactor to stop by the safety interlock system and are shown for comparison with normal shut-down. The initial drop in the plutonium temperature is due to the momentum of the mercury causing continued flow for 30 sec through the reactor pot, even after the pump has stopped. It is seen that no excessive or dangerous temperatures are reached, eliminating the necessity for operating the mercury pump from a diesel generator as originally planned (cf. LAMS-733). This fact makes the normal operation of the reactor simpler.

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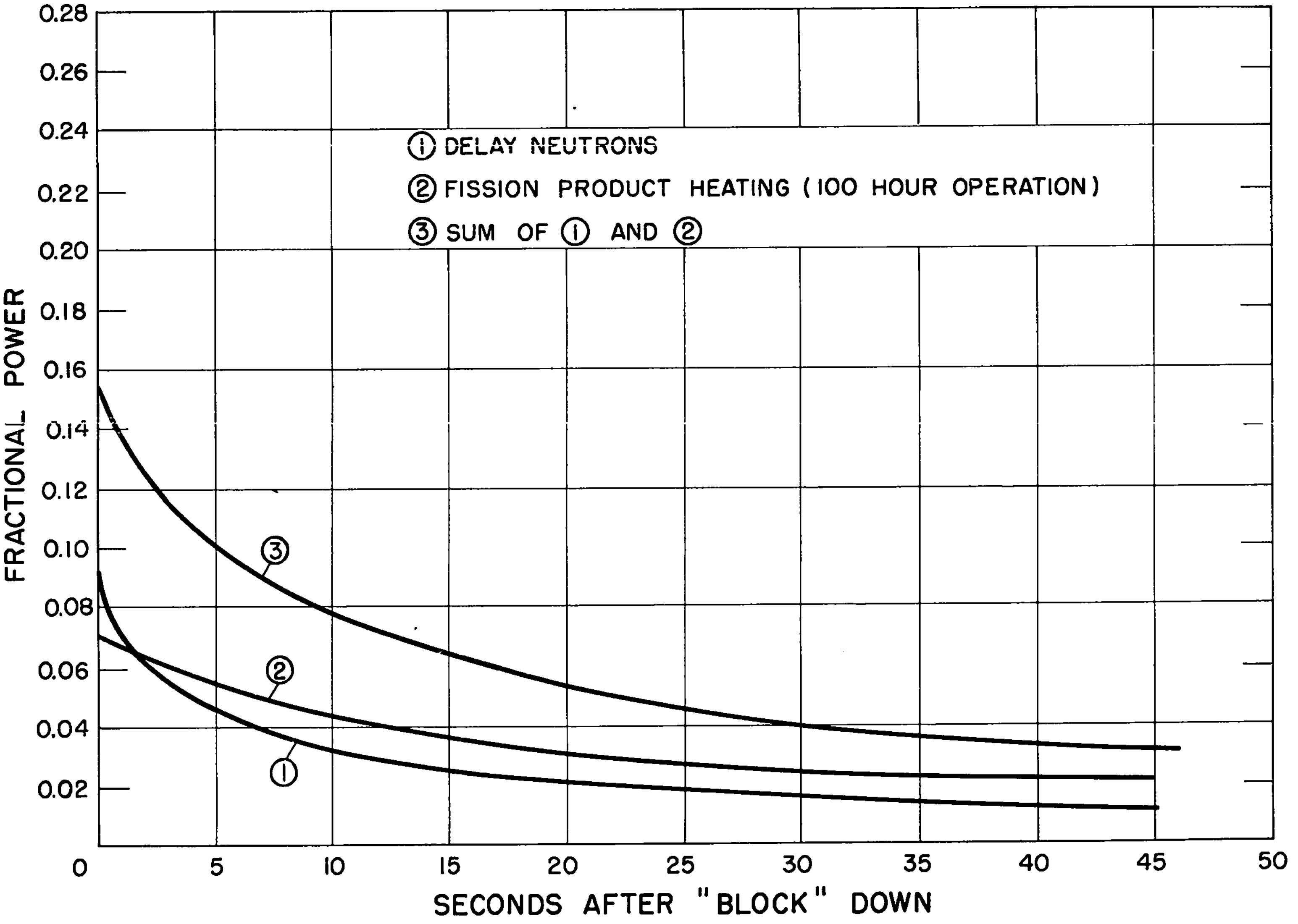

Fig. 51. Normal shut-down characteristics.

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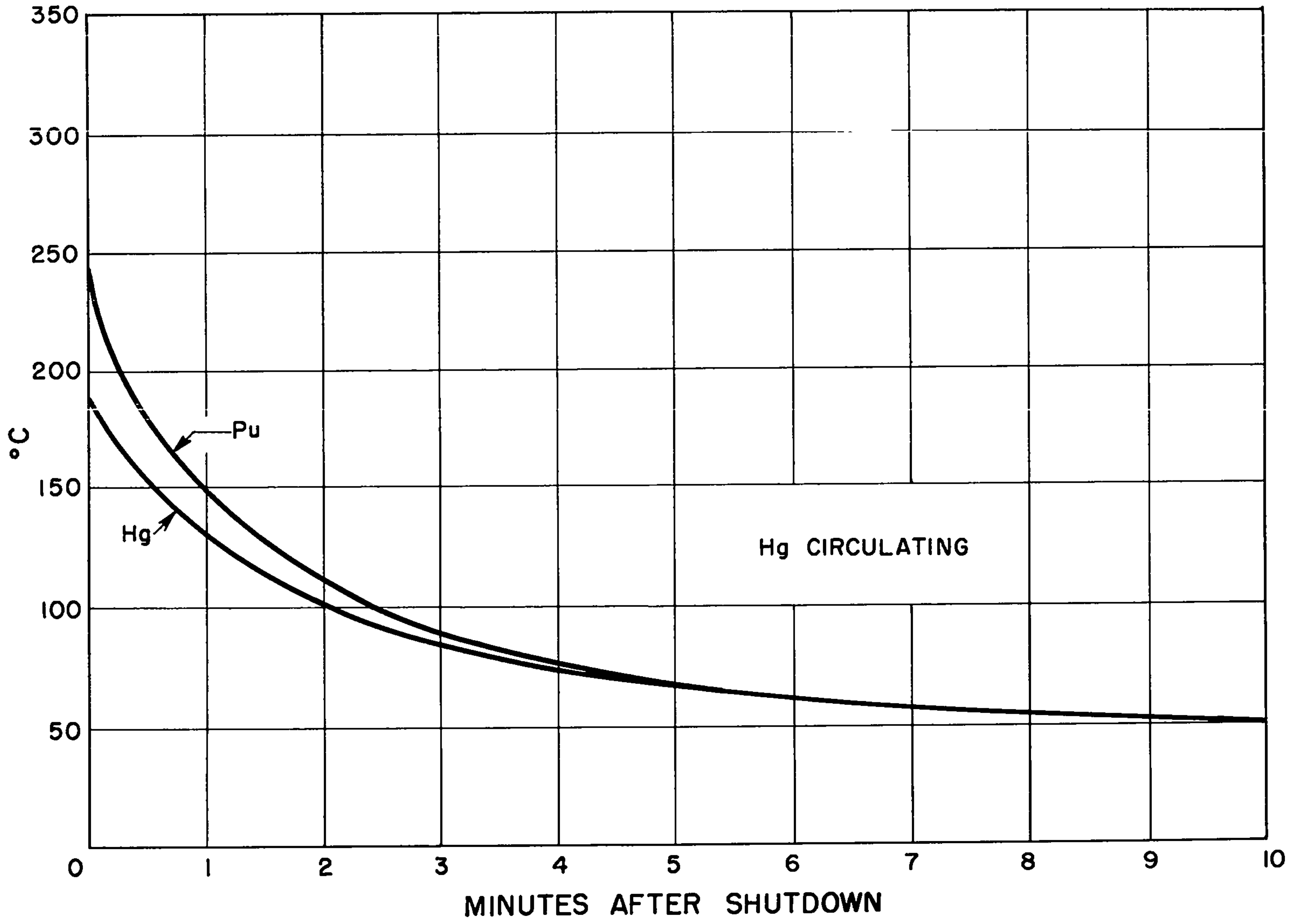

Fig. 52. Core temperatures -- with cooling.

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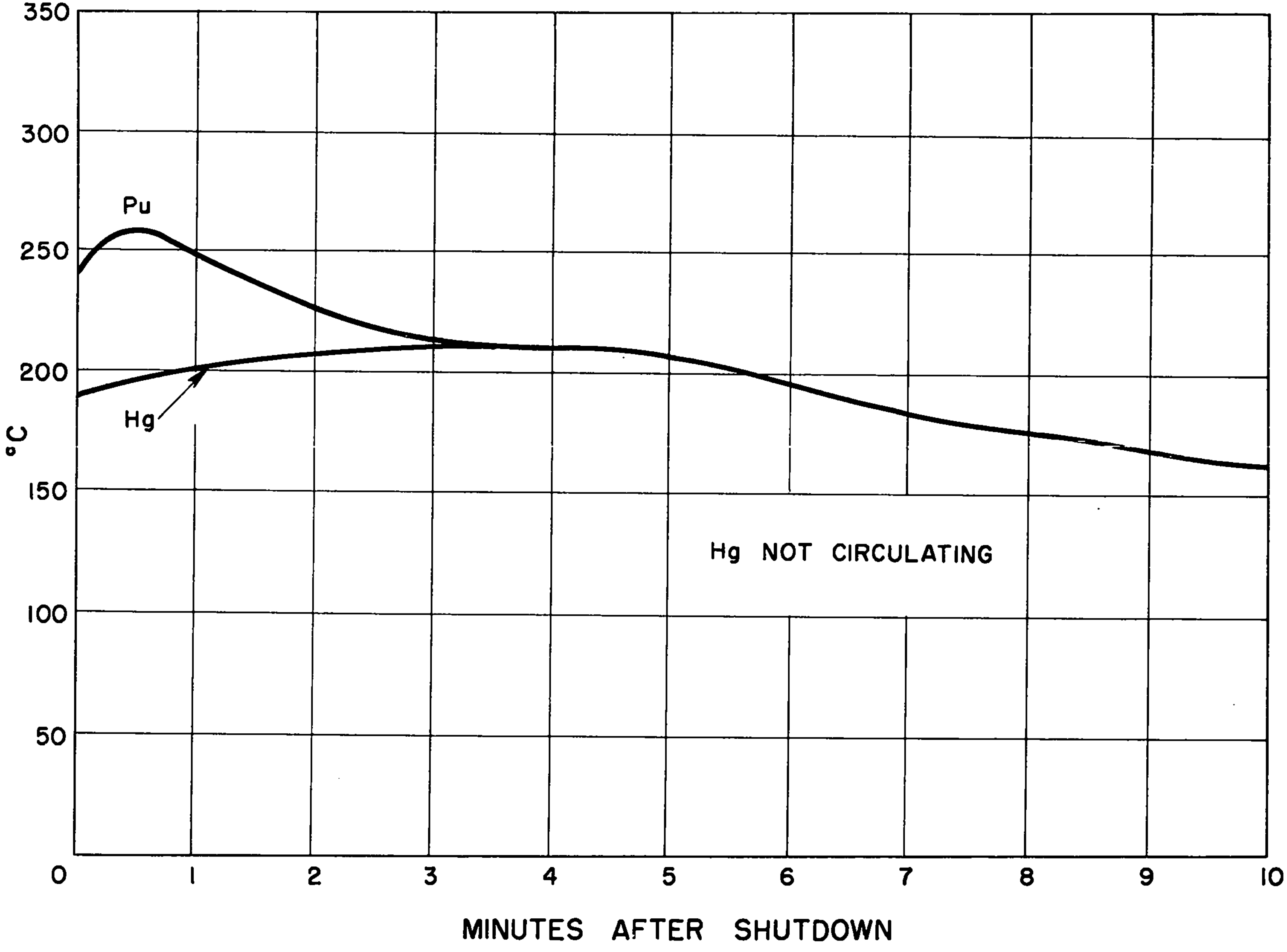

Fig. 53. Core temperatures -- without cooling.

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Chapter 4

NUCLEAR CHARACTERISTICS

4.1 Fast Neutron Spectrum and Flux

Before power operation of the reactor was attained, experiments were done under the direction of N. Nereson to determine the energy spectrum of neutrons at the center of the core under various fuel-loading conditions. The results of these experiments are reported in detail in LA-1192.

After the cooling system had been completed and power operation begun, further experiments were performed, again principally by N. Nereson, to ascertain the energy spectrum in one of the collimated fast neutron beams. These measurements are applicable to the final, sealed-in peripheral loading shown in Fig. 48. A complete summary of the experiments is given in LA-1234, and they will be only briefly described here.

Three different neutron detectors were used: (a) a hydrogen-filled cloud chamber, (b) proton recording nuclear plates, and (c) threshold fission foils. The cloud chamber was used to determine the low-energy region of the spectrum, from 0.1 to 0.8 Mev, and the nuclear plates to establish the high energy region, from 0.5 to 18 Mev. The threshold fission foils could be used to derive an approximate spectrum, but in this experiment they were primarily used as a check on the results of the two better resolving techniques. Absolute flux figures can be obtained from the nuclear plate and fission foil techniques. The experimental arrangement for the measurements is given in Fig. 54.

Figure 55 shows the cloud chamber results in the low energy region of the spectrum, up to 0.8 Mev. Figure 56 is a composite curve showing the cloud chamber results (expressed in units of flux) in the low energy region joined with the nuclear plate results in the high energy part of the spectrum. Although this spectrum gives flux figures for a 3/8 x 3/8-in. collimator, the corresponding fluxes for any collimator size, or, for that matter, for arbitrary positions within a collimator, can be gotten from simple geometry considerations.

Fission foils, U^{233}, Np^{237}, and U^{238}, were exposed to the same collimated beam spectrum to check the nuclear plate and cloud chamber results. In this part of the experiment the fission foils were placed over nuclear plates and this combination was exposed to the neutron beam with the surface of the foil and plate perpendicular to the beam. The fission tracks on the plate were counted and from several experiments an average figure of tracks (or fissions) per fissionable atom per kilowatt per second could be obtained. These results are presented in Table 13.

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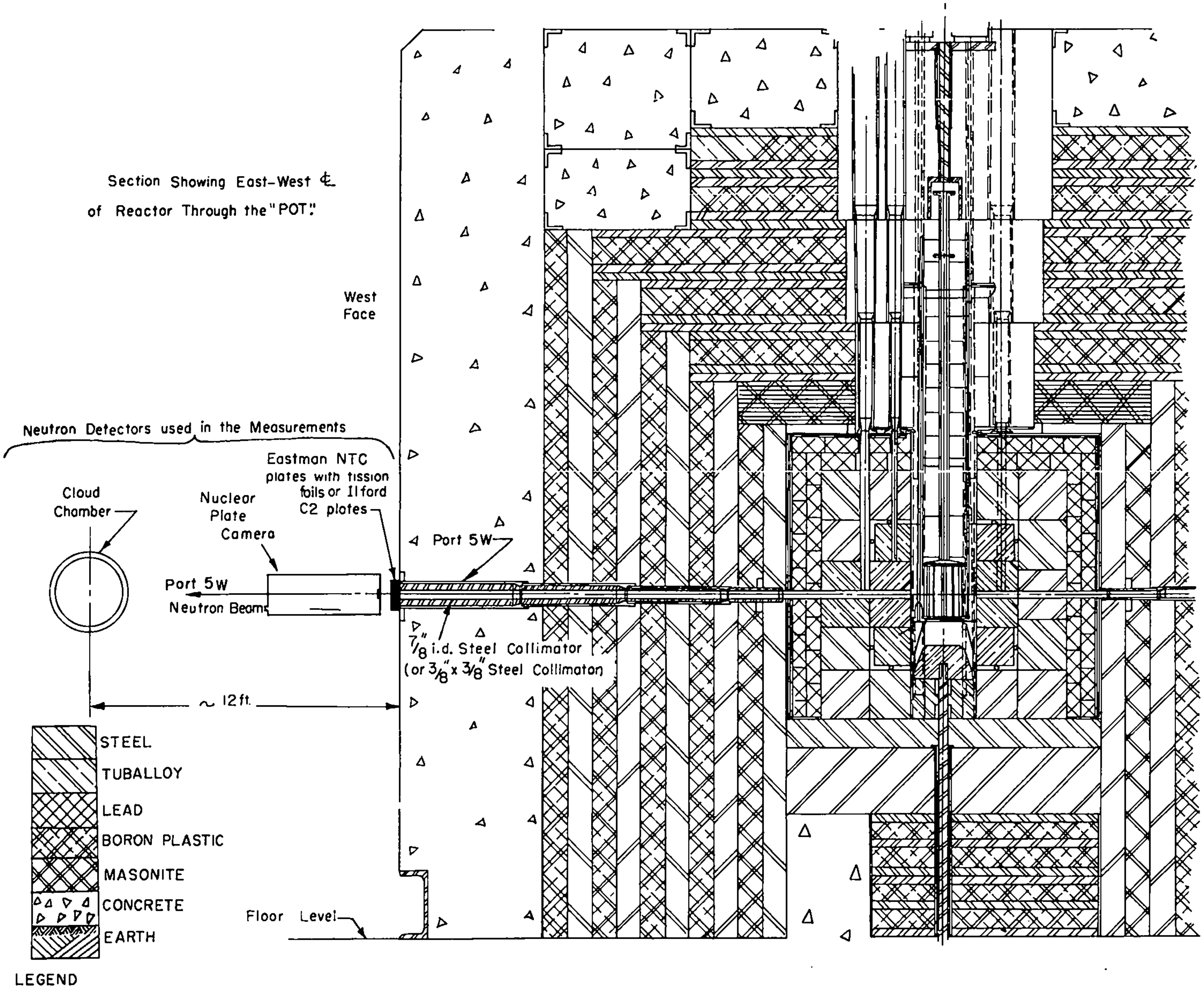

Fig. 54. Experimental arrangement for spectrum measurements.

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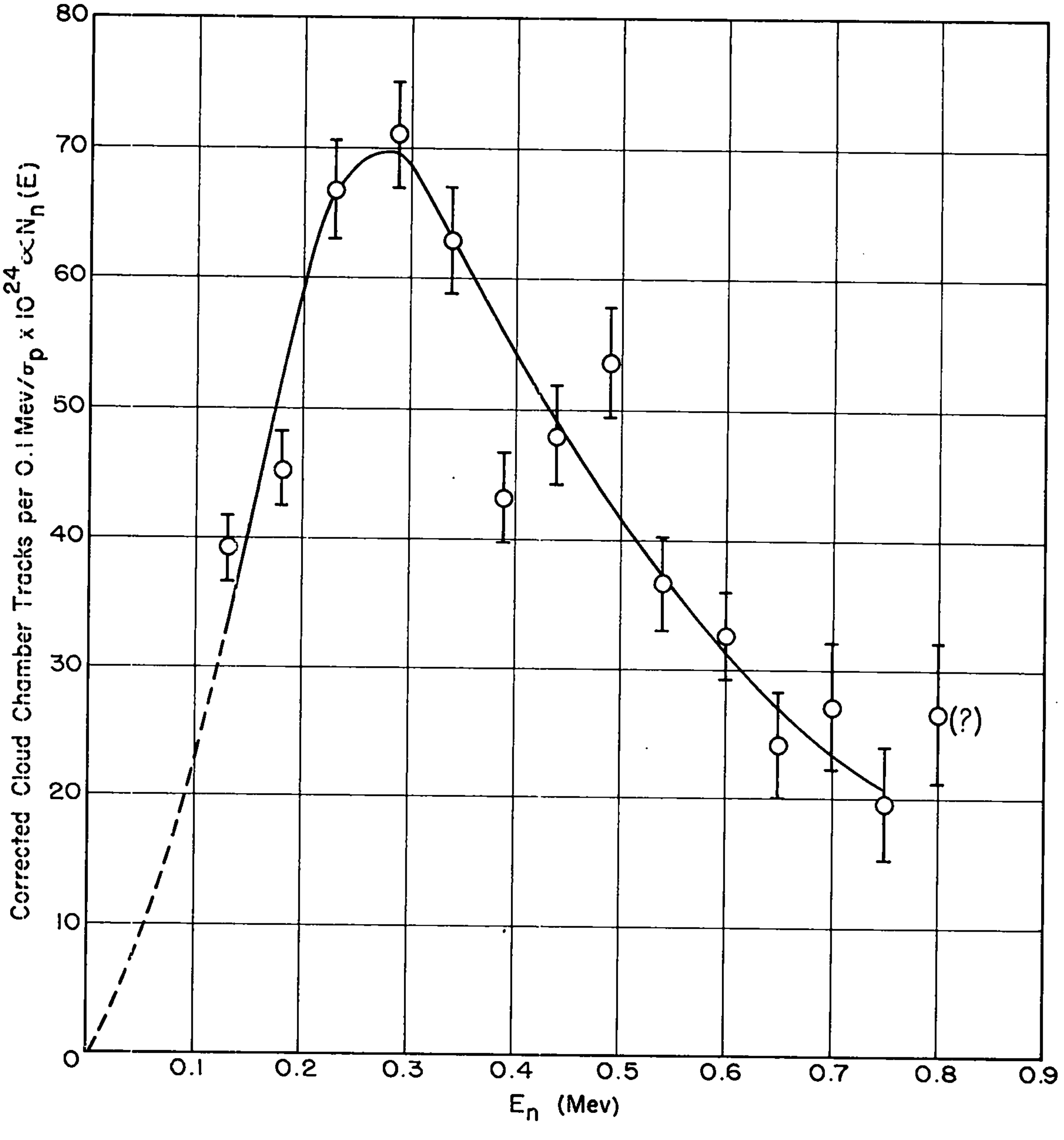

Fig. 55. Cloud chamber spectrum measurements.

[redacted]

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TABLE 13. THRESHOLD FISSION FOIL RESULTS

Foil	Fissions/atom/kw/sec 7.8-in.-ID collimator (area = A)	Calc. fiss/atom/kw/sec 3/8 x 3/8-in. collimator (area = A/4)
U^{235}	$8.0 \pm 0.2 \times 10^{-18}$	$2.0 \pm 0.05 \times 10^{-18}$
Np^{237}	$3.9 \pm 0.1 \times 10^{-18}$	$1.0 \pm 0.02 \times 10^{-18}$
U^{238}	$6.1 \pm 0.1 \times 10^{-19}$	$1.5 \pm 0.03 \times 10^{-19}$

These results now can be compared with values for the fission cross sections of the materials integrated over the spectrum of Fig. 56 (fission cross sections as a function of energy have been taken from LA-994).

$$\int_0^\infty nv(E)\ \sigma_f(235)dE = 2.1 \times 10^{-18} \text{ fiss/atom/kw/sec}$$

$$\int_0^\infty nv(E)\ \sigma_f(237)dE = 1.0 \times 10^{-18} \text{ fiss/atom/kw/sec}$$

$$\int_0^\infty nv(E)\ \sigma_f(238)dE = 1.5 \times 10^{-19} \text{ fiss/atom/kw/sec}$$

4.2 Neutron Flux Distribution in Active Region

Before the pot was sealed an experiment was done in an attempt to measure a profile of the neutron intensity across the fuel region. The reactor was operated at 1 watt for 30 min, and five representative plutonium rods were removed and gamma-counted through a narrow slit over the center of each rod. The results are presented in Table 14.

TABLE 14. PROFILE OF NEUTRON INTENSITY OVER THE FUEL REGION

Position, inches from center	Relative intensity
0	1.00
1.87	1.09
2.12	1.06
2.44	1.04
2.56	0.98

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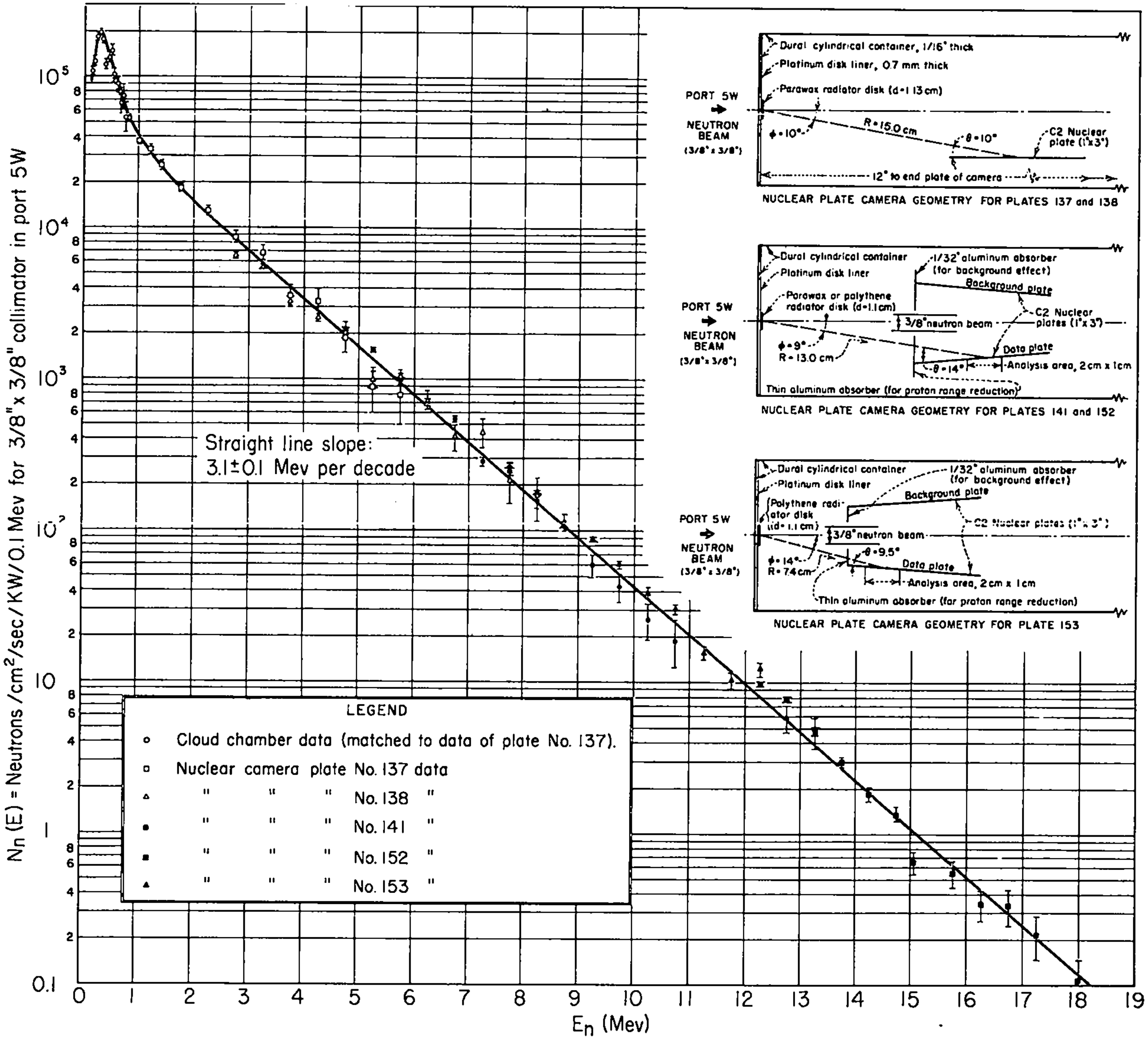

Fig. 56. Fast neutron spectrum.

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The horizontal neutron distribution in the pot is seen to be reasonably constant over the pot, with an average value equal to 1.03 times the central flux.

4.3 Danger Coefficient Experiments*

The change in reactivity when foreign material is introduced into the center of the reactor has been used as a measure of the effective cross section of the material for the neutron spectrum of the reactor. The experiments have been done with two loadings, "peripheral" and "central"; the latter loading yielded results of only academic interest insofar as being able to predict the changes in reactivity which might be caused by the sudden introduction of extraneous material into the core region is concerned, since the peripheral loading was chosen as the permanent fuel configuration.

4.3.1 Experimental Basis

Material introduced into the active region of a nuclear reactor will affect the reactivity (effective k) of the reactor by reason of additional absorption, altering the quality of neutrons sustaining the reaction, or by changing the fraction of neutrons escaping by leakage. The leakage factor can be minimized by restricting the samples to a small volume in the center of the active region. Then, since isotropy exists throughout the central region, scattering processes which do not alter the neutron energy can be neglected.

Absorption of neutrons by elements introduced can be considered as either productive or destructive, according to whether or not a neutron emerges from the reaction. Under this definition, productive absorption will include (n, f), (n, 2n), and (n, n), whereas destructive absorption will include (n, α), (n, p), and (n, γ) processes. The degree of productivity can be described by a number, ν.

Scattering of neutrons (n, n), both elastic and inelastic, can further be considered as either increasing or decreasing the pile reactivity depending on whether ν is greater or less than 1. For example, elements of low atomic mass may, through elastic scattering, cause reduction of neutron energy to regions where σ_f of plutonium is increasing rapidly (below 100 kev) and thereby increase the reactivity. Inelastic scattering in elements of higher atomic weight, however, may easily reduce the neutron energy to the extent that fission in U^{238} is no longer possible, but not far enough to gain by increased fission cross section in plutonium, thereby causing a net decrease in reactivity.

Now, if the change in reactivity produced by an element is compared to the change caused by Pu^{239} or U^{235}, a ratio of the various cross sections of the element under test to the well-established values for the fissionable element is obtained.

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*The material in this section is a duplication and extension of that given in LAMS-734 by David and Jane Hall.

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$$\frac{(\Delta k)_x}{(\Delta k)_f} = \frac{\left[(\nu_p - 1)\sigma_p - \sigma_a\right]_x}{\left[(\nu_p - 1)\sigma_p - \sigma_a\right]_f} \qquad (1)$$

where

σ_p = productive absorption = $\sigma_{(n,2n)}$, σ_f, $P_{e.s.}$, $\sigma_{in.s.}$

σ_a = destructive absorption = $\sigma_{(n,\alpha)}$, $\sigma_{(n,p)}$, $\sigma_{(n,\gamma)}$

ν_p = effective number of neutrons emerging from process p

x = element under test

f = fissionable material

For Pu^{239} and U^{235}, $\sigma_p = \sigma_{\text{fission}}$ and $\nu = \nu_f$, then

$$\frac{(\Delta k)_x}{(\Delta k)_f} = \frac{\left[(\nu_p - 1)\sigma_p - \sigma_a\right]_x}{(\nu - 1 - \alpha)_f}$$

or

$$\left[\sigma_a - (\nu_p - 1)\,\sigma_p\right]_x = -(\nu - 1 - \alpha)\,\sigma_f \frac{(\Delta k)_x}{(\Delta k)_f} \qquad (2)$$

ν_p is used to measure the relative effectiveness of neutrons produced by a reaction compared to the neutron absorbed. For (n, 2n) reactions $\nu_p \sim 2$, for $(n,n)_{e.s.}$ $\nu_p \sim 1$ or >1, depending upon the atomic mass, and for $(n,n)_{in.s.}$ $\nu_p \sim 1$ or <1, again depending upon the atomic mass.

Eq. (2) can be rewritten

$$\left[\sigma_a - (\nu_{n,2n} - 1)\sigma_{n,2n} - (\nu_{e.s.} - 1)\sigma_{e.s.} - (\nu_{in.s.} - 1)\sigma_{in.s.}\right]_x = -(\nu_f - 1 - \alpha)\sigma_f \frac{(\Delta k)_x}{(\Delta k)_f} \qquad (3)$$

If this general relation is considered in terms of atomic mass of the element, the relation can be somewhat simplified.

Elements of low atomic mass will have no $\sigma_{in.s.}$ term ($\nu_{in.s.} \sim 1$) and only two elements are known to have low enough (n, 2n) thresholds to be considered: Be (1.63 Mev threshold) and D (2.18 Mev). Other elements have known thresholds which range from 5 to

[redacted]

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10 Mev but because the neutron energy spectrum of the reactor has only 2 per cent of the total neutrons above 2.5 Mev the (n, 2n) contribution from other elements has been ignored.

For elements from A = 1 to A~15 where $\sigma_{e.s.}$ is important because relatively large energy losses occur in a single collision, $\nu_{e.s.} > 1$ because of the increase in $(\sigma_f \nu)$ of plutonium at the reduced energies. Eq. (3) becomes (with the exception of Be and D) for these elements

$$\left[\sigma_a - (\nu_{e.s.} - 1)\sigma_{e.s.}\right]_x = -(\nu_f - 1 - \alpha)\, \sigma_f \frac{(\Delta k)_x}{(\Delta k)_f} \qquad (4)$$

If $\sigma_a > (\nu_{e.s.} - 1)\sigma_{e.s.}$, the total effect will be to decrease the reactivity, and conversely if $\sigma_a < (\nu_{e.s.} - 1)\sigma_{e.s.}$, the total effect will be to increase the reactivity.

For Be and D

$$\left[\sigma_a - (\nu_{e.s.} - 1)\, \sigma_{e.s.} - \sigma_{(n,2n)}\right] = -(\nu_f - 1 - \alpha)\sigma_f \frac{(\Delta k)_x}{(\Delta k)_f} \qquad (5)$$

Elements in the middle of the periodic table can be considered to have $\sigma_{(n,2n)} \cong 0$, $\nu_{e.s.} \approx 1$ and $\nu_{in.s.} \leq 1$, depending upon the fissile material affected by the degraded neutrons. Little evidence exists for inelastic scattering in which the final neutron energy lies below 200 kev, and in this region the value of $(\sigma_f \nu)$ for plutonium does not change rapidly. Hence, for the reactivity contributed by the inelastically scattered neutrons producing fission in plutonium, $\nu_{in.s.} \sim 1$. For the reactivity contributed in U^{238} fission, $\nu_{in.s.} < 1$ because the neutrons can be degraded below the U^{238} threshold.

The same arguments may be used here as for elements of medium atomic mass. Equation (3) can be written for medium and high atomic mass elements

$$\left[\sigma_a + (\nu_{in.s.} - 1)\, \sigma_{in.s.}\right]_x = -(\nu_f - 1 - \alpha)\sigma_f \frac{(\Delta k)_x}{(\Delta k)_f} \qquad (6)$$

Here, all effects are to decrease the reactivity since $\nu_{in.s.} < 1$ upon the consideration of the effect on U^{238} fission.

4.3.2 Experimental Method

An experimental thimble of thin-walled steel tubing was installed in the center of the active region of the fast plutonium reactor. Figure 57 shows the two fuel configurations used for the experiment. Samples prepared in the form of powders and liquids were enclosed in spun aluminum cups which fitted the cavity.

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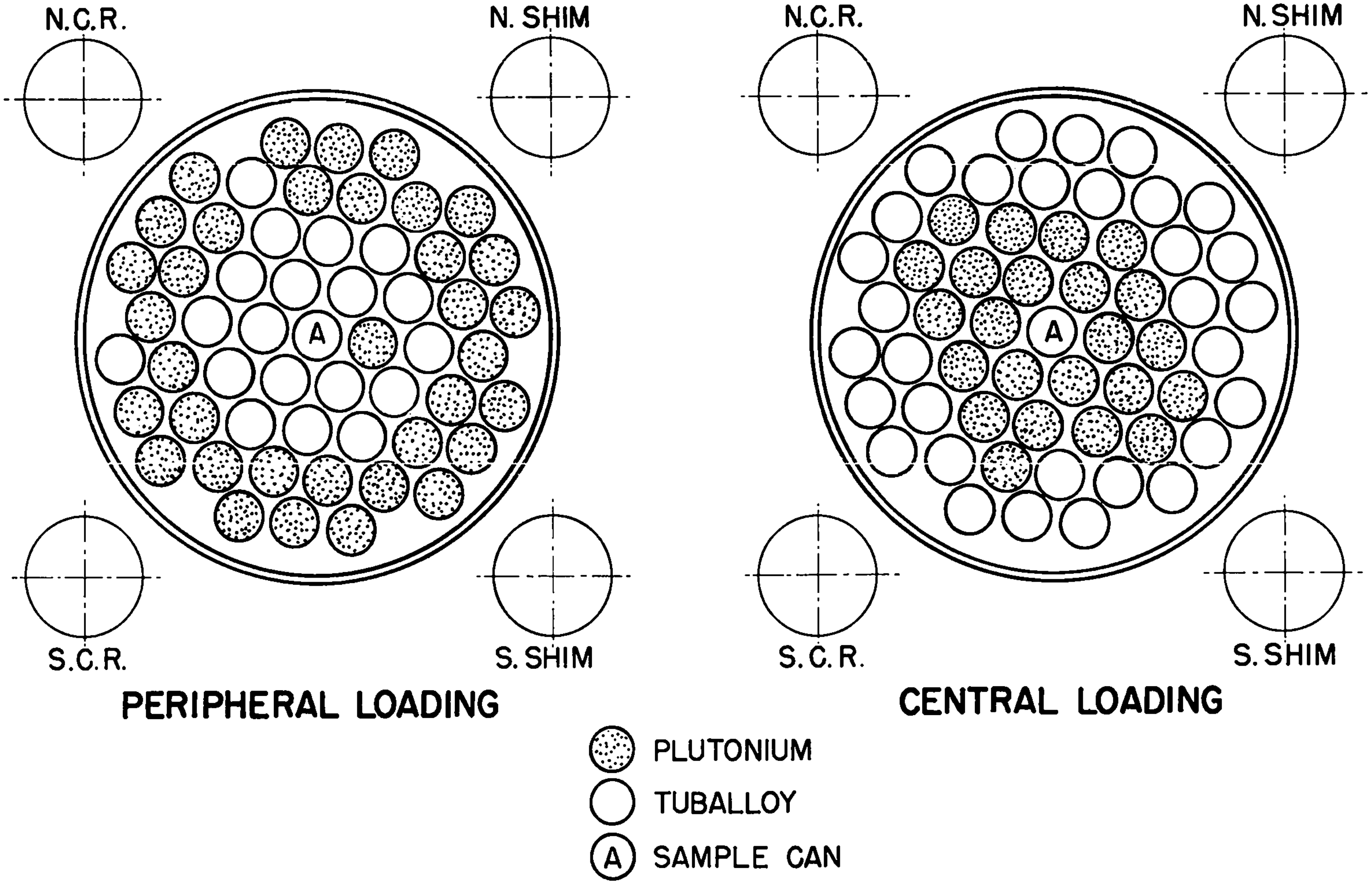

PERIPHERAL LOADING

CENTRAL LOADING

Fig. 57. Fuel loadings for the danger coefficient experiments.

[redacted]

The procedure was first to obtain a careful calibration for one control rod of excess reactivity in terms of reactor period as a function of position. The units used are cents (1/100 of the change in k between critical and prompt critical conditions; in the Fast Plutonium Reactor this has been measured as 1¢ = 2.5×10^{-5} in k.) The calibration and all measurements were done with the reactor operating at 1 watt. With the sample case in place and the cavity empty, the critical position of the calibrated control rod was determined for a base. The sample was then inserted and the new critical position measured. From the calibration curve, the change in reactivity produced by the sample was then interpreted in cents. Following two successive sample measurements, a base point with empty cavity was taken to correct for any changes in reactivity due to temperature.

In order to estimate the relative accuracy of the method, several determinations were made on selected elements such as Fe, Cu, and C. The spread of data indicated that differences in reactivity could be measured with a probable uncertainty of 0.05¢.

4.3.3 Experimental Results

The values of $\bar{\sigma}$ listed in Table 15 are obtained from an average of the constants for U^{235} and Pu^{239}. The values of the fission constants used are

Element	(σ_f)	$(\nu - 1 - \alpha)$
U^{235}	1.37	1.36
Pu^{249}	1.95	1.86

Referred to U^{235}, σ/Δ ¢ $= (1.36)(1.37)/(218) = 8.57 \times 10^{-3}$

Referred to Pu^{249}, σ/Δ ¢ $= (1.86)(1.95)/(417) = \underline{8.72 \times 10^{-3}}$

Average $= 8.65 \times 10^{-3}$

The agreement is better than the accuracy assigned to the constants. Note that $\bar{\sigma}$ is the left-hand side of Eq. (4), (5), and (6) and therefore includes σ_a and σ_s of the element measured, and reactivity effects due to degradation.

TABLE 15. AVERAGE CROSS SECTIONS BY THE DANGER COEFFICIENT METHOD

Material	At. No.	$\bar{\sigma}$(central) mb	$\bar{\sigma}$(peripheral) mb
Be^9	4	+45 ± 2	+23 ± 1
Be^{10}	5	-660 ± 3	-843 ± 5
B	5	-153 ± 3	-145 ± 3
C	6	+6.6 ± 2	+7 ± 1

[redacted]

TABLE 15. Continued

Material	At. No	$\bar{\sigma}$(central) mb	$\bar{\sigma}$(peripheral) mb
Al^{27}	13	-12.4 ± 1	-14 ± 1
Si	14	-12.7 ± 3	
S	16	-77.5 ± 3	
Ca	20	-56.2 ± 2.5	
Ti	22	-27 ± 1.8	
V^{51}	23	-15.1 ± 2.5	-11 ± 2
Cr	24	-22.8 ± 3	-29 ± 1.3
Mn^{55}	25	-12.2 ± 2	-19.5 ± 1.2
Fe	26	-39.5 ± 2	-32.3 ± 1
Co	27	-30.0 ± 1	-28.0 ± 1
Ni	28	-63.0 ± 2	-46.0 ± 1
Cu	29	-44.0 ± 3	-41.8 ± 1
As	33	-78.0 ± 3	
Zr	40	-26.8 ± 3	-37.0 ± 4
Nb^{93}	41	-92.0 ± 7	-102.0 ± 2
Rh	45	-189 ± 4	
Ag	47	-205 ± 2	-271 ± 1
Cd	48	-111 ± 3	-125 ± 1
Sn	50	-78.5 ± 5	
I	53	-75.0 ± 4	
Ta	73	-209 ± 2.5	-259 ± 1
W	74	-119 ± 3	-131 ± 1
In	77	-232 ± 3	-291 ± 2
Au^{197}	79	-178 ± 1.5	-208 ± 1
Hg	80	-93.0 ± 3	-103 ± 1
Pb	82	-19.6 ± 2	-16.0 ± 1.7
Bi	83	-24.8 ± 2.5	-19.7 ± 1.7
Th^{232}	90	-128 ± 2	-170 ± 2
U	92	+150 ± 2.5	+28 ± 1
		Compounds	
H_2O		+463 ± 5	+48.5 ± 1.7
D_2O		+90.8 ± 1	

[redacted]

[redacted]

TABLE 15. Continued

Material	$\bar{\sigma}$(central) mb
LiF	+35.4 ± 2.5
NaF	+5.0 ± 2.5
CaF_2	-15.0 ± 6

4.3.4 Interpretation

The values of $\bar{\sigma}$ obtained in this investigation include scattering and absorption cross sections in a manner previously described. Until more information is obtained about the nature of these specific processes, it is difficult to separate the individual factors which make up the gross observable effect. It is interesting, however, to examine the results of a few elements in the light of the previous discussion.

Using the spectral distribution of neutron energy as determined in LAMS-727, and the absorption curve for boron reported by Bailey et al. (Wall Paper Book), or RMP 19, 265, (1947), it is possible to calculate an effective absorption cross section for the reactor.

$$\bar{\sigma}_a = \frac{\int nv \ \sigma_a(E)dE}{\int nv \ dE} = 156 \text{ mb}$$

The experimental value, measured as B^{10} is 843 mb, which, corrected for isotopic abundance, becomes 155 mb.

This excellent agreement is certainly fortuitous but it probably reflects the fact that $\bar{\sigma}_a$ is large and represents the primary interaction with neutrons.

The same calculation and comparison can be made in the case of Au

$$\bar{\sigma}_r = \frac{\int nv \ \sigma_r(E)dE}{\int nv \ dE} = 157 \text{ mb}$$

The experimental value is 204 mb. The discrepancy of 47 mb possibly measures the inelastic degradation of neutrons by Au.

Several of the light elements produced positive reactivity changes which demonstrate the predominance of the scattering term over absorption. To examine these cases, one can assume absorption to be negligible and that $\sigma_p = \sigma_t$. Substituting the proper constants in Eq. (4), one obtains:

[redacted]

[redacted]

Element	$\bar{\sigma}$, mb	σ_t(0.65 Mev), b	ν
H(in CH_2)	13	5	1.0026
C	7	3	1.0023
B^{11}(in B)	9.5	2.5	1.0038
		Average $\nu_{e.s.}$ =	1.003

In the case of Be, Eq. (5) must be used. Here there are three terms to separate:

(n, n); assume similar to H, C, B^{11} (σ_t = 3.3 b, ν = 1.003)

(n, α); calculate according to B^{10}

(n, 2n); credit with balance to effect

$\left[\sigma_a - (\nu - 1)\,\sigma_{e.s.} - \sigma_{(n,2n)}\right] = -23$ mb

$$\sigma_{(n,2n)} = 23 - 0.003 \times 3.3 \times 10^3 + \frac{\int nv\ \sigma_a(E)dE}{\int nv\ dE}$$

$$= 23 - 10 + 6$$

$$\sigma_{(n,2n)} = 19 \text{ mb}$$

Further interpretation of the results in terms of the component factors will be postponed until additional information is obtained with other fuel rod configurations and activation cross section measurements.

Conversations with Harvey Brooks of Knolls Atomic Power Laboratory, S. Untermeyer of Argonne, and John Menke of Oak Ridge National Laboratory, at the April Information Meeting at Brookhaven, were very helpful in the preliminary interpretation of these data. A private communication from Harvey Brooks pointed out the importance of inelastic scattering in connection with fast fission in U^{238}.

4.4 Experimental Facilities*

The schematic plan view of the reactor in Fig. 58 illustrates the experimental holes with the exception of the vertical holes, which ports are located on top of the reactor. Table 16 gives the U^{235}, U^{238} and Np^{237} fission activities in various regions, describes the sizes, uses, etc., of the holes and in the regions where there is no thermal neutron contribution gives reasonable estimates of the total flux and effective energy existing in these regions. The fluxes were estimated by a method discussed in LAMD-125 and are stated with an error of ±20 per cent. At the present time it is estimated that in the 63-in. position in

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* This section has been issued separately as LAMS-908.

[redacted]

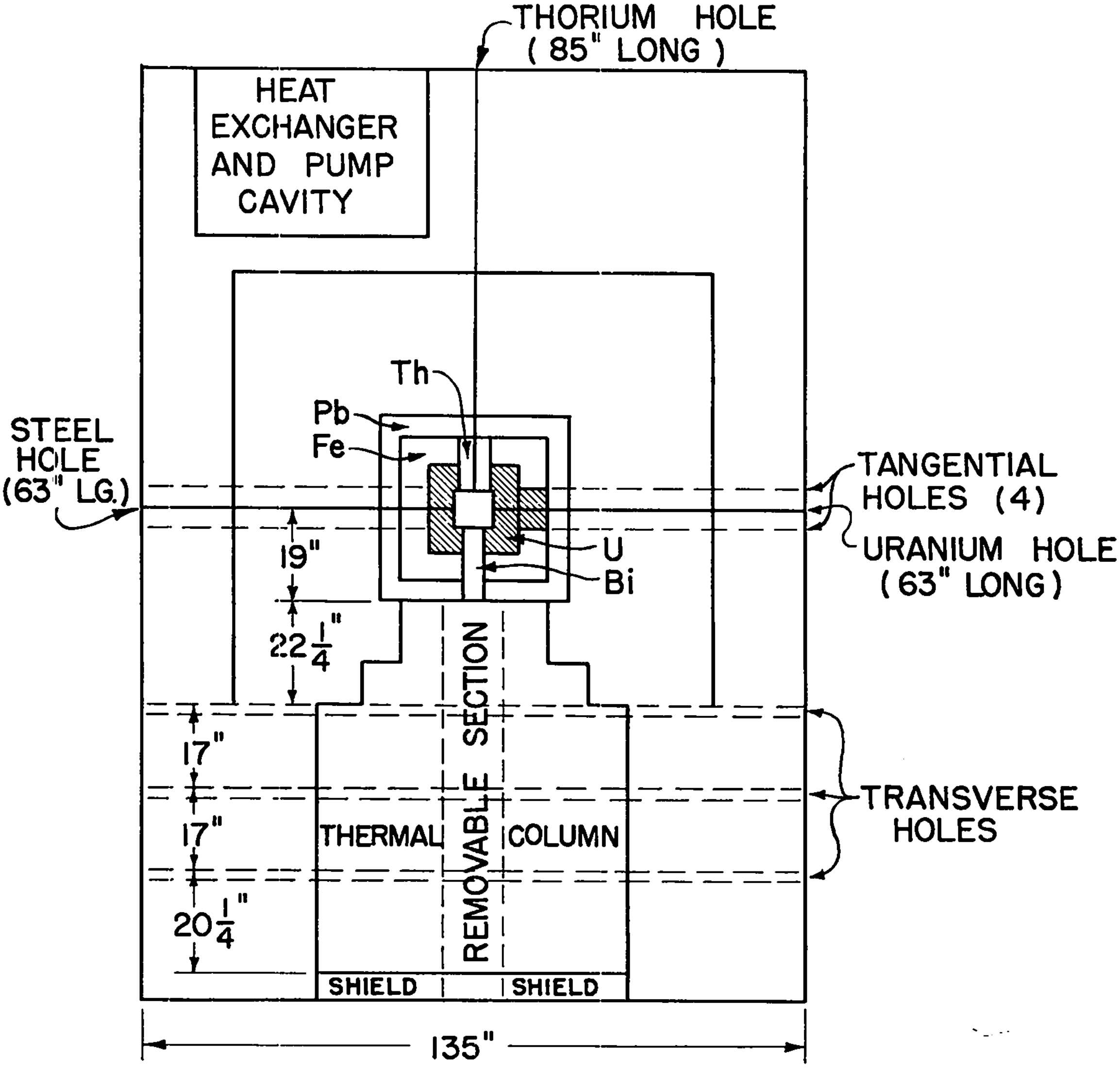

Fig. 58. Fast reactor experimental facilities.

[redacted]

the uranium hole, 8 per cent of the neutrons have energies above 1.4 Mev, 24 per cent have energies between 0.6 and 1.4 Mev, and 68 per cent have energies below 0.6 Mev. Table 17 gives the U^{235} activity as a function of position in tangential hole No. 1.

The maximum power available is 40 kw. It is preferable, however, not to operate for longer than 1 hr at powers exceeding 25 kw in order to avoid over-heating of the uranium reflector. The power equilibrium temperatures in the 63-in. position in the uranium hole are (25 + 4 x No. of kw)°C with a 20°C drop to the 58-in. position. Thus the type of material to be irradiated governs the power level unless auxiliary cooling for the sample is provided.

The graph, Fig. 59, which shows the thermal fluxes and cadmium ratios in the thermal column is self-explanatory.

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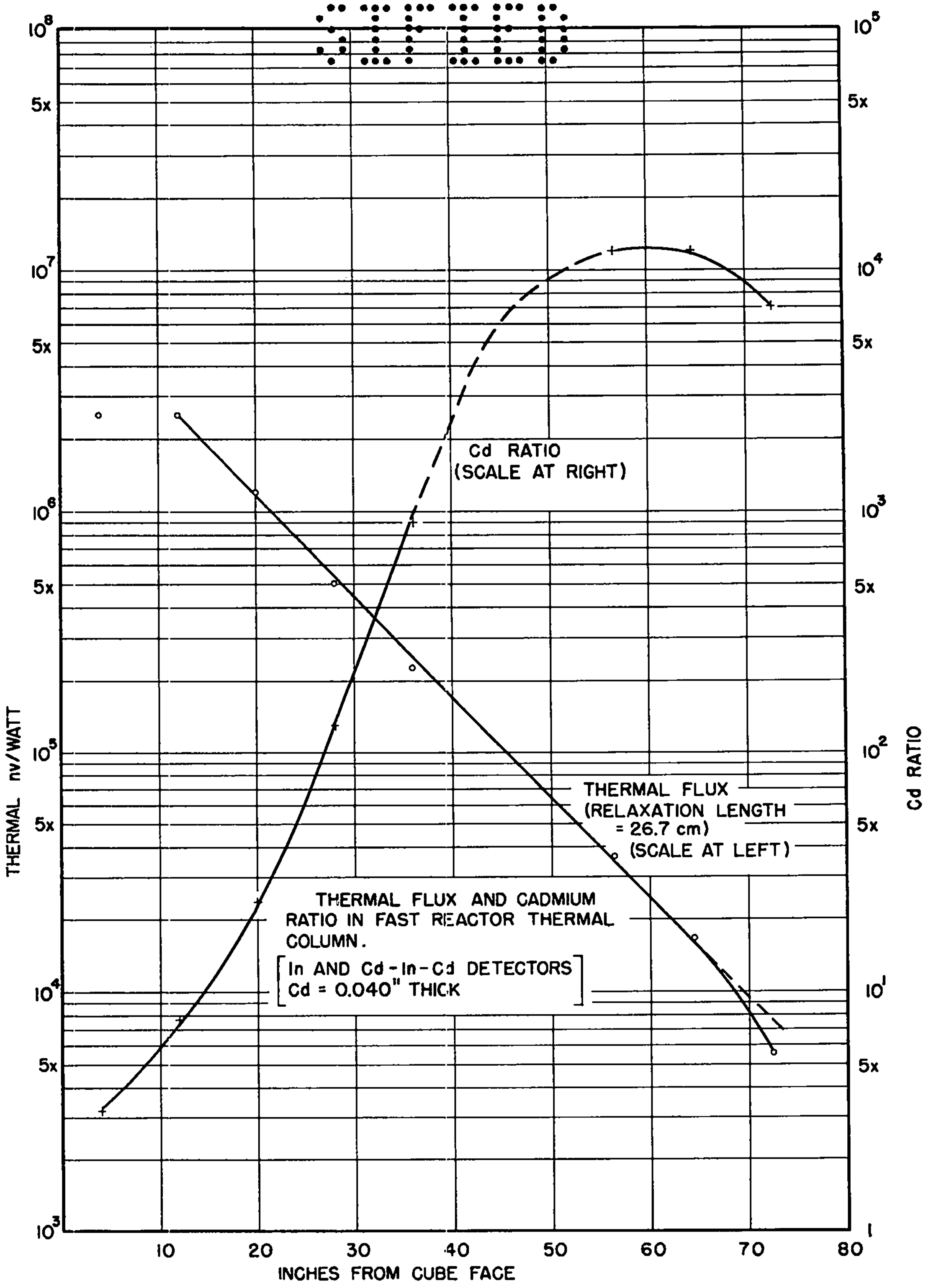

Fig. 59. Flux in the thermal column.

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TABLE 16a. FAST REACTOR EXPERIMENTAL FACILITIES

							Neutron spectrum, fissions/sec-g-watt Np^{237}: Effective threshold = 0.6 Mev U^{238} : Effective threshold = 1.4 Mev				
Facility	Use*	Maximum size of sample, inches	Distance from floor, inches	Depth of hole, inches	Description	Depth of sample in hole, inches	U^{235}	Np^{237}	U^{238}	nv/watt	$E_{eff.}$, Mev
Uranium	B or I	0.90	41	63	Hole extends horizontally through shield on center line of reactor to 1 in. from edge of active material region. A volume of uranium 8 x 8 x 11 in. surrounds hole to lead shield.	63	6.6×10^5	2.8×10^5	2.7×10^4	1.7×10^8	0.4
						58	1.8×10^5	3.6×10^4	3.8×10^3	4.4×10^7	0.3
						0	60.2	42.4	3.6	1.5×10^4	0.4
Thorium hole	B or I	0.65	41	85	Same as uranium except a volume of thorium 6 in. diameter x 11 in. surrounds hole to lead shield.	85	6.3×10^5	2.5×10^5	2.2×10^4	1.6×10^8	0.4
						82	3.0×10^5	7.5×10^4	5.2×10^3	7.3×10^7	0.3
Steel hole	I	0.55	41	63	Same as uranium except volumes of U(8 x 8 x 5 in.) and of Fe(8 x 8 x 6 in.) surround hole to lead shield. Not suitable for beam work because of wall proximity.	Approximately same as U and Th holes.				Not measured.	
Tangential holes	I	1) 0.80	45-1/2	135	Holes go completely through reactor tangentially to active material region on the corners of a 9 x 9 in. area section.	1) 67	3.8×10^5	1.0×10^5	1.0×10^4	9.5×10^7	0.3
		2) 0.80	45-1/2	135		2) 67	3.8×10^5	1.0×10^5	1.0×10^4	9.5×10^7	0.3
		3) 0.70	36-1/2	135		3) 67	3.5×10^5	8.6×10^4	6×10^3	8.5×10^7	0.3
		4) 0.80	36-1/2	135		4) 67	3.5×10^5	8.6×10^4	6×10^3	8.5×10^7	0.3
Thermal column removable section	B or I	Varies	41	76	8 removable graphite stringers each 4-1/4 x 4-1/4 x 76 in. One stringer has holes (with plugs) 3 x 2 in. ID spaced at 8-in. intervals.			See Fig. 59.			
Transverse holes (3)	B or I	2 x 2	33	135	2 x 2-in. holes extending transversely through thermal column.						

*B = beam; I = irradiation.

[redacted]

TABLE 16b.

Facility, vertical holes	Use*	Maximum size of sample, inches	Location of bottom of hole from center of active material, inches	Description	Neutron spectrum, fissions/sec-g-watt				
					U^{235}	Np^{237}	U^{238}	nv/watt	$E_{eff.}$, Mev
1 T	I	0.90	9-1/8 up; 9.5 radius steel-uranium interface. Depth = 107-3/8	All vertical holes extend from top housing through shield and into reflector regions indicated. Holes 3, 4, 5, 6, 7 are in use by P-5.	$1.3x10^5$	$7.4x10^3$	240	--	--
2 T	I	0.90	1/4 up; 7.0 radius uranium. Depth = 116-1/4		$2.8x10^5$	$6.7x10^4$ q	$4.4x10^3$	$6.8x10^7$	0.3
8 T	I	0.90	1/2 up; 9.5 radius uranium. Depth = 116		$1.4x10^5$	$2.4x10^4$	$1.5x10^3$	$3.0x10^7$	0.25
9 T	I	0.90	9-1/8 up; 9.8 radius steel-uranium interface. Depth = 107-3/8		$1.3x10^5$	$7.4x10^3$	240	--	--

* I = irradiation.

[redacted]

TABLE 17.

VARIATION OF U^{235} FISSION ACTIVITY WITH POSITION IN TANGENTIAL HOLE NO. 1

Distance in from west face, inches	Fissions/ sec-g-watt
59	1.4×10^5
63	2.7×10^5
65.5	3.6×10^5
67	3.8×10^5
67.5 (center)	3.8×10^5
69.5	3.5×10^5
72	2.6×10^5
76	1.7×10^5
78	1.8×10^5
80	1.8×10^5