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DESIGN SUMMARY REPORT ON THE JUGGERNAUT REACTOR

by

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Reactor Engineering Division

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DISCLAIMER

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I. INTRODUCTION

The JUGGERNAUT (see Fig. 1) is a light-water-cooled-and-moderated, graphite-reflected, heterogeneous, thermal reactor at Argonne National Laboratory. The reactor is designed to provide experimental facilities for the conduct of basic research in the range of neutron flux up to 4.0 x 10^{12} n/(cm^2)(sec) at an operating power level of 250 kw. The major design and operating characteristics of JUGGERNAUT are summarized in Table I.

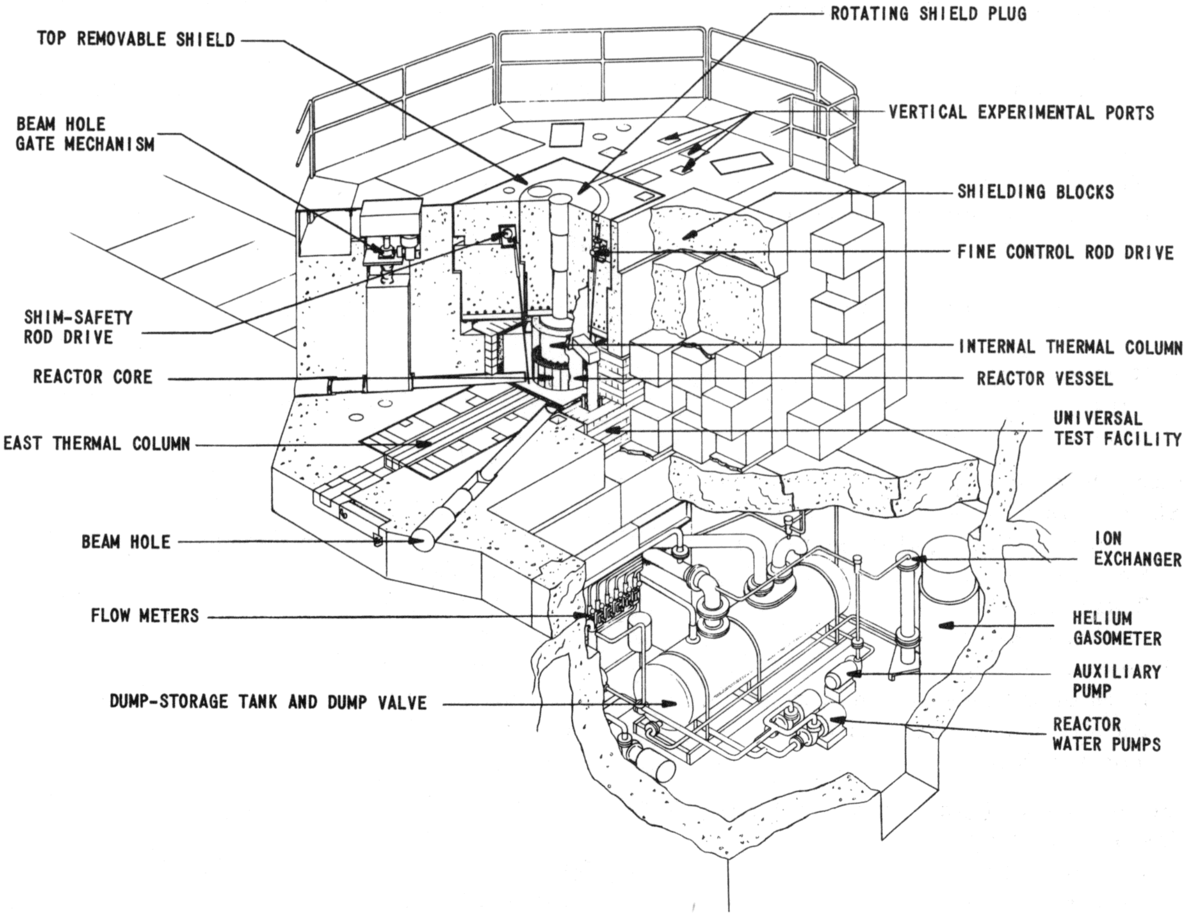


Fig. 1. JUGGERNAUT Reactor

Table I

SUMMARY OF JUGGERNAUT DESIGN AND OPERATING CHARACTERISTICS

Power level	250 kwt
Pressure	Atmospheric
Coolant-moderator	H_2O
Core (annular)	
Inside diameter	46 cm (18 in.)
Outside diameter	61 cm (24 in.)
Active height	57.2 cm ($22\frac{1}{2}$ in.)
Fuel assemblies	
Total number	20
Fuel plates per assembly (maximum)	12
Plate dimensions	66 x 7.3 x 0.178 cm (26 x $2\frac{7}{8}$ x 0.070 in.)
Fuel composition	15.2 wt-% uranium, 84.8 wt-% aluminum
Thickness of "meat" in plate	0.102 cm (0.040 in.)
Fuel enrichment	93% U^{235}
Cladding (Type 1245 aluminum)	0.038 cm (0.015 in.)
Control Rods	
Configuration	Blade
Shim	3
Safety	4
Fine control	1
Dimensions (Control Section)	
Shim-safety rods	48 x 17.8 x 0.274 cm (19 x 7 x 0.108 in.)
Fine control rod	29.2 x 2.54 x 0.020 cm ($11\frac{1}{2}$ x 1 x 0.008 in.)
Material	
Shim-safety rods	2 wt-% natural boron-steel
Fine control rod	Cadmium
Control Rod Drives	
Shim-safety rods	Window-shade type
Rate of withdrawal (maximum)	0.30 cm/sec (0.118 in./sec)
Rate of reactivity addition	0.01% $(\Delta k/k)$/sec
Total travel	50 cm ($20\frac{3}{4}$ in.)
Scram time	<0.5 sec
Fine control rod	Rack and pinion
Rate of withdrawal (maximum)	0.33 cm/sec (0.13 in./sec)
Rate of reactivity addition	<0.003% $(\Delta k/k)$/sec
Total travel	20 cm (8 in.)
Reactor Vessel (two welded sections)	
Inside diameter	
Upper section	74.6 cm ($29\frac{1}{2}$ in.)
Lower section	61 cm (24 in.)
Overall height	196 cm (77 in.)
Wall thickness	0.48 cm ($\frac{3}{16}$ in.)
Material	Type 5052-H34 aluminum

Table I (Cont'd.)

Nuclear Data	
Neutron flux	
Thermal	
Maximum	4.0 x 10^{12} n/(cm^2)(sec)
Core average	1.7 x 10^{12} n/(cm^2)(sec)
Fast	
Maximum	7.0 x 10^{12} n/(cm^2)(sec)
Core average	5.2 x 10^{12} n/(cm^2)(sec)
Minimum critical mass	3.3 kg U^{235}
Maximum loading (~6.5% k_{ex})	4.2 kg U^{235}
Fuel consumption	62 gm/yr
Average H^1:U^{235} atom ratio	380
Average H_2O:Al volume ratio	2.93
Average void coefficient of reactivity	-0.15% (Δk/k)/% void
Average prompt temperature coefficient of reactivity (20° to 65°C)	-0.015% (Δk/k)/°C
Reactivity effect of equilibrium xenon at 250 kw	-0.80% Δk/k
Maximum excess reactivity controlled by shim rods	4.2% Δk
Combined worth of shim-safety rods	7.0% Δk
Heat Transfer and Fluid Flow	
Total coolant volume	600 liters (21.2 ft^3)
Coolant volume in core	56 liters (2.0 ft^3)
Maximum coolant flow (250 kw)	7.9 liters/sec (125 gpm)
Coolant velocity in fuel channel	8.2 cm/sec (0.26 ft/sec)
Inlet coolant temperature	~32°C (90°F)
Average power density in core coolant	4.5 kw/liter (4.35 x 10^4 Btu/ft^3)
Average heat flux	1.73 w/cm^2 (39 Btu/ft^2)
Average surface temperature of fuel plates	69°C

JUGGERNAUT achieved criticality on January 11, 1962. Supplementing the present research reactor facilities at Argonne, the immediate objective of JUGGERNAUT is to provide neutron-flux levels of medium intensity for the research and development experiments of the fast reactor program. These experiments include:

(1) flux mapping of lattice units for proposed reactors;

(2) developmental activities concerning the use of reactors for fuel assaying;

(3) measurement of the properties of neutron waves;

(4) testing of new neutron-measuring instruments;

(5) the development of cold-neutron technology.

The design, construction, and startup of JUGGERNAUT was the responsibility of the Reactor Engineering Division. Assistance was received from the Central Shops Department, Electronics, Plant Engineering, and Reactor Operations Divisions of Argonne.

II. DESIGN SUMMARY

A. Building

The reactor is housed in a prefabricated metal structure, 18 x 24 m (60 x 80 ft), of standard design, which is adjacent to a conventional two-story brick structure, 12 x 30 m (40 x 100 ft) (see Fig. 2). As shown in the plan views (see Fig. 3), the brick structure houses the project offices, shops, laboratories, and utilities.

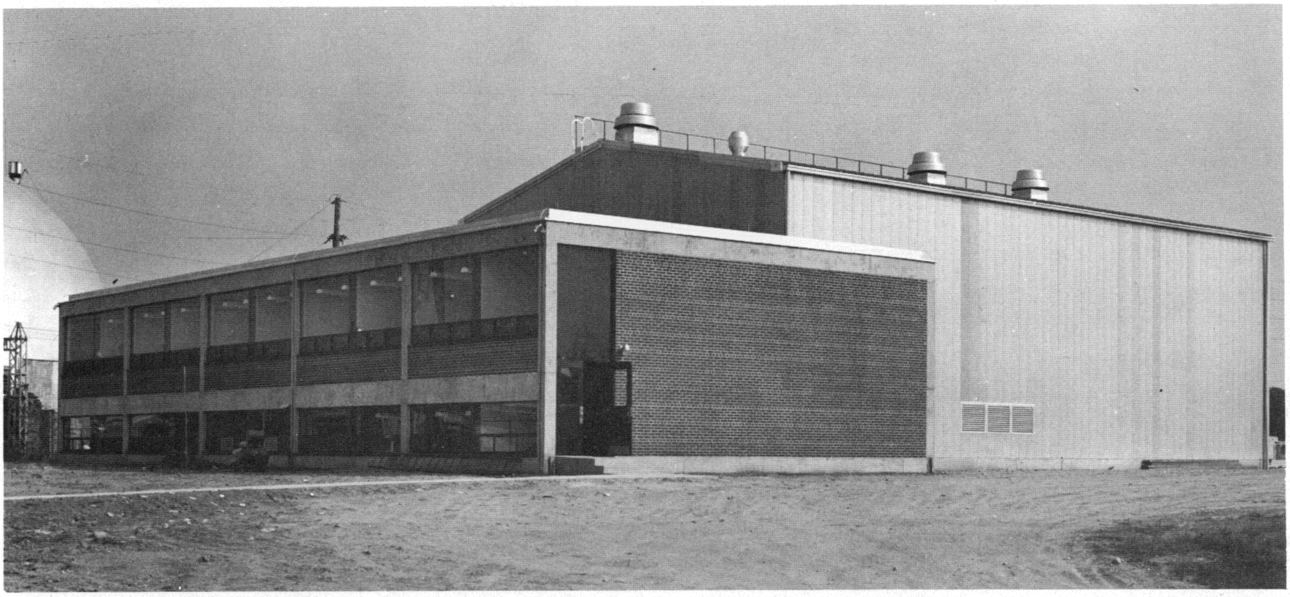


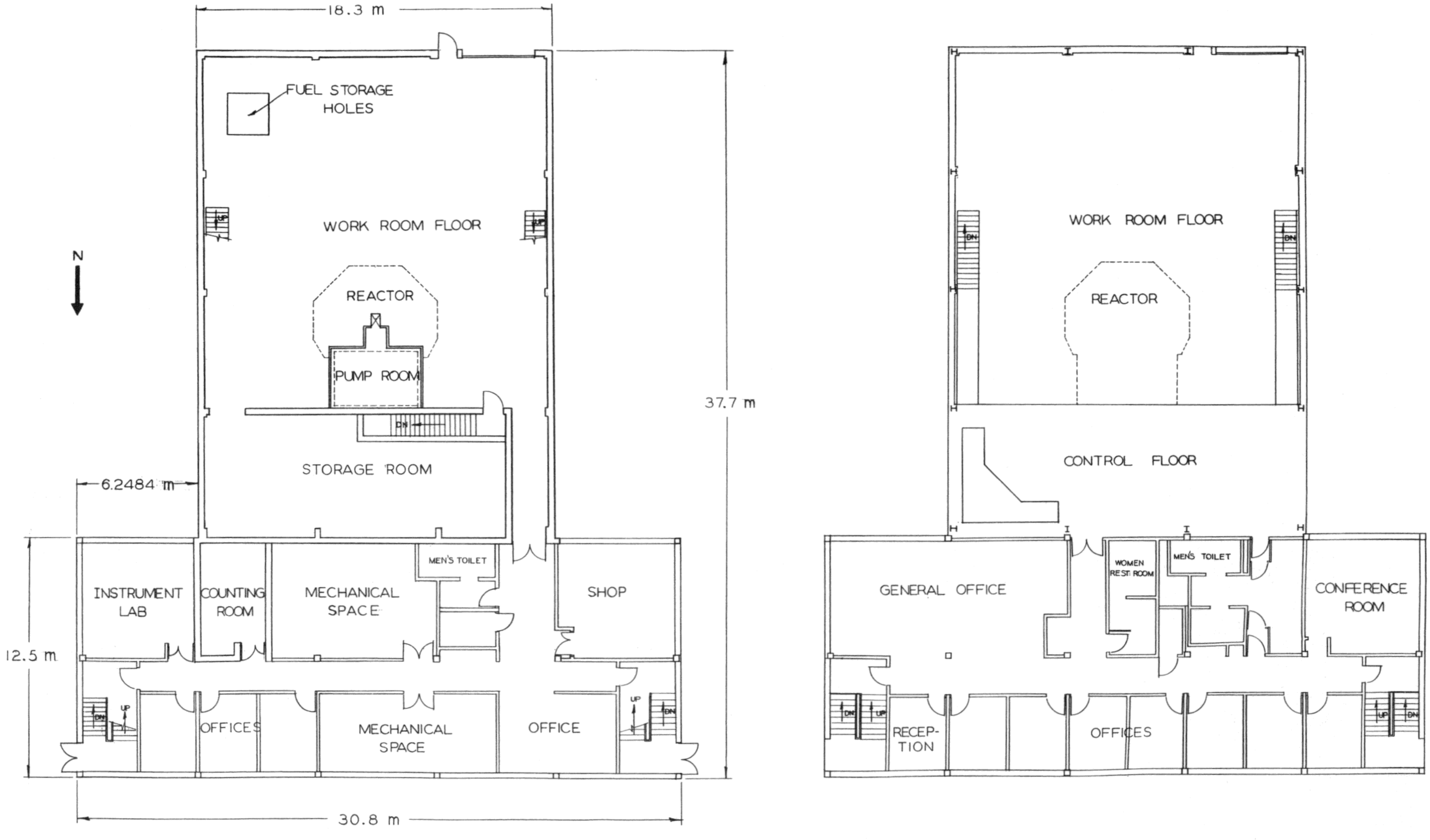
Fig. 2. JUGGERNAUT Reactor - Building 335

Personnel access between the metal and brick structures is available through two doors, one leading to the reactor work-room floor, and the other to the control floor. A third door for personnel and a freight door in the south wall of the reactor building are available for direct access from ground level outside to the work-room floor level.

The capacity of the work-room floor, 14,700 kg/m^2 (3000 lb/ft^2), is adequate to support the load of the reactor and equipment that may be moved adjacent to the reactor.

The reactor building is serviced by a 17-m (56-ft) span, overhead travelling crane rated at 9 tonne (10 ton), and a 1-tonne (1-ton) auxiliary crane for lighter loads. The maximum lift distance for both cranes is 7 m (23 ft) from the main floor and 4 m (13 ft) from the top of the reactor.

The reactor auxiliary systems are located in the sub-reactor (pump) room (see Figs. 1 and 3) beneath the north reactor shield. A cooling tower is located approximately 7.5 m (25 ft) southeast of the reactor building (see Fig. 4).



BASEMENT PLAN

FIRST FLOOR PLAN

Fig. 3. JUGGERNAUT Building 335 - Floor Plan

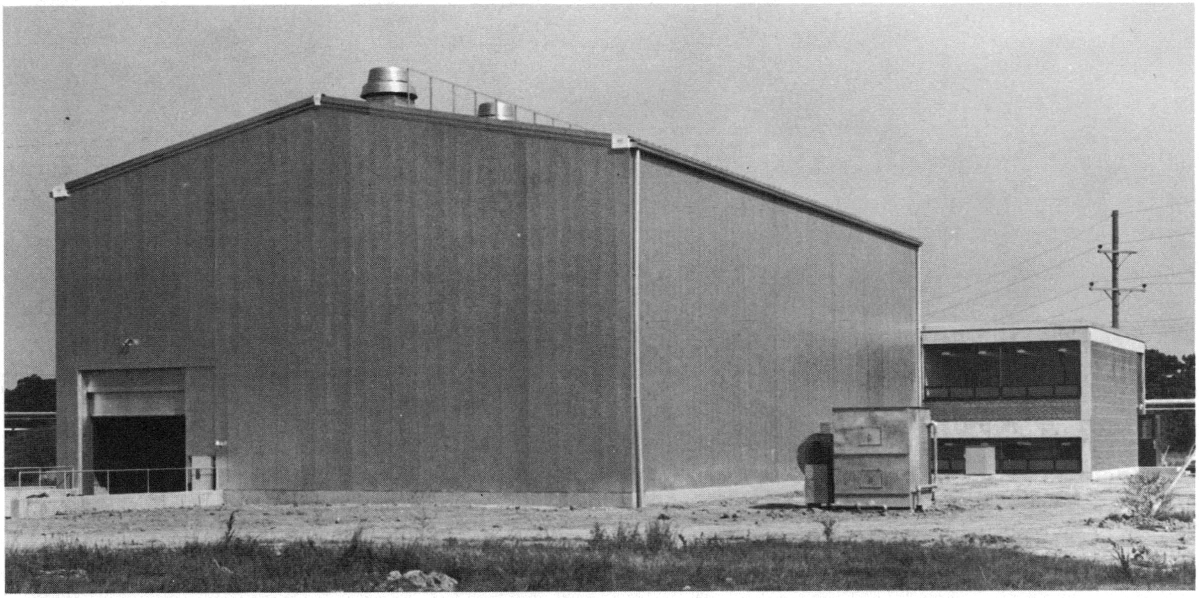


Fig. 4. Rear of Reactor Building - Cooling Tower in Right Foreground

The large equipment in the pump room can be serviced, by means of the overhead crane, by removing concrete biological-shield blocks and floor slabs directly above the room. Personnel access to the pump room is available by means of the stairwell located near the northwest corner of the building.

Radioactive spent fuel is stored in a storage pit in the southeast corner of the work-room floor (see Fig. 3). Storage of clean fuel is maintained in a separate building.

During normal reactor operation, the reactor building is ventilated by three power-driven roof exhaust fans. The air intake for the building is through louvers in the east and west walls. A small, isolated blower system serves to vent the pump room. In the event of a large-scale release of fission products, the louvers and roof vents are automatically shut; the blower system in the pump room is automatically switched off; and the building air is exhausted to the atmosphere through high-efficiency filters by means of an emergency exhaust fan.

In addition to the normal site facilities and utilities, an auxiliary, diesel power system is available in the building for emergency lighting and ventilating service.

B. Reactor

The JUGGERNAUT, derived in concept from the ARGONAUT, features an internal (central) graphite thermal column and a water-cooled annular core positioned within an aluminum reactor vessel (see Fig. 5).

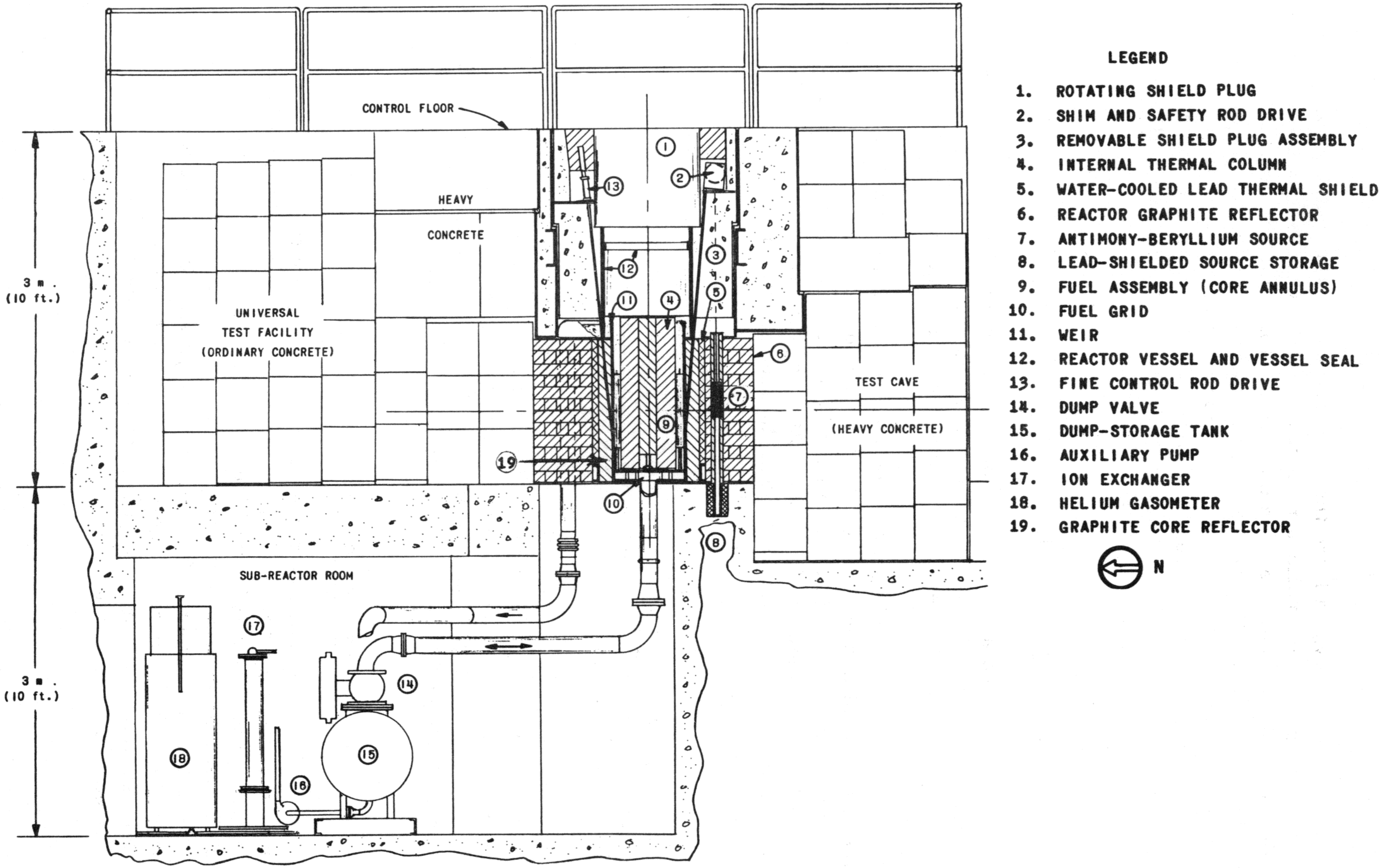


Fig. 5. Elevation Along North-South Axis of Reactor

Located radially outward from the reactor vessel, the reactor components include a graphite core reflector, sections of the water-cooled lead thermal shield, the reactor graphite assembly (reflector), and the bulk biological shielding that houses the horizontal experimental facilities. Located axially above the annular core, the reactor components include a water reflector, a section of the water-cooled lead thermal shield, and removable concrete plugs and blocks that outline various vertical experimental facilities.

1. Core

a. Fuel Assemblies

The annular core, of 46-cm (18-in.) ID and 61-cm (24-in.) OD, is composed of 20 fuel assemblies. Each assembly includes 12 fuel plates separated by spacer buttons and aluminum end fittings.

The fuel assemblies are aligned and supported by insertion of the bottom end fittings into guide tubes arranged around the periphery of a circular aluminum grid. The grid is positioned within the reactor vessel by pins that project up from the bottom of the reactor vessel. The upward flow of reactor water through the fuel assemblies, 8.2 cm/sec (0.26 ft/sec), is sufficiently low that no holddown mechanism is required.

Each of the 12 fuel plates in a fuel assembly has an active fuel-bearing section, 57.2 x 6.0 x 0.10 cm (22.5 x 2.4 x 0.040 in.), which contains 16.7 gm U^{235} (93% enrichment) (fuel plates containing 20 gm U^{235} are available) clad in aluminum, 0.038 cm (0.015 in.) thick.

The core loading can be varied by replacing the active fuel plates with dummy aluminum counterparts. The cold, clean critical mass is 3.3 kg U^{235}. The maximum loading ($\sim$6.5% k_{ex}) contains 4.2 kg U^{235}. However, the prescribed operating procedures will limit the core loading to a value that can be held subcritical by three of seven boron-steel shim-safety rods.

b. Cooling Systems

The core is cooled and moderated by the Reactor Water (primary) System which, in turn, is cooled by the Coolant Water (secondary) System. The primary system circulates water to and from the reactor core and through a shell-and-tube heat exchanger and a dump-storage tank located in the pump room. The secondary system circulates water to and from the primary heat exchanger (shell), removing reactor heat from the primary system, and through a cooling tower where the reactor heat is dissipated to the atmosphere.

An auxiliary system within the primary system cleans the reactor water by circulating it to and from the dump-storage tank and through a cation-anion mixed-bed exchange column.

An inert helium atmosphere is maintained over the primary system to inhibit corrosion, particularly in the reactor vessel. A gasometer adjusts the gas volume in the system in response to changes in the atmospheric pressure and the helium temperature.

2. Reactor Control

a. Control Rods and Drives

The reactor is controlled at the control console through the manipulation of eight control rods (three shim rods, four safety rods, and one fine control rod), which constitute the movable solid poison control for JUGGERNAUT. The control rods are flat blades which travel through individual, diagonal guide channels, or sheaths, in the shielding and the graphite core reflector. The lower section of each guide channel is adjacent to the periphery of the reactor vessel. As a bank, the shim-safety rods, each having a poison section of 2 wt-% natural boron-steel, 48 cm (19 in.) long, 17.8 cm (7 in.) wide, and 0.274 cm (0.11 in.) thick, control 7.0% Δk. The fine control rod, having a poison section fabricated from cadmium, which measures 29.2 cm ($11\frac{1}{2}$ in.) long, 2.54 cm (1 in.) wide, and 0.020 cm (0.008 in.) thick, controls 0.15% Δk.

The shim-safety rod drives are of the ARGONAUT window-shade type, and the fine control rod is actuated by a rack-and-pinion mechanism. Rates of rod withdrawal are limited to speeds which do not compromise criteria for reactor safety.

For fast shutdown (rod scram), release of the magnetic clutch in the drive mechanisms of the shim-safety rods effects the fall of these rods to their full IN position within 0.5 sec. Withdrawal and insertion of the fine control rod is manually controlled at the console.

b. Instrumentation and Plant Protection

There are eight channels of information by which the nuclear instrument system monitors the neutron-flux level of the core. Channels I-III are provided with BF_3 proportional ionization chambers as sensing elements. Channels IV-VIII are provided with B^{10}-lined, gamma-compensated ion chambers. The eight chambers are located in vertical instrumentation holes in the top removable shield.

Channels I, II, and III are the startup, pulse, or counting rate channels used during low-power operation.

Channels IV, V, and VI are used for power-level safety during intermediate- and full-power operation. Current signals from these channels can effect a reactor shutdown if the operating power level exceeds 120% of normal operating power.

Channel VII is used to record the flux level of the core on a linear recorder.

Channel VIII drives the period meter and can effect a reactor shutdown on a period less than 10 sec.

Non-nuclear instrumentation is provided to monitor temperature, pressure, and flow for the safety and control of the reactor systems. The pressure and flow data are transmitted to the control console by pressure lines, and the temperature data are transmitted electrically.

Reactor control and protection is also maintained by systems of radiation monitoring and safety interlocks. Various plant operating parameters and fail-safe interlocks can cause reactor shutdown (rod scram or scram which includes both a rod scram and a water dump) and/or audible and visual alarm indication at the control console. In addition, audible alarms and warning lights can be actuated inside the reactor building at the onset of and during reactor operation.

3. Shielding and Experimental Facilities

a. Biological Shielding

The reactor shield structure is 3 m (10 ft) high and 6 m (20 ft) in length along an east-west axis (see Fig. 6). Stacked blocks of ordinary and high-density concrete comprise 60% of the radial biological shielding; the remainder is poured high-density concrete, 3.2 tonne/m^3 (196 lb/ft^3).

The monolithic (poured) concrete shield contains an opening, 1.52 m (5 ft) square, for a removable shield plug assembly of high-density concrete, 3.5 tonne/m^3 (214 lb/ft^3). This removable shield plug assembly contains a stepped opening for a cylindrical concrete, rotating shield plug. Four auxiliary plugs are located in the rotating plug; three of these plugs seal experimental access holes leading to the internal thermal column. The fourth plug seals the refueling access hole which leads to the core fuel assemblies.

b. Thermal Shield

Below the rotating shield plug and the top removable shield plug and between the core reflector and reactor graphite, a water-cooled, sectional, lead thermal shield encloses the core on the top and sides.

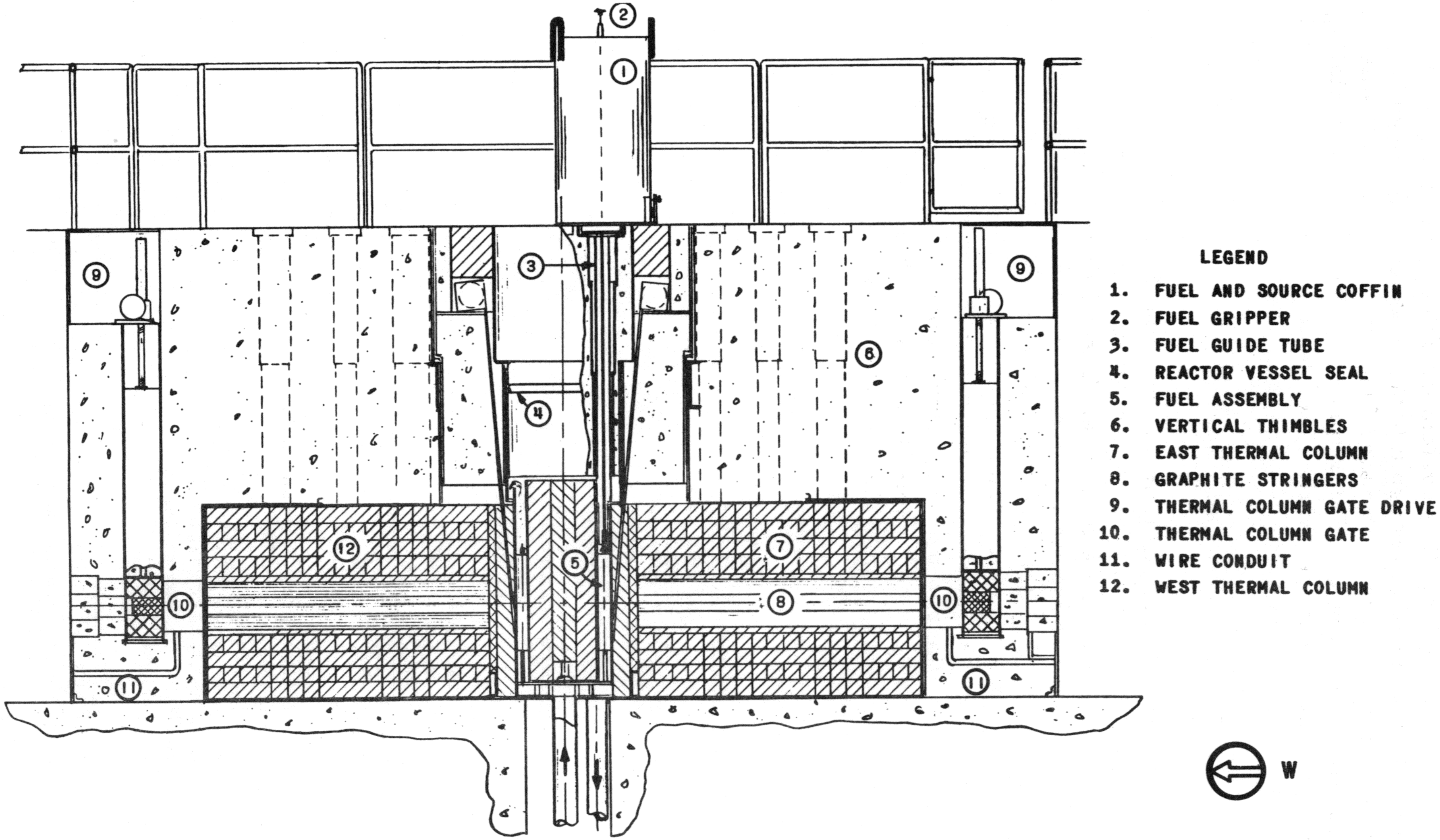


Fig. 6. Elevation Along East-West Axis of Reactor (Fuel and Source Coffin in Position Above Core)

A shield-cooling system circulates water to and from the thermal shield sections and through a heat exchanger. The Coolant Water (secondary) System performs the same function for the Shield Water System as it does for the Reactor Water (primary) System by circulating cooling water to and from the shield water heat exchanger (shell) and through the cooling tower.

c. Experimental Facilities

The reactor contains 14 vertical facilities for irradiation experiments, four horizontal beam holes, two thermal column openings, a universal test facility, and a test cave. The latter two facilities consist of shielding blocks which can be removed to expose the north and south faces of the reactor graphite. Access to all vertical facilities is available from the top of the reactor. Each opening is sealed with stepped concrete shield plugs for protection against radiation streaming. The four beam holes and the two thermal column openings are shielded with motor-operated gates and concrete-filled plugs. Shielding for the two thermal columns includes removable, square cross-sectional graphite blocks or stringers.

C. Cost (Summary)

The costs of the JUGGERNAUT project are summarized in Table II. The total figure represents the cost to reproduce this reactor in the Chicago area as presently designed.

Table II

SUMMARY OF THE JUGGERNAUT COSTS

Internal Thermal Column	$ 3,342.00
Core	12,105.00
Fuel-assembly Grid	1,428.00
Reactor Vessel	1,875.00
Core Reflector	3,100.00
Lead Thermal Shield	2,396.00
Cooling Systems	21,572.00
Source	1,827.00
Control Rods	10,026.00
Control Console and Instrumentation	40,866.00
Thermal Columns	19,182.00
Test Facilities	4,430.00
Horizontal Beam Holes	13,480.00
Steel Forms and Encasements	13,621.00
Monolithic and Block Shielding	45,276.00
Top Removable Shield	11,636.00
Rotating Shield	16,826.00
Surface Finishing	1,235.00
Fuel and Source Coffin	5,444.00
Storage Pit (Installed with Building)	3,460.00
Installation (Total)	13,586.00
Miscellaneous (Total)	7,286.00
Total	$257,721.00

III. COMPONENT DESCRIPTION

A. Core Assembly

The core assembly (see Fig. 7), located at the center of the reactor, consists of an internal thermal column, an annular core (20 fuel assemblies), and a fuel assembly grid. The internal thermal column is surrounded by the annular core. The fuel-assembly grid serves to align and support both the column and the individual fuel assemblies of the core within the reactor vessel.

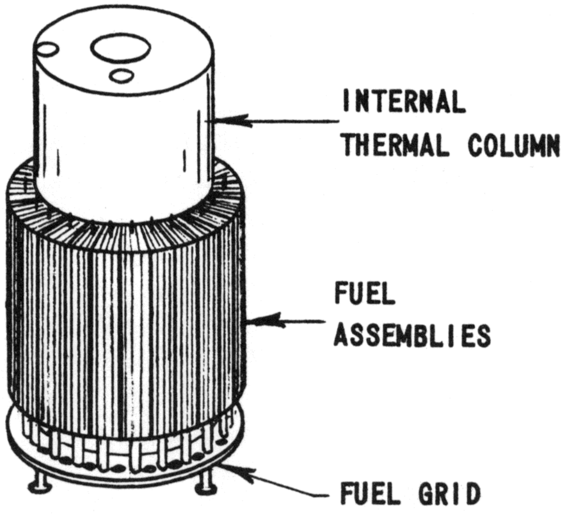


Fig. 7. Core Assembly

1. Internal Thermal Column

The internal thermal column (see Fig. 8), 46 cm (18 in.) in diameter and 125 cm (49 in.) high, is a graphite cylinder canned in a water-tight aluminum container. The column contains three vertical holes, 5, 5, and 15 cm (2, 2, and 6 in.), respectively, for experimentation in the region of maximum thermal-neutron flux. Three cylindrical graphite stringers occupy the holes and aluminum plugs fitted with O-rings seal the ports at the top of the column when the holes are not in use. A locating hole in the bottom of the internal thermal column is used to align the column on the fuel grid with respect to the rotating shield.

Based on an assumed condition of constant power and a hypothetical core, 61 cm (24 in.) high and 7.6 cm (3 in.) wide, the diameter of the internal thermal column at which the maximum thermal-neutron flux would occur was calculated to be 30 cm (12 in.) (see Appendix A). However,

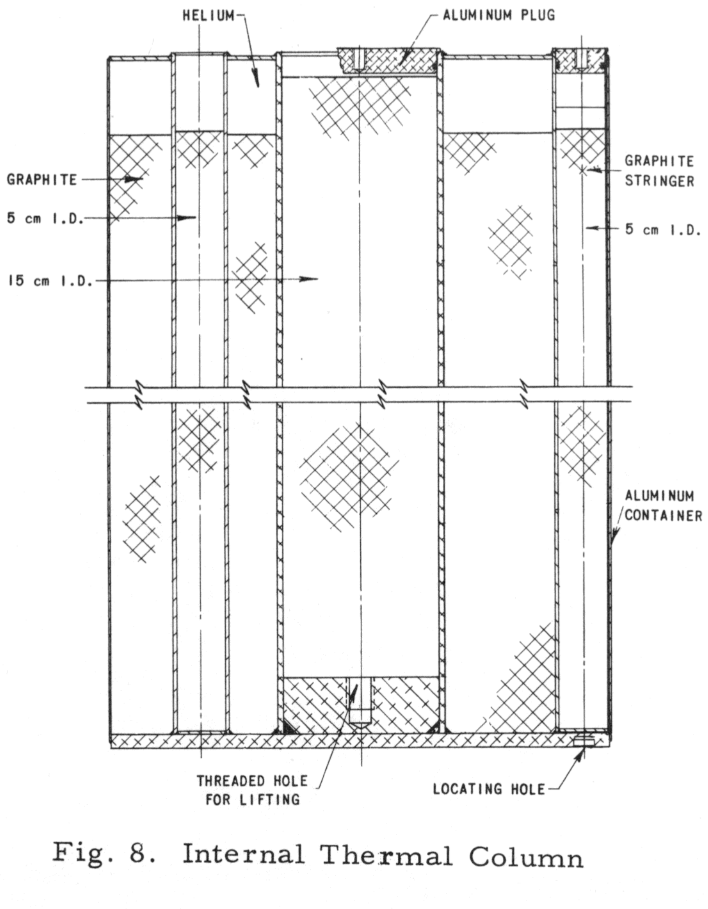


Fig. 8. Internal Thermal Column

adequate space for experimentation would not have been available with a cylinder of this diameter. Therefore, a compromise was made to obtain that diameter which would afford the necessary space with a minimum reduction of the maximum thermal-neutron flux available at the optimum diameter. The result was the selection of a 46-cm (18-in.)-diameter column and a concomitant reduction, less than 9%, of the maximum flux available at the optimum diameter.

2. Core (Fuel Assemblies)

The annular core, active height and width of 57.2 cm (22.5 in.) and 6.0 cm (2.4 in.), respectively, is composed of 20 fuel assemblies (see Fig. 9). Each fuel assembly (see Fig. 10) consists of 12 fuel plates, two curved bolts, spacer buttons, a gripper tip, and a guide pin.

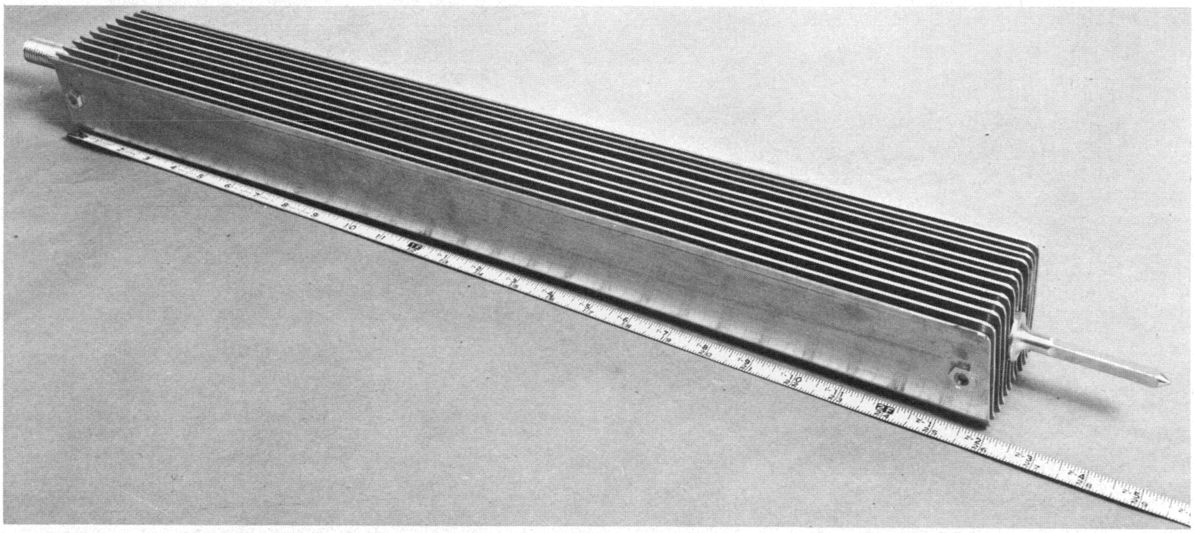


Fig. 9. Fuel Assembly

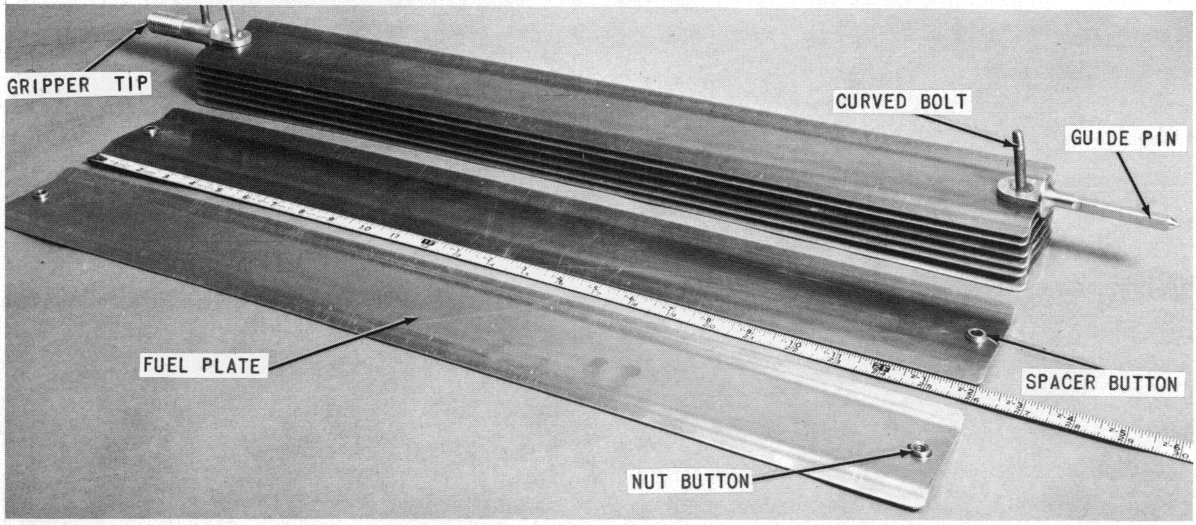


Fig. 10. Fuel Plates and Assembly Parts

The fuel plates are arranged in a radial pattern within the fuel annulus (see Fig. 7) to achieve:

(1) an almost uniform fuel density, which eliminates the need for graphite fillers as used in the ARGONAUT;

(2) adequate shutdown cooling by radiative transfer alone; and

(3) an ideally symmetric lattice for the measurement of the effective delayed-neutron fraction (β_{eff}) by the poison-substitution method.

The dimensions for fuel plate thickness and spacing, 0.18 cm (0.07 in.) and 0.51 cm (0.2 in.), respectively, were selected as a compromise to combine rigidity of structure with a large negative void coefficient without departing significantly from a condition of minimum critical mass; to provide an adequate cooling area; and to ensure that JUGGERNAUT would be self-limiting in nuclear excursions prompted by large reactivity inputs.

These fuel-plate dimensions permitted a total of 240 fuel plates to be loaded into the core; thus, the maximum fuel loading possible is 4.2 kg U^{235}, with an initial configuration of 170 fuel plates at 16.7 gm per plate and 70 fuel plates at 20 gm per plate. This maximum fuel loading should provide an excess reactivity of 6.5% Δk over the clean, cold critical condition (3.3 kg). If necessary, more fuel plates can be loaded into the core by swaging the spacer buttons to reduce the plate spacing. If the plate spacing were to be reduced to 0.43 cm (0.17 in.), a total of 280 plates containing 4.9 kg U^{235}, with a configuration of 210 fuel plates with 16.7 gm per plate and 70 fuel plates with 20 gm per plate, could be loaded into the core. This maximum fuel-loading configuration should provide an excess reactivity of 9.5% Δk over the clean, cold critical condition (3.4 kg).

This method of providing additional excess reactivity, although not as convenient as providing the maximum loading configuration initially, is preferable because:

(1) With the initial configuration the probability that a fuel loading error will result in a rapid nuclear excursion is nullified, since the control system is capable of maintaining a subcritical condition even if the maximum fuel loading with the initial configuration is loaded within the core.[1] However, if the maximum fuel-loading configuration [plate spacing of 0.43 cm (0.17 in.)] had been provided initially and a fuel loading error occurred, an excess reactivity (approximately 4% Δk) greater than the total rod worth could have been made available. If the critical experiments indicate the necessity for a reactivity margin greater than that possible with the present fuel-loading configuration, plate spacing can be

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[1] J. R. Folkrod et al., Hazards Summary Report on the JUGGERNAUT Reactor, ANL-6192 (Feb 1961).

reduced in some or all of the fuel assemblies to provide only the minimum necessary reactivity.

(2) For the measurement of the effective delayed-neutron fraction (β_{eff}) of the reactor, anything that destroys the ideal symmetry of the core should be discouraged. Since it is preferable to have a minimum number of dummy plates in the core during this measurement, a lower initial fuel loading is indicated.

The core lifetime is uncertain; however, a span of 2 yr was assumed for the purpose of design physics. After operating at a power level of 250 kw for a 2-yr period, the burnup of U^{235} will total approximately 3.5 at-% (load factor = 0.55). If, at the end of this period, corrosion difficulties have not been encountered, the core lifetime may be extended another 2 yr by replacing spent fuel assemblies containing 12 fuel plates with fresh assemblies containing 14 fuel plates. An additional 150 gm of U^{235} could be added to the core in this manner, if only the presently available extra fuel plates (~70) are used. If necessary, other methods of increasing the core lifetime include reduction of power level and reduction in reactivity allowance for experiments.

a. Fuel Plate

The standard manufactured fuel plate (see Figs. 10 and 11), 66 x 7.3 x 0.178 cm (26 x 2.875 x 0.070 in.), is of pure aluminum. It contains a centrally located fuel-bearing region, 57.2 x 6.0 x 0.102 cm (22.5 x 2.4 x 0.040 in.), of enriched (93%) uranium alloyed with aluminum. The two end pieces of the fuel plate, of solid aluminum, have hole penetrations, located on the centerline of the plate, 1.5 cm ($\frac{5}{8}$ in.) from the ends. The two longitudinal edges of each plate are bent 1.27 cm ($\frac{1}{2}$ in.) from each edge, with a 0.80-cm ($\frac{5}{16}$-in.) inside radius, at an angle of approximately 30 degrees, to increase the rigidity of the plate.

An attempt was made to bend the plates at a distance of 0.63 cm ($\frac{1}{4}$ in.) from the longitudinal edges, but several plates ruptured because of stretching of the aluminum clad or "orange peeling" in the region of the edge bond. On all succeeding plates the bend was successfully made 1.27 cm ($\frac{1}{2}$ in.) from the edge. All bends in this location proved to be acceptable.

It was also noted that wider fuel plates (including a wider "meat" section) should be used for future core loadings to have the fuel assemblies fit more snugly within the fuel annulus.

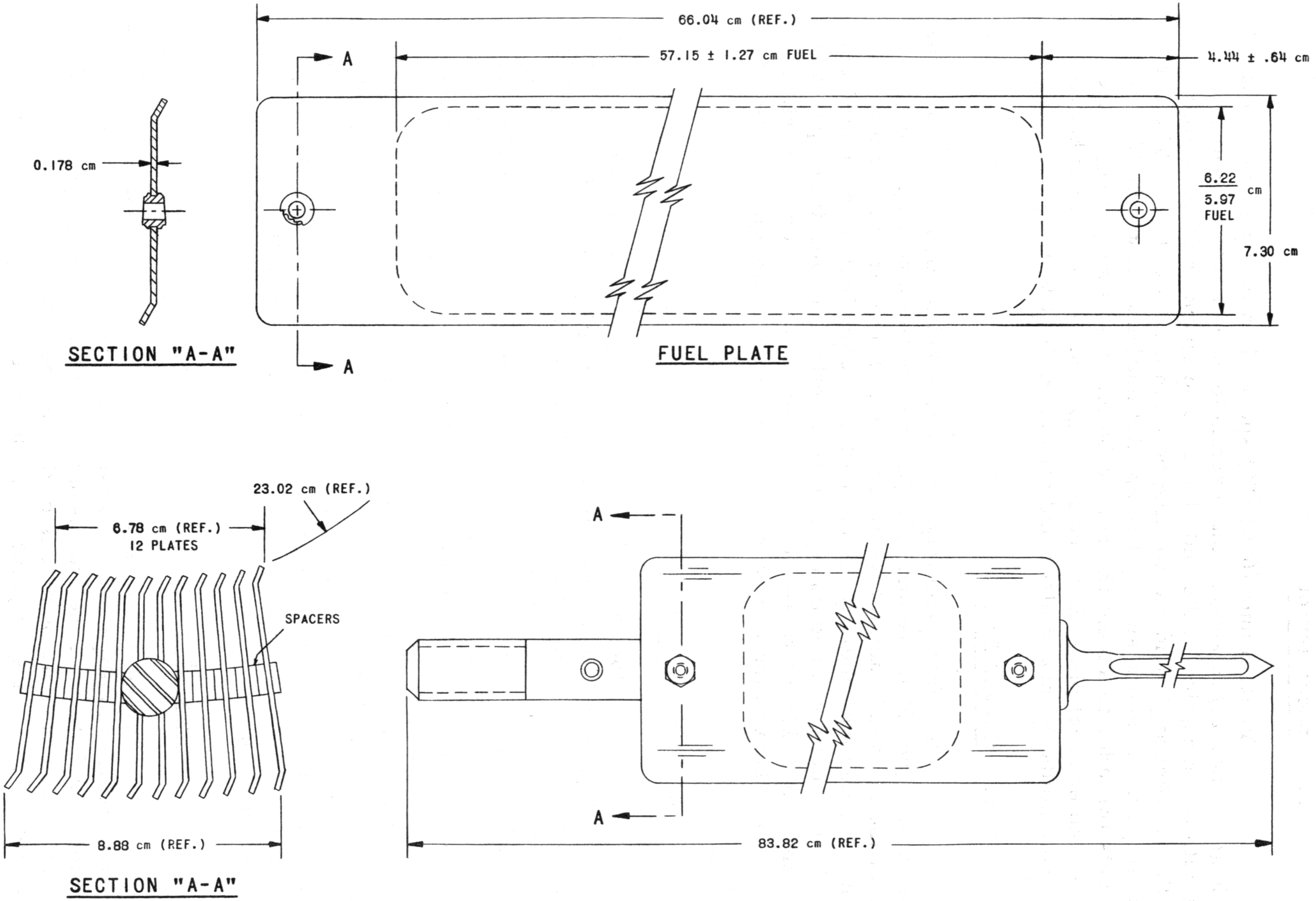

Fig. 11. Fuel Assembly - Details

b. Spacer Button

An aluminum (6061-T6) spacer button (ring configuration) (see Figs. 10 and 11) is swaged into each hole at both ends of each fuel plate with the exception of the end plates. The spacer buttons maintain both the correct angle and the spacing between the fuel plates. The end or outer plate in each assembly has special nut buttons, which are hex-head nuts threaded to accept the curved bolts. A retaining ring, in the holes of the end fuel plate, is fitted into a groove around the nut button, which both holds the nut in place and also permits it to rotate.

c. Curved Bolt

In a fuel assembly, two curved bolts align and support the 12 fuel plates (see Figs. 10 and 11). One bolt is fitted through each of the holes at the top and bottom of the fuel plates. The bolts are secured to the end or outer fuel plate by the nut buttons. Each bolt is fabricated from 6061-T6 aluminum rod and tubing welded together; an upsetting operation forms the head. The bolts are then machined to the proper dimensions, threaded, and bent to the arc necessary for correct alignment of the fuel plates.

d. Gripper Tip

Each fuel assembly includes a cylindrical gripper tip for handling purposes (see Figs. 10 and 11). The gripper tip is designed for alternative methods of attachment to handling equipment. The gripper tip is centered over the fuel assembly, aligned longitudinally, and attached to the assembly by the curved bolt. Approximately half the length of the gripper tip is tubular and externally threaded. When using the fuel and source coffin for fuel-assembly handling, the standard method of remotely engaging the gripper tip is to thread a nut assembly onto the peripheral screw thread of the gripper tip. During procedures for loading clean fuel a secondary engagement method is available by means of a ball pip-pin hand tool in conjunction with a horizontal groove on the internal surface of the tubular section of the gripper tip. For emergency engagement, a crossbar is available, which passes through the solid cylindrical section of the gripper tip.

e. Guide Pin

The guide pin (see Figs. 10 and 11), machined from 6061-T6 aluminum, is used to align the fuel assembly in the fuel grid. The pin is centered at the bottom of the fuel assembly, aligned longitudinally, and attached to the assembly by means of the curved bolt. The pin has a square cross section and a tapered point which decreases the contact area between the pin and the guide tube of the fuel grid, permitting water to flow around the contact area. This water circulation should prevent an excessive buildup of corrosion deposits and resultant seizure of components in these areas.

3. Fuel Assembly Grid

The fuel-assembly grid (Fig. 12) was fabricated entirely from 6061-T4 and 6061-T6 aluminum. As there was the possiblity that welding might distort the assembly, all mating parts of the grid were swaged together. The grid is used to:

(1) position and support each fuel assembly;
(2) position and support the internal thermal column; and
(3) align the core assembly within the reactor vessel.

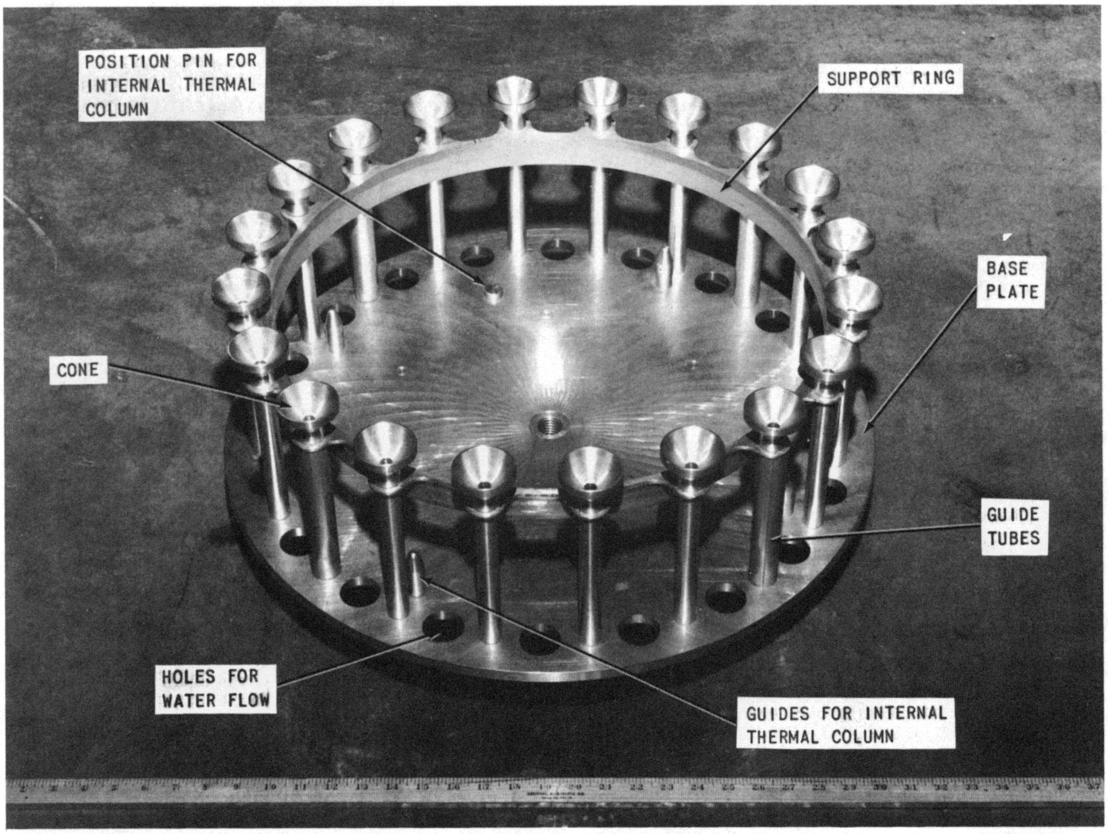

Fig. 12. Fuel Grid

There are 20 cone-fitted vertical guide tubes equally spaced in the perimeter of a circular base plate of the fuel grid. The guide tubes are anchored to the base plate and attached to each other by a support ring of aluminum angle stock. The guide pin of each fuel assembly fits into a cone-fitted guide tube, and the edge of the cone flange acts as a seat for the fuel assembly. The cone on each guide tube facilitates the entry of the guide pin into the guide tube. There are 20 holes through the base plate, alternating with the guide tubes on the same perimeter, for the flow of reactor water to the fuel assemblies.

Within the guide-tube perimeter, four vertical tapered pins, located on the base plate, serve as guides to center the internal thermal column with respect to the fuel grid. The correct angular position of the internal thermal column with respect to the rotating shield is determined by a position pin on the base plate which fits into a locating hole in the bottom of the column.

A threaded hole is provided, in the center of the base plate, for handling purposes.

On the underside of the base plate, five legs support the fuel grid above the bottom of the reactor vessel and the reactor water inlet. Two support legs contain reamed holes which fit two pins located on the bottom plate of the reactor vessel to align the core assembly in the vessel.

A centrally located cone on the underside of the base plate acts to deflect the inlet flow of reactor water toward the guide-tube perimeter and the inlet holes of the base plate and the guide tubes.

B. Reactor Vessel and Vessel Seal

1. Reactor Vessel

The reactor vessel (see Fig. 13), 1.96 m (77 in.) high, contains the core assembly and the reactor water coolant and moderator. The vessel is composed of two welded cylindrical (concentric) sections fabricated from 5052-H34 aluminum, 0.48 cm ($\frac{3}{16}$ in.) thick. The lower section of the vessel, of 61-cm (24 in.) ID and 138 cm ($54\frac{1}{4}$ in.) high, protrudes into the upper section, 74.6 cm ($29\frac{1}{2}$ in.) in ID and 77 cm ($30\frac{1}{4}$ in.) high, and a flat ring is welded between the two sections to effect a weir and trough arrangement (see Fig. 14) for uniform distribution of reactor water flow through the core.

The bottom plate, 1.27 cm ($\frac{1}{2}$ in.) thick, of the vessel rests on an aluminum floor plate, 1.27 cm ($\frac{1}{2}$ in.) thick, bolted to the concrete floor. Two vertical pins on the bottom plate serve to align the core assembly in the vessel. At a maximum flow rate of 7.9 liters/sec (125 gpm), the reactor water level in the vessel would be 1.9 cm ($\frac{3}{4}$ in.) above the top of the weir.

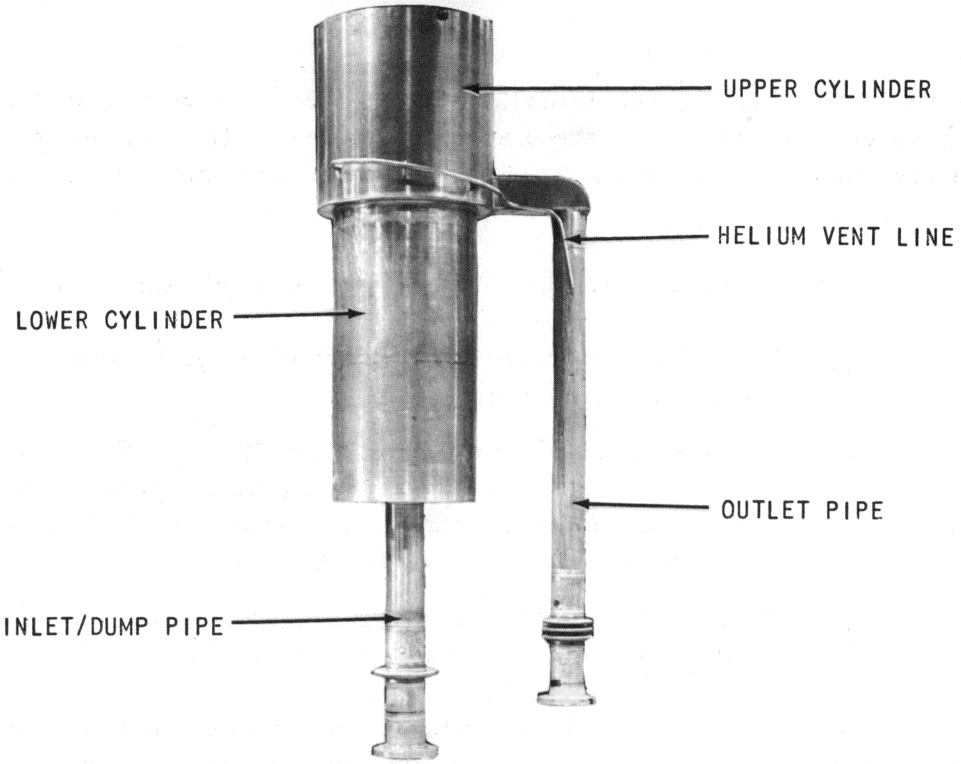

Fig. 13. Reactor Vessel

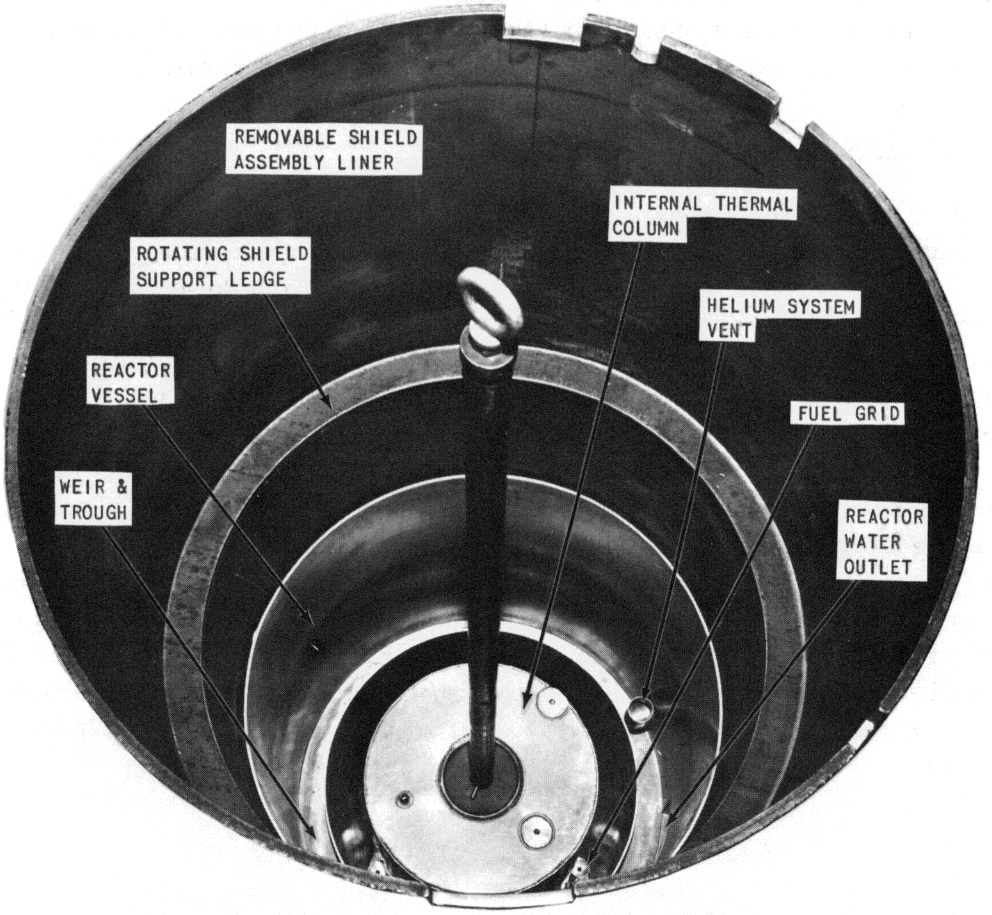

Fig. 14. Reactor Vessel Interior

Under these conditions, the internal thermal column would be 1.27 cm ($\frac{1}{2}$ in.) above the surface of the water. Closure of the vessel is effected by the insertion of a concrete, rotating shield plug into the upper section of the vessel.

Penetrations into the reactor vessel include:

(1) In the bottom plate - a 15-cm (6-in.), Schedule 40, reactor water inlet/dump pipe.

(2) In the upper cylinder - a 13-cm (5-in.), Schedule 40, reactor water-outlet pipe which has a square cross section at the point of attachment to the vessel to conform to the bottom contour of the trough.

(3) In the upper cylinder - two helium lines, one of 5.1-cm (2-in.) OD and the other of 1.9-cm ($\frac{3}{4}$-in.) OD.

The reactor water inlet/dump and outlet lines and the helium lines interconnect the vessel with a reactor water dump-storage tank in the pump room. The helium lines are sloped toward the dump-storage tank to drain off condensate and ensure an open flow path. During normal operation, the helium lines maintain a gas atmosphere above the water-filled core to retard corrosion of the aluminum vessel. If necessary, the reactor vessel can be removed for repair or replacement.

2. Vessel Seal

A helium atmosphere (at a pressure equivalent to 2 in. H_2O) is retained within the vessel by a rubber tube (bicycle inner tube), of 66-cm (26-in.) overall diameter and 5.4-cm ($2\frac{1}{8}$-in.) tube diameter, which, when inflated, seals the space between the internal surface (perfect roundness and smoothness of this surface was maintained but not required) of the uppermost 23 cm (9 in.) of the vessel and the corresponding surface of the rotating shield plug. The vessel seal tube is positioned in an area of low neutron flux, $\sim 10^7$ n/(cm^2)(sec), to minimize radiation damage. If necessary, the tube can be removed and replaced by removing the rotating shield plug. The tube is hand pumped to a pressure of 1.3 atm ($4\frac{1}{2}$ psig) using an air line which extends from the seal-valve stem on the N.W. instrument rack through the rotating shield to the rubber tube. Vessel seal pressure is indicated on the N.W. instrument rack. The simplicity of the seal design, as evidenced by the avoidance of "tight" tolerances and precision work, reduced the capital cost of the vessel and the rotating shield plug.

C. Core Reflector and Thermal Shield

1. Core Reflector

The reactor vessel is radially surrounded by a rectangular section of graphite, 86.5 cm (34 in.) on a side and approximately 124 cm (49 in.) high (see Figs. 15 and 16). This graphite functions to reflect and thermalize neutrons emanating radially from the core. The water in the reactor vessel, above and below the core, functions as the axial reflector.

The graphite core reflector has a centrally bored hole with a diameter of 62.3 cm ($24\frac{1}{2}$ in.). This hole accommodates the lower section of the reactor vessel while eight milled slots in the graphite, cut on a 5-degree angle with the vertical axis, house the control rod sheaths. These slots, equally spaced around the perimeter of the reactor vessel, start at the top surface of the reflector and merge into the centrally located hole for the reactor vessel approximately 20 cm (8 in.) below the midplane of the core.

The reflector is composed of high-purity nuclear graphite, Grade AGOT, manufactured by the National Carbon Company. This graphite has an average[2] specific density of 1.67 gm/cm^3 (104 lb/cu ft).

2. Thermal Shield

The thermal shield consists of six individually fabricated slabs of lead. They are located as follows:

(1) Four sections, each 5 cm (2 in.) thick and 91.5 cm (36 in.) square, surround the vertical faces of the graphite core reflector (see Fig. 16).

(2) One section, 7.6 cm (3 in.) thick, is located below the top rotating shield plug.

(3) One section, 7.6 cm (3 in.) thick, is located below the top removable shield.

The thermal shield reduces the gamma flux incident on the concrete biological shield. Consequently, the heat generation and thermal stresses in the concrete are kept to safe levels.

Surrounding the lower section of the graphite core reflector, a channel iron base, 5 cm (2 in.) by 15 cm (6 in.), supports the four vertical sections of the lead thermal shield (see Fig. 15).

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[2] The Industrial Graphite Engineer's Handbook, National Carbon Company.

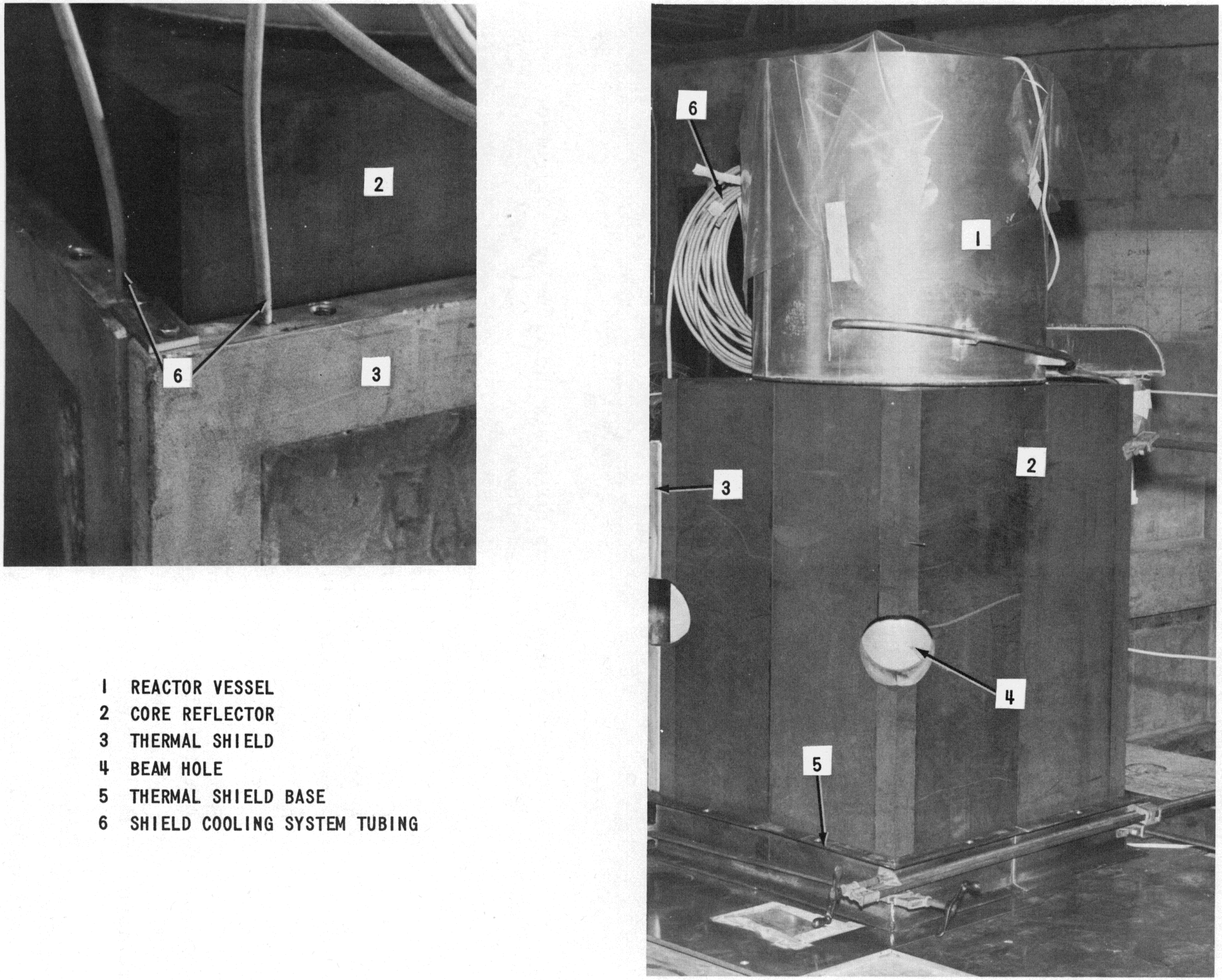


Fig. 15. Core Reflector and Thermal Shield

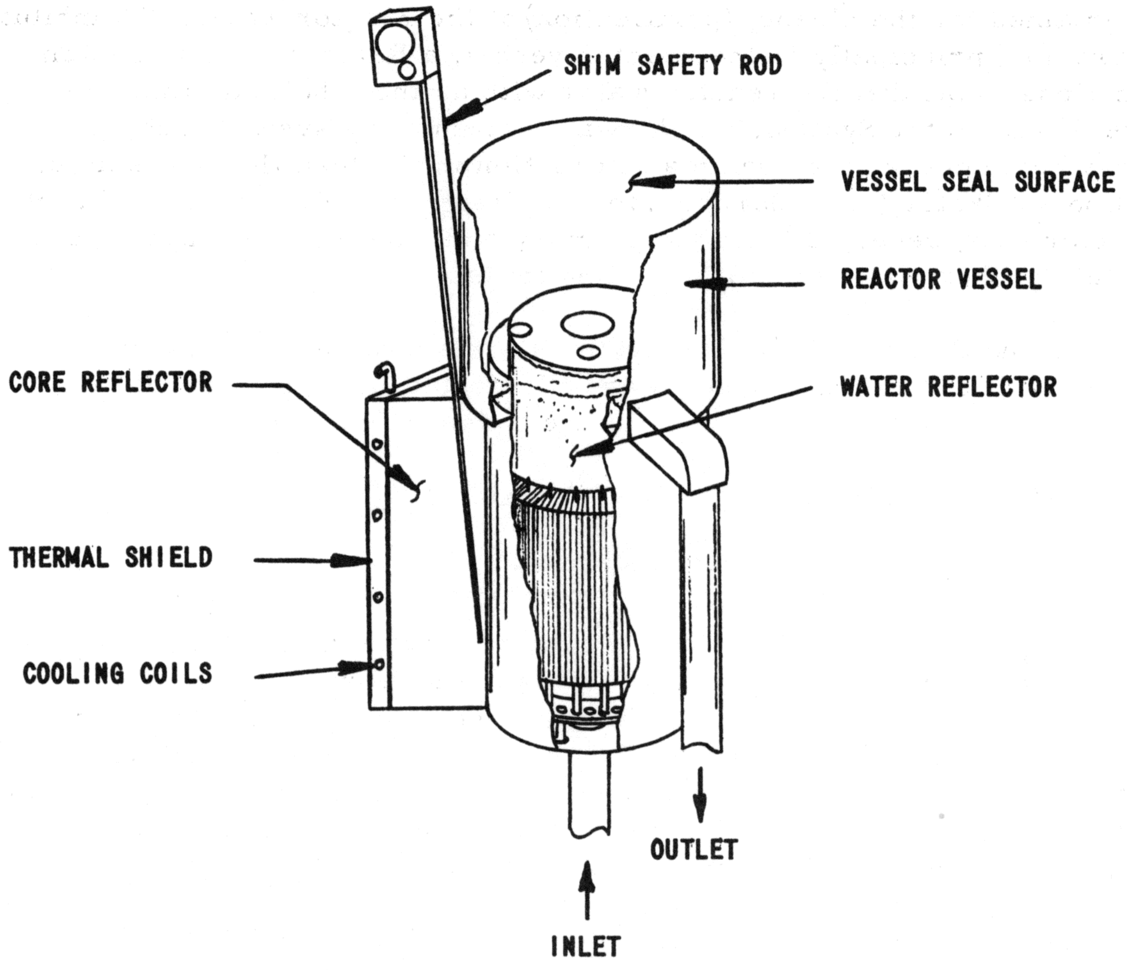


Fig. 16. Thermal Shield in Relation to Core

The inner face of this lead wall is 12.7 cm (5 in.) away from the outer perimeter of the core at its closest point. This distance from the core is sufficient to result in a relatively small reduction in control rod worth and a small increase in critical mass. A more distant location from the core would have reduced the utility of the graphite thermal columns and necessitated the piercing of the lead by the thermal column stringers.

Cooling coils, 1.2 cm ($\frac{1}{2}$ in.) in diameter, of the Shield Cooling System are contained within each of the individual sections of the thermal shield. Heat produced in the shield section by gamma-ray attenuation is removed by the cooling system water circulating through the cooling coils.

D. Cooling Systems

The core of the reactor is cooled and moderated by means of a light-water circulating system, the Reactor Water (primary) System. Within this closed system, a separate flow path, or auxiliary system, is maintained for the cleanup (purification) of the reactor water. To inhibit corrosion, principally in the reactor vessel, a Reactor Helium System functions to blanket the reactor water with an inert helium atmosphere. The Shield Water System, a light-water circulating system, acts to remove heat generated by gamma attenuation in the lead thermal shield. A Coolant Water (secondary) System is designed to dissipate 250 kw of reactor heat, received from the primary and shield cooling systems, to the atmosphere by means of a cooling tower.

The flow paths of these systems are shown schematically in Fig. 17. The major components are illustrated in Figs. 18a-18f, and the major commercial components are listed in Table III.

1. Reactor Water (Primary) System

a. Initial Fill - Pump Interlock

To limit the addition of reactivity during the initial water-fill of the reactor, an interlock prevents the startup of the main reactor pump until the reactor has been filled to overflowing. The auxiliary pump, RWP3, is used to fill the reactor to overflowing acting through valve RWV13 (see Fig. 17) which is preset and locked in position to regulate the fill rate to 0.19 liter/sec (3 gpm). A flowmeter, RWF2, is used to monitor this fill rate, and local indication is provided in the pump room.

The two main reactor pumps, RWP1 and RWP2, one operational and the other on standby, are both interlocked with an overflow switch located in the reactor water-outlet pipe from the reactor vessel. This switch must be actuated by an overflow from the reactor vessel before the plant operator can start the operational main reactor pump. In addition to its permissive function, the overflow switch also actuates level-indicating lights on the control console.

b. Heat Transfer

The reactor water heat exchanger is a single-pass, counterflow type containing 128 0.95-cm ($\frac{3}{8}$-in.) OD tubes. To obtain the required heat transfer of 250 kw at a reactor coolant inlet temperature of 58.4°C (137°F), the reactor water flow is required to be 7.9 liter/sec (125 gpm). This flow rate is 100% greater than that required during normal operation (at 250 kw) with an expected water inlet temperature of 32°C (90°F). (See core Heat Transfer Calculations in Appendix D.)

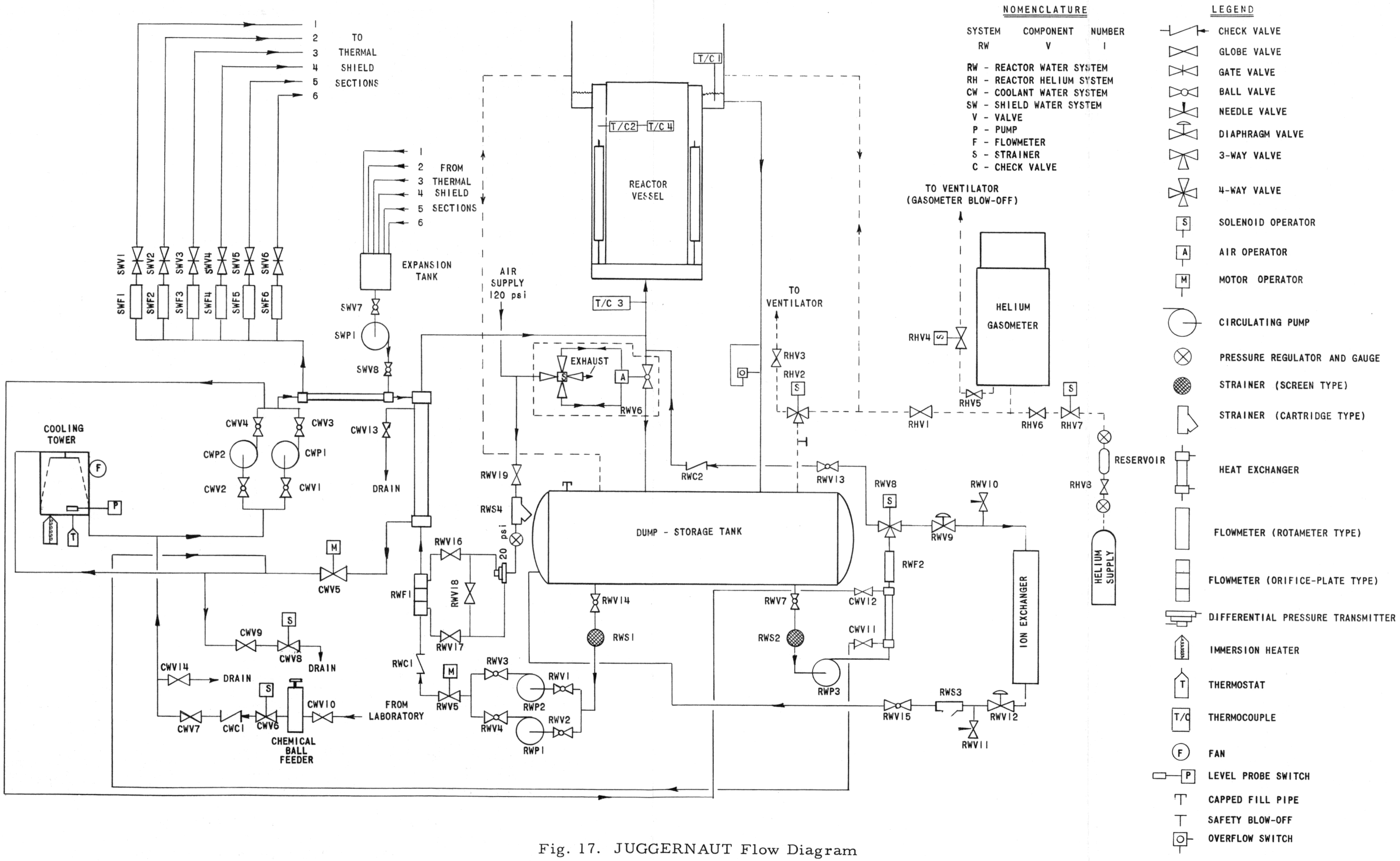
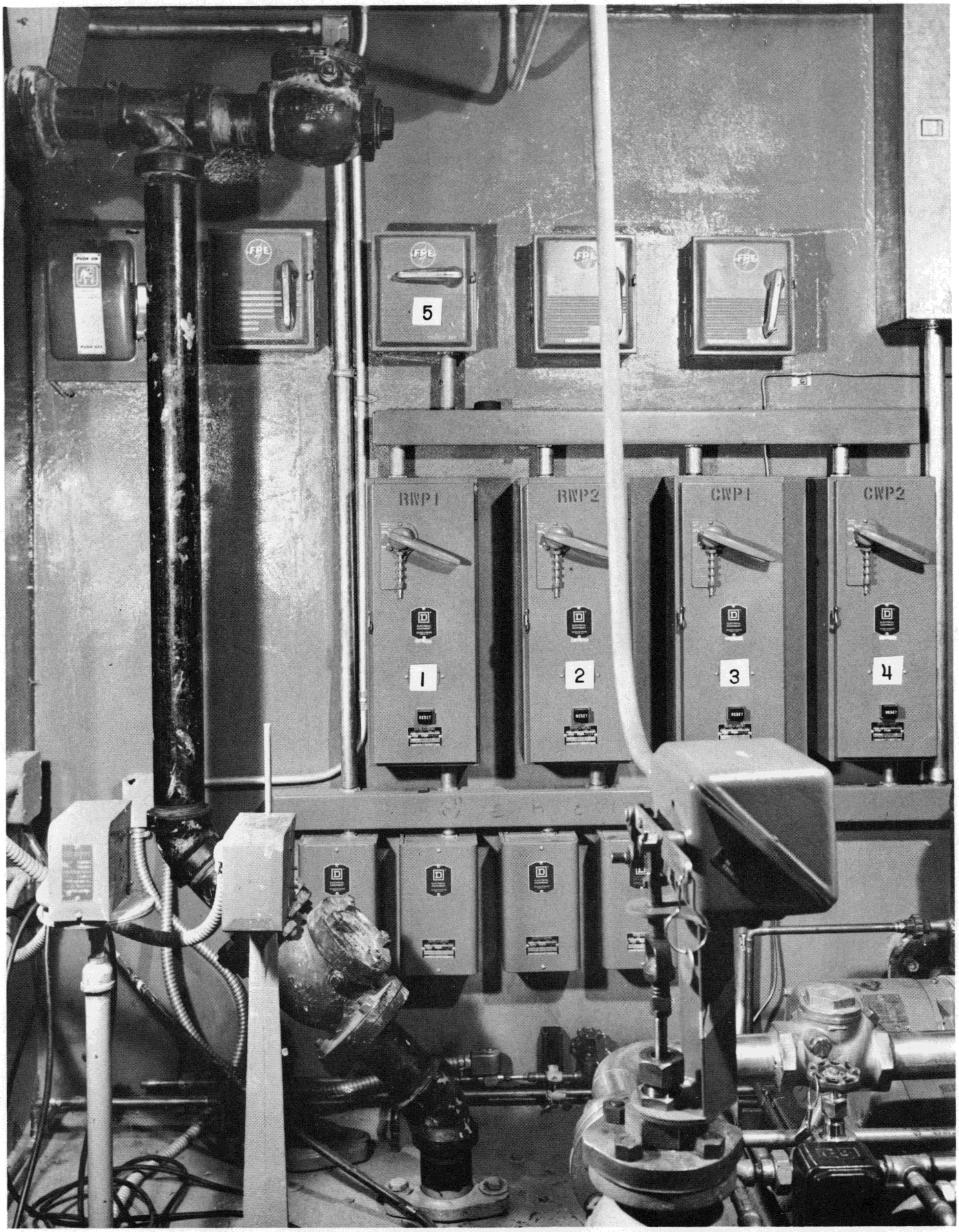


Fig. 17. JUGGERNAUT Flow Diagram

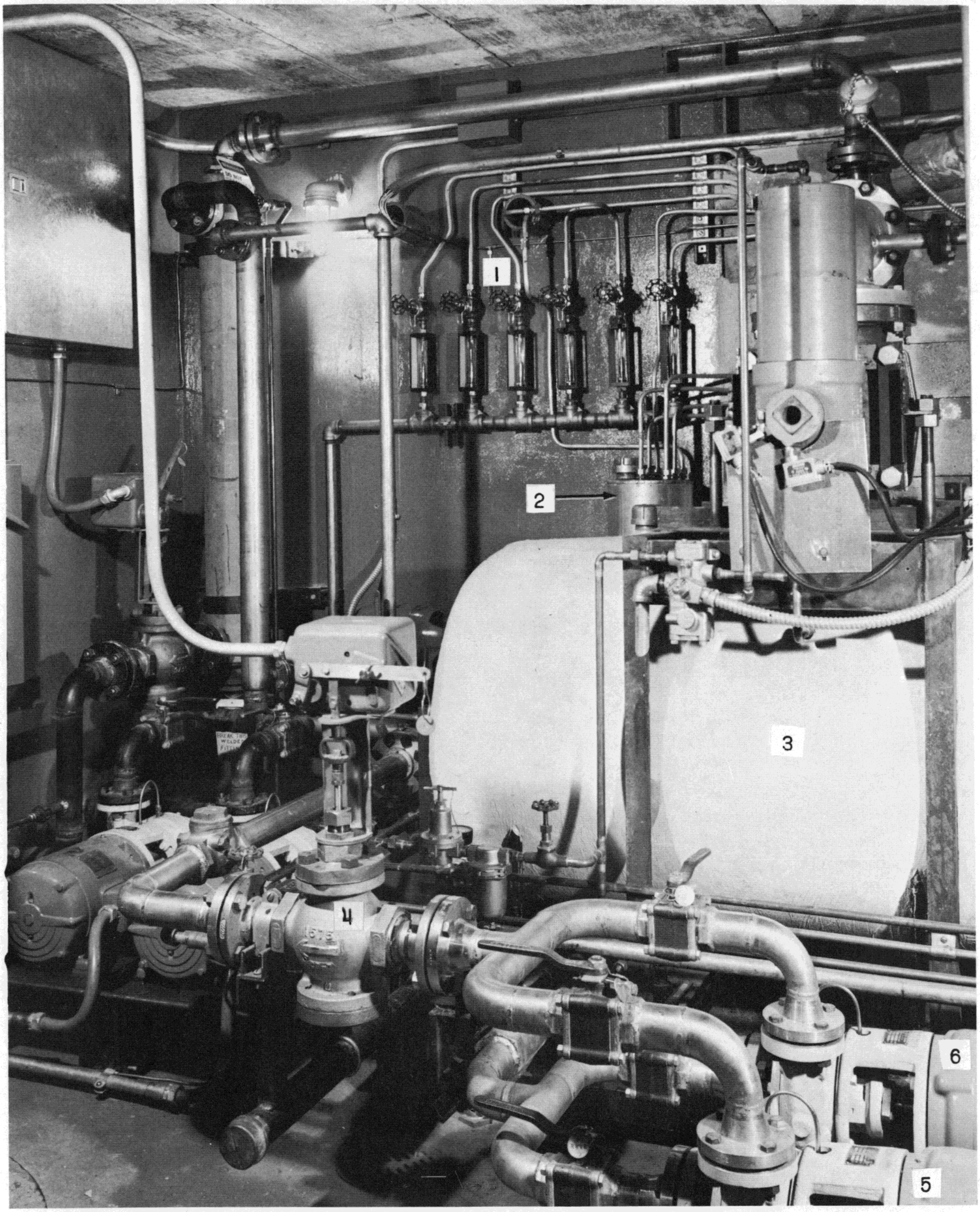


1 SAFETY SWITCH FOR REACTOR WATER PUMP NO. 1
2 SAFETY SWITCH FOR REACTOR WATER PUMP NO. 2
3 SAFETY SWITCH FOR COOLANT WATER PUMP NO. 1
4 SAFETY SWITCH FOR COOLANT WATER PUMP NO. 2
5 MAIN POWER SWITCH (FOR PUMPS ABOVE)

Fig. 18a. Pump Room - Major Components

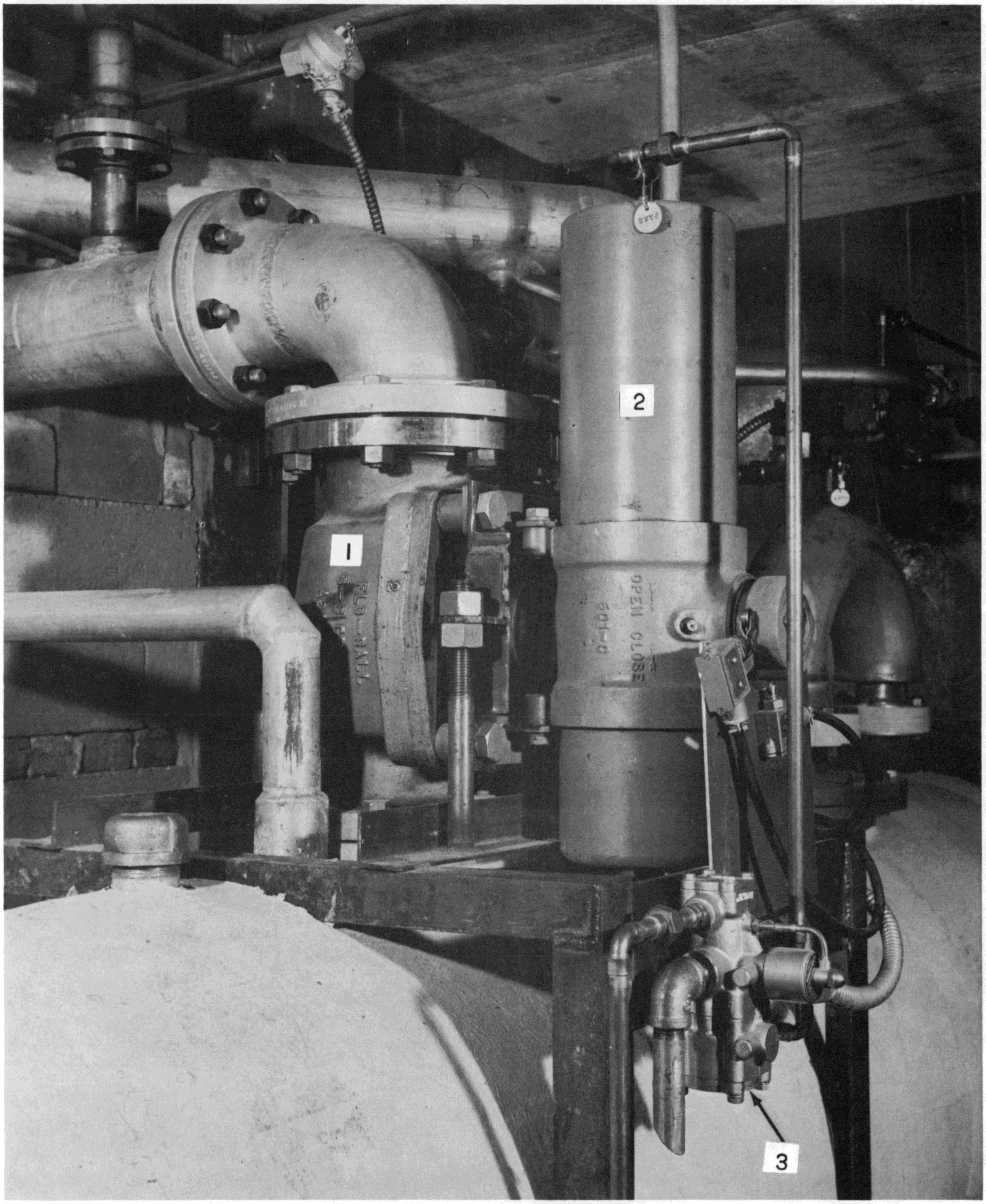
1 REACTOR WATER HEAT EXCHANGER
2 SHIELD WATER HEAT EXCHANGER
3 MOTORIZED THROTTLE VALVE (CWV5)
4 COOLANT WATER PUMP NO.1 (CWP1)
5 COOLANT WATER PUMP NO.2 (CWP2)

Fig. 18b. Pump Room - Major Components



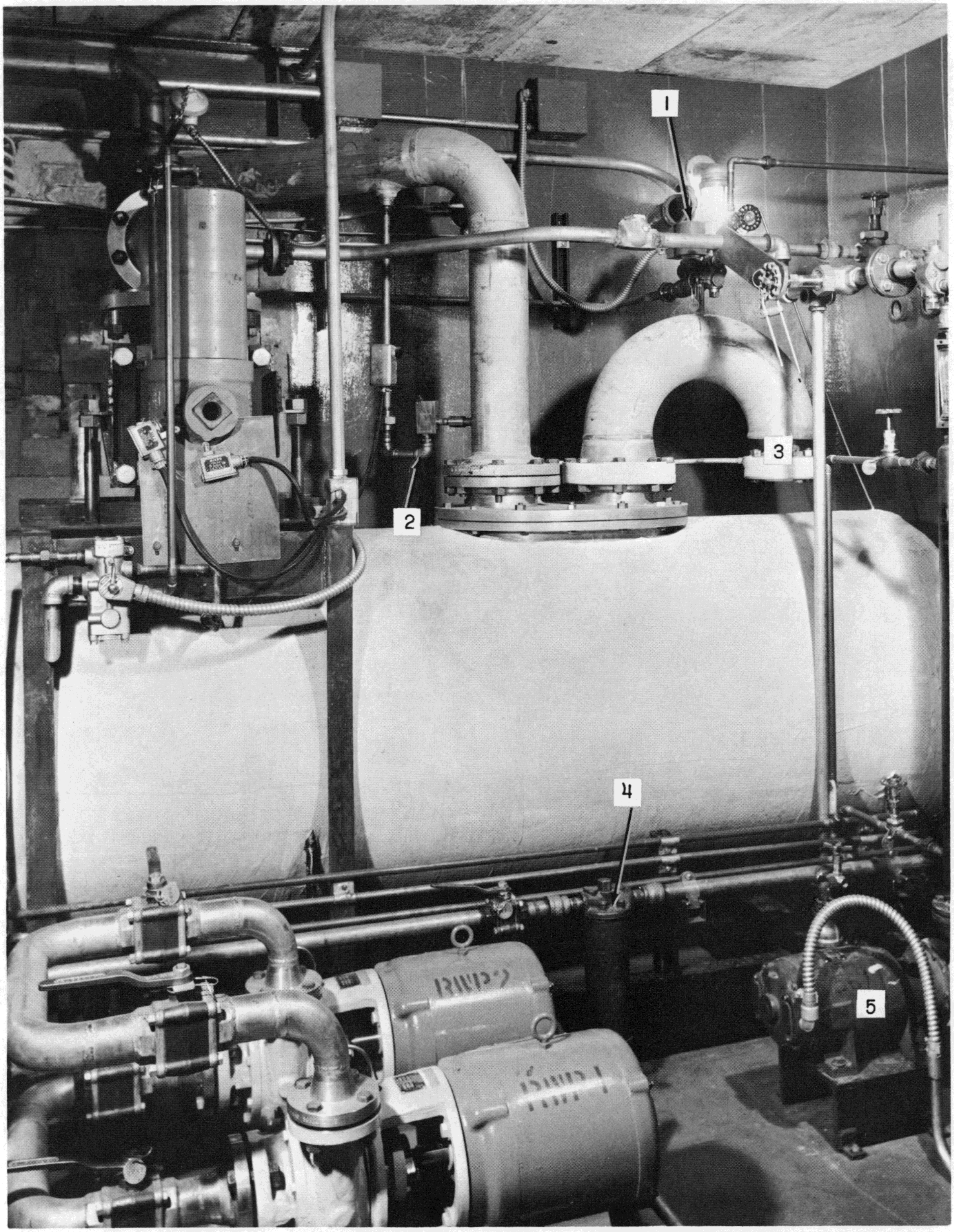
1 FLOWMETERS (SWF1 - SWF6)
2 SHIELD WATER EXPANSION TANK
3 DUMP - STORAGE TANK
4 MOTORIZED THROTTLE VALVE (RWV5)
5 REACTOR WATER PUMP NO. 1 (RWP1)
6 REACTOR WATER PUMP NO. 2 (RWP2)

Fig. 18c. Pump Room - Major Components



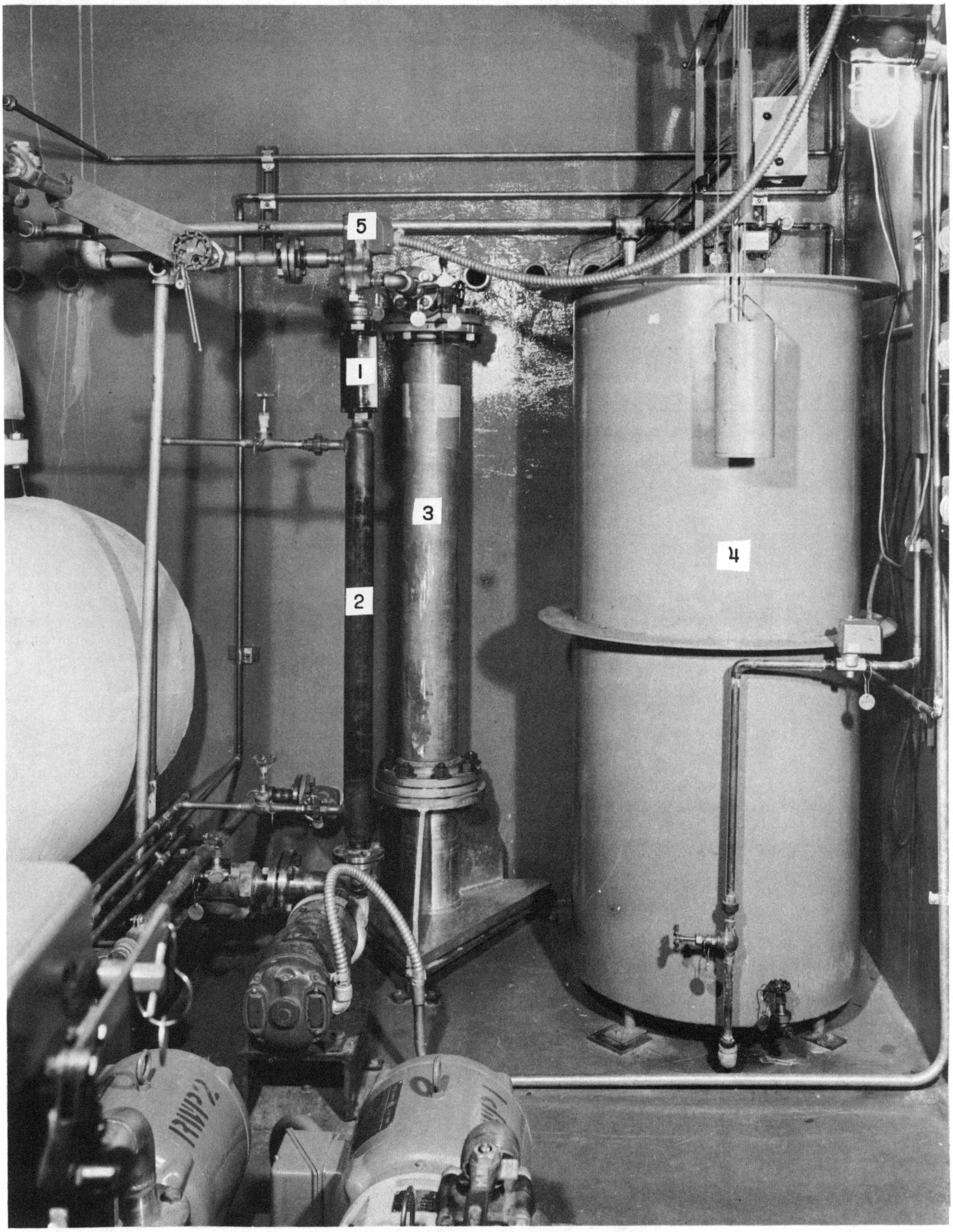
1 DUMP VALVE (RWV6) - BALL VALVE SECTION
2 DUMP VALVE (RWV6) - AIR OPERATOR
3 DUMP VALVE (RWV6) - SOLENOID OPERATED 4-WAY VALVE

Fig. 18d. Pump Room - Major Components



1 SOLENOID OPERATED 3-WAY VALVE (RHV2)
2 OVERFLOW SWITCH
3 SAFETY BLOWOFF DISK
4 STRAINER (RWS3)
5 AUXILIARY PUMP (RWP3)

Fig. 18e. Pump Room - Major Components



1 FLOWMETER (RWF2)
2 CLEANUP SYSTEM HEAT EXCHANGER
3 ION EXCHANGER
4 HELIUM GASOMETER
5 SOLENOID OPERATED 3-WAY VALVE (RWV8)

Fig. 18f. Pump Room - Major Components

Table III

MAJOR COMMERCIAL COMPONENTS OF REACTOR COOLING SYSTEMS

Component	Manufacturer	Manufacturer's Designation	Material	Design Rate Capacity
Auxiliary Pump (RWP3)	Eastern Industries	W8	Stainless Steel	0.63 liter/sec (10 gpm) at 2.3 atm (20 psig)
Main Reactor Pumps (RWP1 & RWP2)	Byron Jackson Pumps, Inc.	1-1/2 "TLM Bilton"	Type 316 Stainless Steel	7.9 liter/sec (1.25 gpm) at 4 atm (34.8 psig), (85 ft head)
Flowmeter (RWF1)	Fischer and Porter Company	Orifice-Plate	Type 316 Stainless Steel	400-in. water column differential at 150 gpm and Schedule 5 stainless steel pipe
Differential Pressure Transmitter (with RWF1)	Fischer and Porter Company	10B 1466A-1303 WB01	Stainless Steel Flanges	To operate in conjunction with flowmeter (transmits 3-15 lb signal)
Flowmeter (RWF2)	J. R. Simpson and Company	Brooks 1305, Sho-rate, Size 10	Type 316 Stainless Steel	Direct reading scale. Capacity: 0-15 gpm water
Flowmeters (SWF1-SWF6)	J. R. Simpson and Company	Brooks 1305, Sho-rate, Size 8	Type 316 Stainless Steel	Direct reading scale. Capacity: 0-5 gpm water
Throttling Valve (RWV5)	Pro-Quip, Inc.	2-in. Motorized Globe	Type 304 Stainless Steel	
Heat Exchanger (Reactor Water System)	Young Radiator Company	No. SSF-607-ER-IP	Stainless Steel	8.5×10^5 Btu/hr
Overflow Switch	Norman Engineering Company	FS-900	Stainless Steel	Range: 0.005-0.05 liter/sec (0.08-0.8 gpm)
Dump Valve (RWS6)	Pro-Quip, Inc.	Hydromatic Flo-Ball, 8 in.	Stainless Steel	150-lb pneumatic operator - opens on loss of air
Solenoid Valve, Four-Way (with RWV6)	Automatic Switch Company	834427	Bronze Body	115-V ac, 60-cycle, 100 psi air NEMA-1
Thermocouples (T/C 1, 2 & 3)	Thermo Electric Company	CEAL-116-ET	Chromel Constantan	
Thermocouple (T/C 4)	Thermo Electric Company	CEAL-18-AT	Iron Constantan	
Filter (RW53)	Cuno Engineering Corporation	IB1-2278-B3	Type 304 Stainless Steel	5-micron filter cartridge
Shield Water Pump (SWP1)	Eastern Industries	W8	Stainless Steel	
Cooling Tower (with level probe switch)	Binks Manufacturing Company	4B-40	Hot-Dipped Galvanized	Cool 6.3 liter/sec (100 gpm) from 42°C (108°F) to 32°C (90°F) at 24°C (75°F) wet bulb temperature
Immersion Heater	Tru Heat Corporation	#FA-123	Sheath Material - Copper	12 kw, 480 V, 3 phase
Secondary Water Pumps (CWP1 & CWP2)	Byron Jackson Pumps, Inc.	1-1/2 TLM Bilton	Cast Iron, Bronze Fitted	6.3 liter/sec (100 gpm) at 3.7 atm (31.8 psig), (80 ft head)
Throttle Valve (CWV5)	Pro-Quip, Inc.	2-in. Motorized Globe	Brass or Steel	
Chemical Ball Feeder	Nalco Chemical Company	4-200 Bypass Type		Operating Pressure: 200 psi Capacity in Balls: 4 Volume: 0.7 gal

c. Low-flow Trip

An orifice-plate-type flowmeter, RW-F1, is installed in the outlet piping from the main reactor pumps to measure the flow rate of reactor water to the heat exchanger. The flowmeter is connected to a differential pressure transmitter and a drum indicator on the S.W. instrument rack.

If the flow rate decreases below 4 liter/sec (60 gpm), a low-flow trip will automatically initiate reactor shutdown (rod scram). Audible and visual indicators at the control console will be simultaneously actuated.

Adjustments of flow rate are controlled through the use of a motorized throttling valve, RW-V5, located at the outlet of the main reactor pumps. This valve is remotely controlled from, and its position indicated on, the S.W. instrument rack.

d. Temperature Monitoring and High-temperature Trip

Reactor water inlet and outlet temperatures and the temperature of the water in the core annulus are measured by chromel-constantan thermocouples (T/C 3, 1, and 2, respectively). The output of one of these thermocouples or the differential output of any two of the thermocouples is plotted on a temperature recorder on the N.W. instrument rack.

If the temperature at the reactor water outlet, as detected by a fourth thermocouple (T/C 4), of iron-constantan, located in the core annulus, exceeds a set value of 50°C (122°F) higher than the temperature of the cooling tower water, a high-temperature trip will automatically initiate reactor shutdown (rod scram). Audible and visual indicators at the control console will be simultaneously actuated.

e. Water Dump (Scram)

In addition to its cooling function, reactor water also acts as the core moderator; therefore, removal of the reactor water from the core is an effective safety device. An emergency reactor shutdown (scram), effected either manually or automatically, includes both a rod scram and a water dump.

During a water dump, the water in the reactor vessel is drained to the dump-storage tank in approximately 4 sec through the dump valve, RWV6, installed in the reactor vessel inlet piping. Within 2 sec of the initiation of a water dump, the top reflector (from the reactor vessel weir down to the top of the core) is removed, effecting a decrease in reactivity of one to two per cent. In an additional 2 sec, the entire core annulus is drained.

To accomplish a water dump during full-flow conditions, when the inlet/dump line is full of water, the reactor vessel is vented by the Reactor Helium System vent lines which interconnect the reactor vessel and the dump-storage tank.

The dump valve is an air-operated, spring-assisted, fail-safe unit that can be opened in 0.2 sec by 9 atm (132 psi) of air pressure or at a slower rate by spring pressure alone. The opening and closing of the valve is initiated by a four-way solenoid valve which interconnects an air supply to the dump valve.

When the solenoid is energized, the air supply is directed against the dump-valve spring to hold the valve closed. When a scram is initiated, or the solenoid valve fails, the solenoid is de-energized, causing the air pressure holding the spring to be exhausted and the air supply to be redirected to the air operator which, assisted by the spring action, opens the dump valve.

For material compatibility with the piping and the dump-storage tank, aluminum was originally selected as the dump-valve material. However, as the manufacturer could not deliver an aluminum valve, stainless steel was accepted as a substitute.

The dump-storage tank is a salvaged 1150-liter (300-gal) aluminum vessel having a large manhole and auxiliary openings at top and bottom. Two separate horizontal baffle plates were welded on the inside of the tank, one directly above the outlet line to the main reactor pumps and the other directly above the outlet line to the auxiliary pump. These baffles prevent the pumps from pulling air into their intake and becoming air bound during a low water level (a few centimeters above the plates) in the tank. Without the baffle plates a much higher water level would be necessary to accomplish the same function.

A safety blowoff disk is installed in the Reactor Helium System purge line outlet from the dump-storage tank as a safeguard against high pressures in the primary system. This safety device consists of an aluminum diaphragm which is designed to rupture at 1.3 atm (5 psig). The gas or steam is released into the pump room from which it is vented by a blower which exhausts at the roof level of the brick building.

f. Cleanup (Purification) System

Following startup of the main reactor pump, the plant operator can either: (1) shut down the auxiliary pump; or (2) de-energize the three-way solenoid valve, RWV8, which reroutes the auxiliary pump outlet to the ion exchanger and the Cleanup System flow path. The function of the Cleanup System is to maintain reactor water resistivity at 7 megohms and at a pH level of 7.25.

Reactor water is pumped from and back to the dump-storage tank, after having passed through the mixed-bed (Type NR-6 resin, Illinois Water Treatment Company) ion exchanger, at a flow rate of 0.25 liter/sec (4 gpm). A flowmeter, RWF2, is used to monitor this flow rate, and local indication is provided in the pump room. Water-sampling valves, RWV10 and RWV11, are provided so that samples of water may be taken for chemical analysis before and after the water passes through the ion exchanger.

g. Component Materials

All primary system components were fabricated from either aluminum (Type 6061) or stainless steel (300 series). All aluminum-stainless steel joints are located in the pump room for accessibility in the event repair or replacement is required. The number of aluminum-stainless steel joints made is the minimum necessary. No sacrificial joints are employed; however, if destructive corrosion occurs at an aluminum-stainless steel joint, the joint can be removed and replaced. Flexitallic gaskets of aluminum or stainless steel with Teflon fill were used on all flanges. Material compatability was maintained for all gasket and flange combinations.

2. Reactor Helium System

a. Volumetric Control

A gasometer (see Fig. 19) supplies helium directly to the reactor vessel, from which the helium flows to the dump-storage tank. During normal operation, volumetric control of the helium in the system is maintained by the gasometer, which adjusts the gas volume relative to atmospheric pressure and helium temperature.

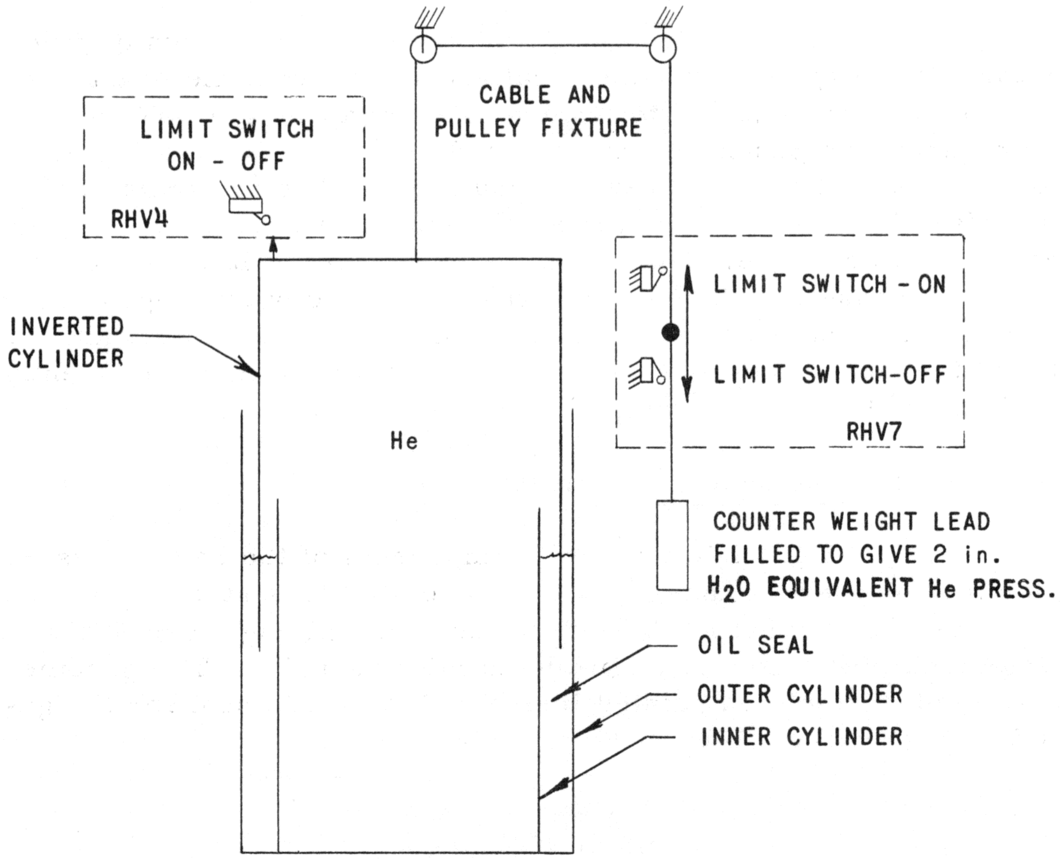


Fig. 19. Helium Gasometer - Volumetric Controls

A slight pressure, equivalent to 2 in. of water, is maintained throughout the system as a result of the gasometer reactions. Helium pressure in the system and the number of fill cycles performed by the gasometer are indicated on the N.W. instrument rack. Visual indication of a helium fill is provided at the control console.

Should gas volume in the system increase excessively, the gasometer reaction trips a limit switch which energizes the solenoid valve RHV4, automatically venting (blowoff) the excess gas. Visual indication of a gasometer blowoff is provided on the control console. As an added precaution against high pressure in the system, an aluminum diaphragm is installed in the helium outlet line from the dump-storage tank. This disk is designed to rupture at 1.3 atm (5 psig) pressure.

Helium makeup is controlled by limit switches on the gasometer. When the on limit switch is tripped by the gasometer, solenoid valve RHV7 is actuated, permitting helium to flow from a supply tank to the gasometer. When a sufficient volume of helium enters the gasometer, the off limit switch is automatically tripped and the solenoid valve is deenergized.

b. Helium Purge

After a reactor shutdown and prior to startup (when the reactor is sealed), it is assumed that air has entered the reactor and that a helium purge is required to remove the entrapped air. To initiate a helium purge, the gasometer is returned to the line by opening valve RHV1 (this valve is shut during a reactor shutdown). The three-way solenoid valve RHV2 is then energized, from the instrument cubicle, to open the vent to the atmosphere. The gasometer reaction initiates helium flow to the reactor vessel, to the dump-storage tank, and out the open vent line, forcing out the entrapped air. Visual indication of a helium purge is provided at the control console. When the system is purged sufficiently, RHV2 is deenergized.

c. Component Materials

Materials used for components of the helium system include steel, copper, bronze, cast iron, and stainless steel. Stainless steel is used instead of steel in those sections of the piping close to the dump-storage tank where corrosion products might develop. The gasometer is constructed of steel and painted inside and out. The seal for the gasometer is a high vacuum oil.

3. Shield Water System

In the Shield Water System, water is pumped from an expansion tank through a fabricated shell-and-tube heat exchanger to a manifold. From the manifold, the water is channeled through six flowmeters at a rate of 0.12 liter/sec (2 gpm) into six separate flow paths to the cooling coils, 1.2 cm ($\frac{1}{2}$ in.) in diameter, embedded in the six sections of the thermal shield. The flowmeters SWF1-SWF6 provide local indication in the pump room. To complete the flow cycle, the six flow paths converge into one upon their return to the expansion tank. The shell side of the shield-water heat exchanger is cooled by the Coolant Water System. The shield water pump is actuated from the control console. Visual indication of pump operation is also provided at the control console.

The cooling coils in the four sections of the thermal shield which surround the vertical faces of the graphite core reflector are fabricated from aluminum, whereas the coils in the shield sections below the top removal shield and the rotating shield plug are of stainless steel.

4. Coolant Water (Secondary) System

a. Pump Operation

Two coolant water pumps (one operational and one on standby), CWP1 and CWP2, are provided for the circulation of coolant water from a cooling tower through the shell side of the Reactor Water, Cleanup, and Shield Water System heat exchangers at a rate of 6.3 liters/sec (100 gpm). Flow rate is controlled by a throttle valve, CWV5, operable from the instrument cubicle. Position indication for this valve is also provided in the instrument cubicle. Both coolant water pumps are operable from the control console, and visual indication of their operation is provided.

Pump operation energizes solenoid valve CWV8, which opens the drain line to the sump in the pump room. This drain line, on the pressure side of the pumps, functions as a blowdown line through which solids are removed from the coolant.

b. Cooling Tower

The cooling tower is a metal-enclosed structure, approximately 1.82 m (6 ft) square and 2.34 m ($7\frac{1}{2}$ ft) high, located approximately 7.5 m southeast of the reactor building. The cooling tower features a counter-flow fan, an immersion heater and thermostat, and a level probe switch. The cooling tower is capable of cooling secondary water from 42°C (108°F) to 32°C (90°F) at a wet bulb temperature of 24°C (75°F), assuming a coolant flow of 6.3 liters/sec (100 gpm) and that the blower fan is on. The tower fan is operable from the instrument cubicle and visual indication of its operation is provided.

During the winter months the tower water is maintained above freezing temperatures by a thermostatically controlled 12-kw immersion heater. The thermostat controls the temperature of the water between 16°C (60°F) and 21°C (70°F). Visual indication of heater operation is provided at the control console.

Water makeup to the cooling tower is controlled by a level probe switch located in the tower basin. The switch is interlocked with solenoid valve CWV6. When the probe is dry, the solenoid is actuated to permit makeup water to flow from the laboratory supply through a chemical ball feeder to the inlet line of the coolant water pumps. Visual indication of a low water level in the tower is provided at the control console.

E. Neutron Source

An antimony-beryllium source is used to provide neutrons for reactor startup. The source consists of an aluminum-clad, solid cylinder, 3.2 cm ($1\frac{1}{4}$ in.) OD and 4.1 cm ($1\frac{5}{8}$ in.) long, of irradiated antimony suspended within an open-end beryllium cylinder, 8.9 cm ($3\frac{1}{2}$ in.) OD x 20.3 cm (8 in.) long x 2.5 cm (1 in.) thick wall, located at the core midplane in the reactor graphite (see Fig. 5). A yield of approximately 10^8 n/sec can be obtained after irradiation of the antimony in a thermal-neutron flux of approximately 10^{13} n/(cm^2)(sec) for ten days.

After irradiation, the antimony is transported to the reactor by placing it in the bottom section of a source container (see Fig. 20), directly under 12.7 cm (5 in.) of lead.

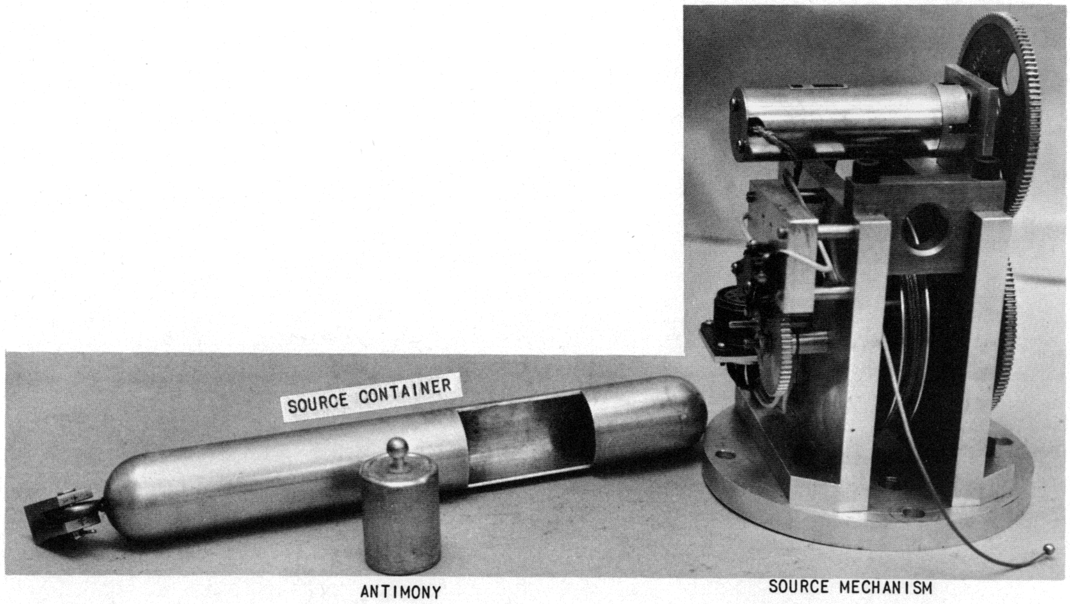


Fig. 20. Source and Source Mechanism

One end of a wire rope is then attached to the top of the source container; the other end is threaded into and through the JUGGERNAUT fuel and source coffin. The source container is then drawn into the coffin. After the coffin has been transported to the reactor and placed over the open "source" hole, the source container is lowered to the bottom of the hole (below floor level) where a lead pot completely surrounds the container (see Fig. 5).

The "source" hole, located in the test cave graphite, contains an aluminum sheath which centers the beryllium cylinder at the core midplane. The beryllium cylinder can be removed, if necessary, by screwing a threaded rod into the top threaded portion of the aluminum sheath. The bottom end of the aluminum sheath makes contact with the lead pot.

The source container with the gamma source is raised into the beryllium cylinder and lowered out of the cylinder by winding and unwinding the wire rope on a motor-operated (Globe Industries, Inc., No. 5A1683N, Type No. 49, LL Series, 24-V dc) drum equipped with limit switches (see Fig. 21). This mechanism is mounted on top of the "source" hole shield plug after the antimony has been lowered to the bottom of the hole. The wire rope is removed from the coffin, threaded through a hole in the "source" hole shield plug, and pulled taut while the shield plug is lowered into the opening of the "source" hole. The rope is then cut to length and secured to the motorized drum. To remove the antimony, the procedure is reversed.

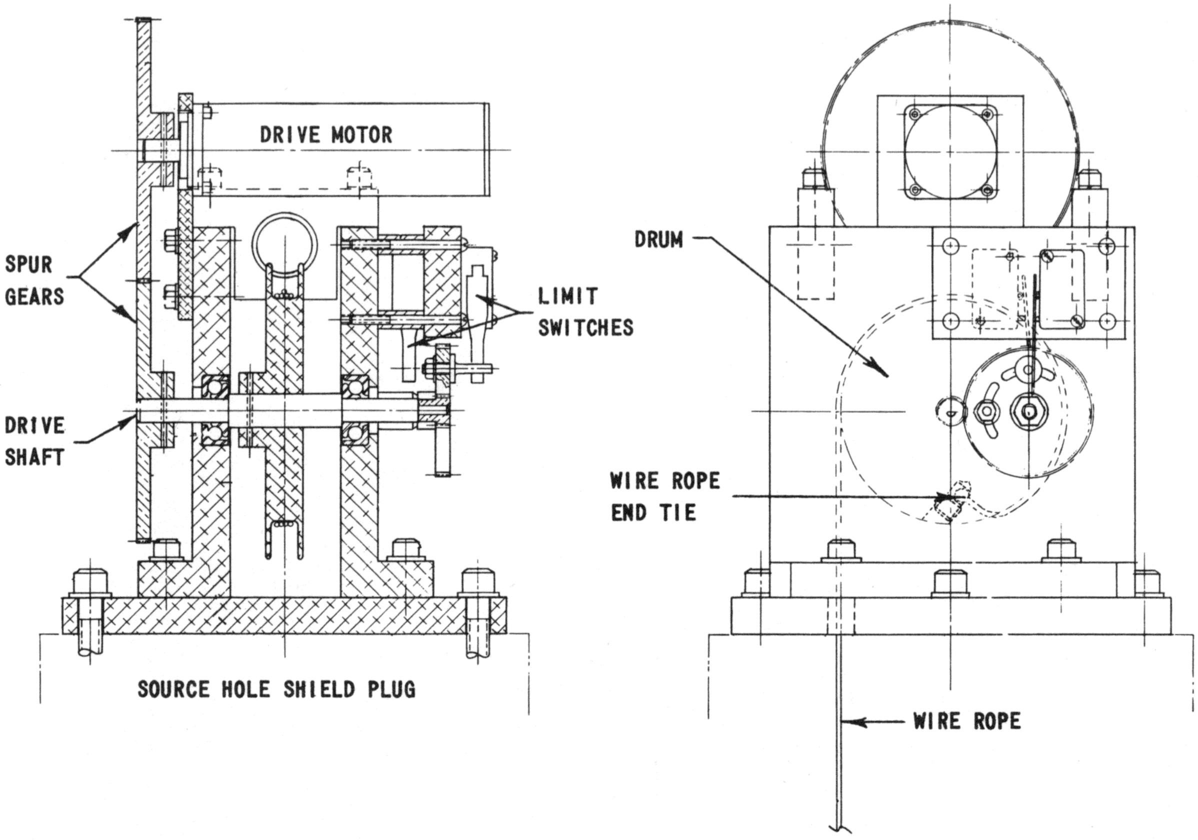


Fig. 21. Source Mechanism - Details

The raising and lowering of the source is controlled from the control console. A safety interlock prevents rod withdrawal unless the source has been raised into position. Visual IN and OUT indication of the source position is provided at the control console.

F. Control Rods and Drive Mechanisms

The eight control rods which constitute the movable solid poison control for JUGGERNAUT include seven coarse control rods and one fine control rod. These rods and their drive mechanisms have the same basic conceptual design as those used on the ARGONAUT with modifications to suit the needs of the JUGGERNAUT.

During reactor operations at least four coarse control rods must be completely withdrawn from the reactor to function as safety rods. Position indication for these safety rods is provided at the control console but is limited to their full IN and full OUT positions. Continuous position indication is provided at the control console for the other three coarse or shim control rods and the fine control rod.

Equally spaced around the perimeter of the reactor vessel (see Figs. 22a and 22b), each rod operates in a stainless steel and aluminum sheath or channel which penetrates the shielding and the graphite core reflector surrounding the lower section of the reactor vessel. The aluminum section of each sheath is located in the graphite; the stainless steel section, located in the shielding, is attached to the aluminum section with rivets. The sheaths are inclined at a 5-degree angle to the vertical to clear the rotating shield step and still place the active section of each rod close to the core for effective control.

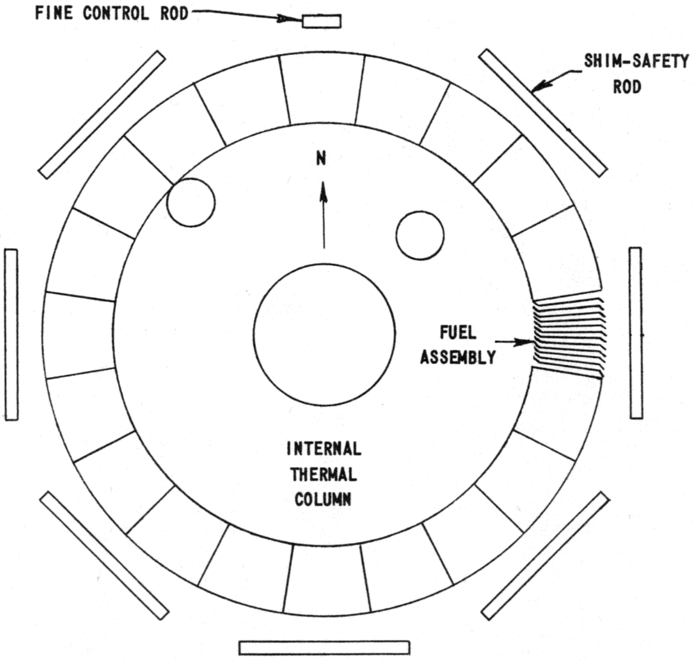
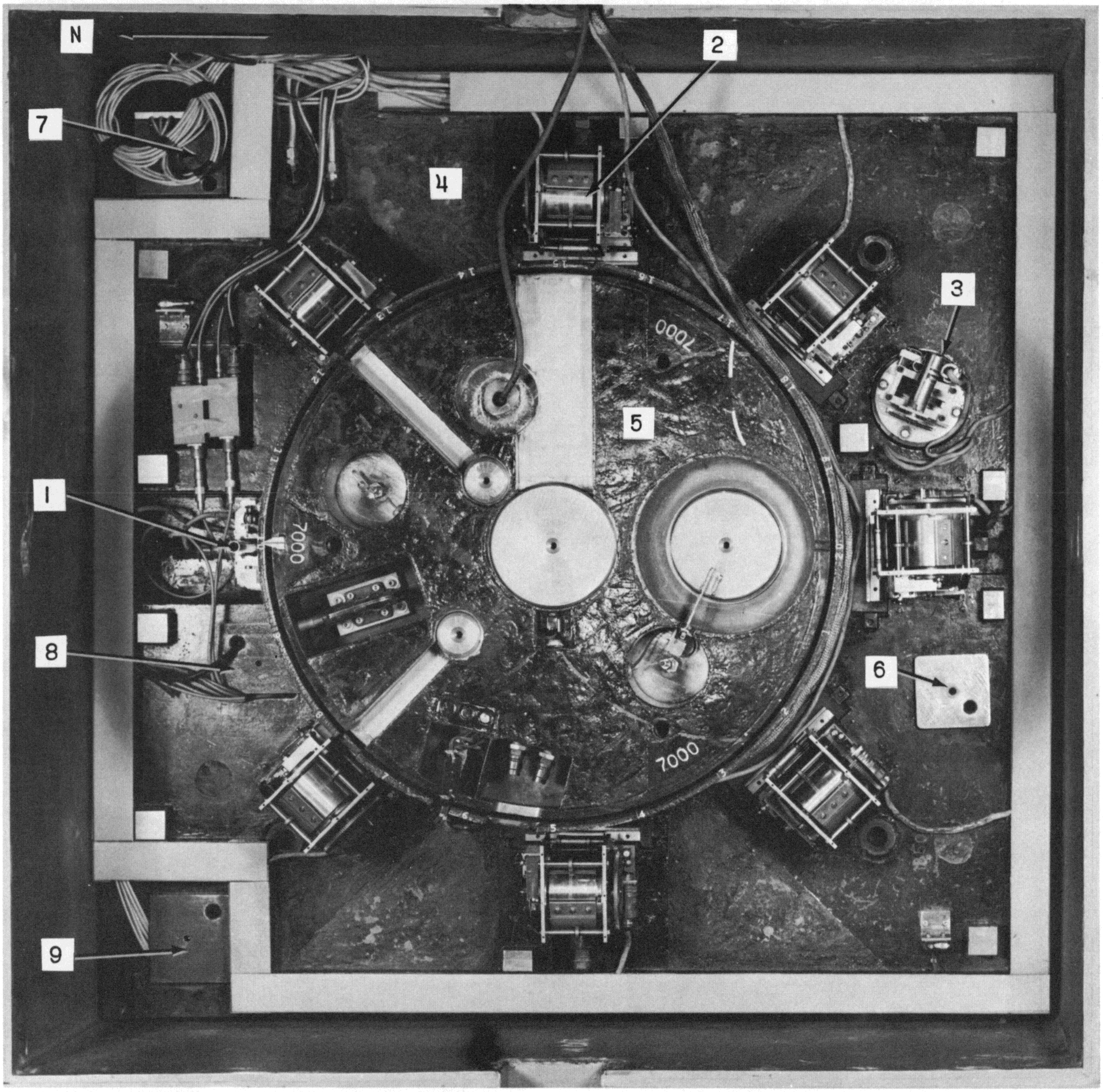


Fig. 22a. Control Rod Arrangement in Relation to Core



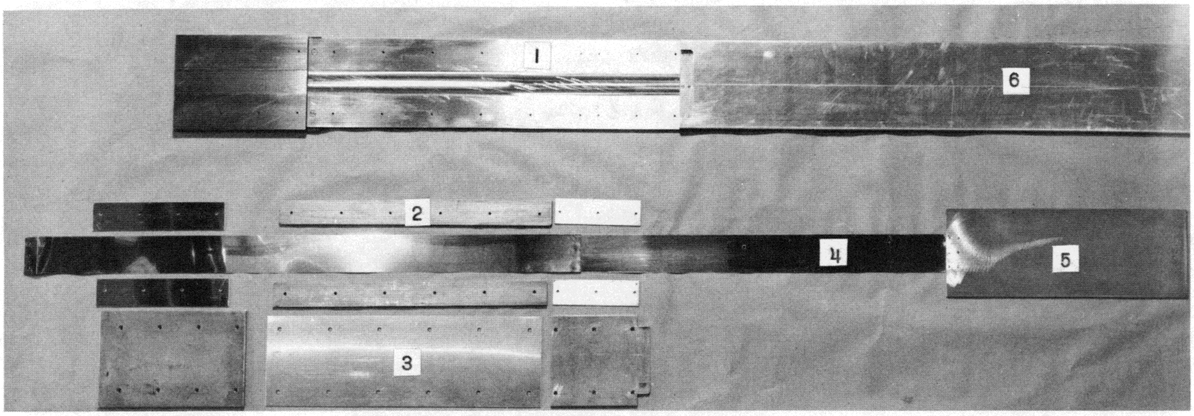
1 FINE CONTROL ROD MECHANISM
2 SHIM-SAFETY ROD MECHANISM
3 SOURCE MECHANISM
4 LOWER SECTION OF REMOVABLE SHIELD ASSEMBLY
5 ROTATING SHIELD
6 VERTICAL (EXPERIMENTAL) PORT
7 INSTRUMENTATION HOLE (C1)
8 INSTRUMENTATION HOLE (C3)
9 INSTRUMENTATION HOLE (C2)

Fig. 22b. Control Rod Arrangement in Relation to the Reactor Top Shielding

Requirements for excess reactivity and worths of control rods are discussed in Appendix B.

1. Shim-Safety Rods and Mechanisms

The seven shim-safety rods (see Fig. 23) feature a poison section of 2 wt-% natural boron-steel, 48 cm (19 in.) long, 17.8 cm (7 in.) wide, and 0.274 cm (0.108 in.) thick, to control in excess of 1% Δk per rod. As a bank, these rods control 7.0% Δk. Boron-steel was used as the control material to eliminate any possibility that the rods would melt if an accidental release of Wigner energy in the graphite occurred.



1 STAINLESS STEEL SHEATH
2 SIDE SHIMS FOR STAINLESS STEEL SHEATH COVER PLATE
3 STAINLESS STEEL SHEATH COVER PLATE
4 STAINLESS STEEL RIBBION
5 STAINLESS STEEL - BORON POISON SECTION
6 ALUMINUM SHEATH

Fig. 23. Shim-Safety Rod and Sheath

Each shim-safety rod is actuated independently by an ARGONAUT-type window shade-drive mechanism (see Figs. 24 and 25). The drives are installed on top of the lower section of the removable shield assembly and are attached directly to the respective control rod sheath. Vertical motion is imparted to the rod by an interconnecting stainless steel spring ribbon that is attached to a rotating drum. The drum is rotated by a dc drive motor (Globe Industries, Inc., No. 5A1683, Type No. 49, LL Series, 25-v dc) operating through a system of gears and a magnetic clutch (Warner Electric No. SF-400-90, dc). The gearing system limits the rate of rod withdrawal to 0.30 cm/sec (0.118 in./sec), or to a total time of 2.7 min, corresponding to an average rate of addition of reactivity of 0.01% (Δk/k)/sec.

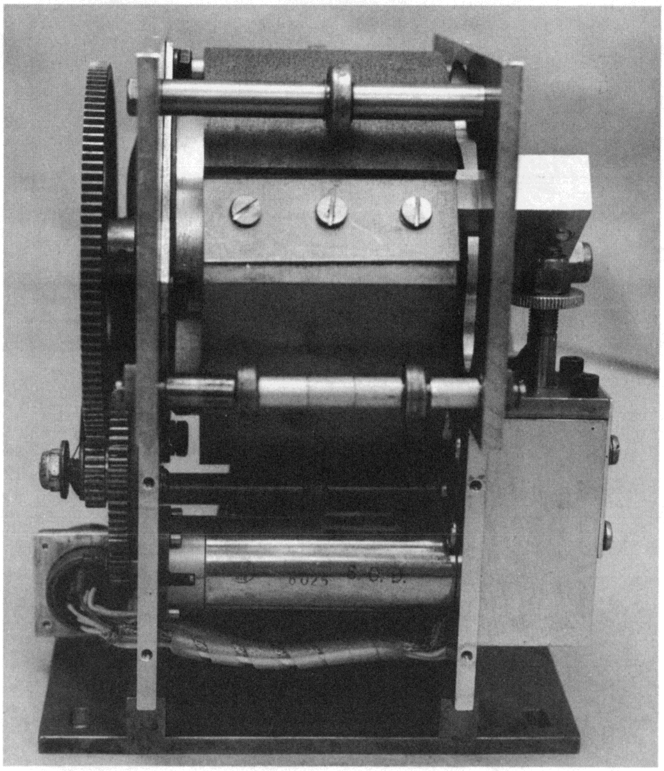


Fig. 24. Shim-Safety Rod Mechanism

Fast shutdown (rod scram or scram) is effected either manually or automatically by deenergizing the magnetic clutch which couples the drum to the drive. In this event, the rods are spring-assisted and gravity-accelerated to their fully inserted position in a free-fall time of less than 0.5 sec. The rod is decelerated near the end point of its travel by a snubber arm and an oil-filled snubber pot. The recorded free-fall time includes deceleration time. The total travel of the shim-safety rods is limited to 50 cm ($20\frac{3}{4}$ in.).

The dc drive motor and, therefore, the motion of the shim-safety rods, can be stopped, started, or reversed at any point of rod travel. When fully withdrawn, the bottom of a rod is poised 1 cm above a plane corresponding to the top of the core. When fully inserted, a rod extends to a point 18.4 cm ($7\frac{1}{4}$ in.) below the core midplane.

Each rod mechanism can be disconnected from the spring ribbon, removed from the reactor, and replaced by a spare mechanism in one hour. The sheath with the rod inside can be raised into a coffin. However, no work may be performed on either the mechanism or the rods unless the dump valve is open.

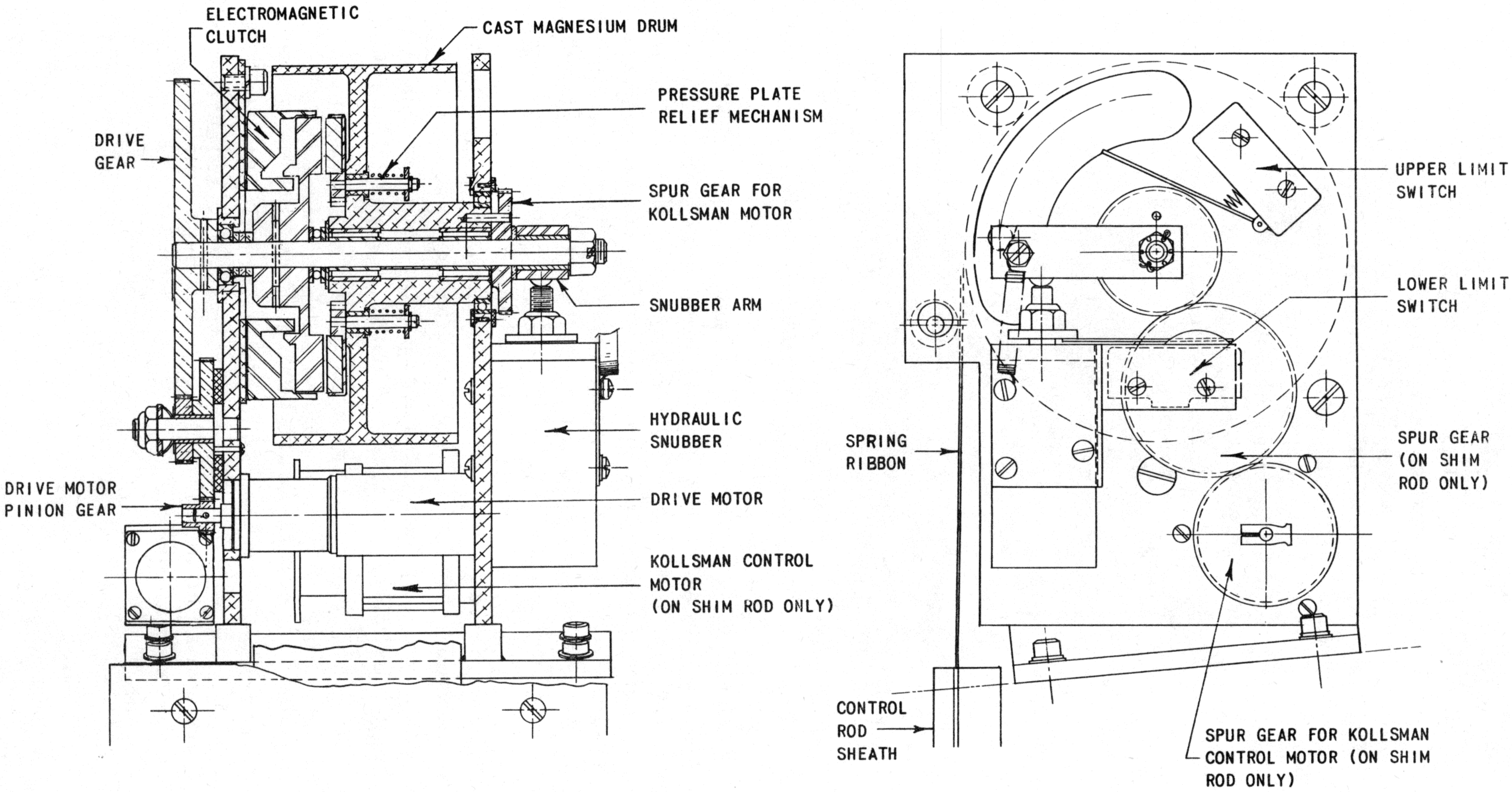


Fig. 25. Shim-Safety Rod Mechanism - Details

The three shim rod drives each feature a synchro transmitter that is geared directly to the rotating drum for continuous position indication. Synchro receivers, interconnected with the transmitter on the drives, are mounted on the control console. The position-indicating dials on the console are calibrated in increments of 1.27 cm (0.5 in.). Both shim and safety rod drives include a set of cams that operate limit switches for rod travel. The limit switches for each rod illuminate corresponding full IN or full OUT panel lights on the control console.

All shim-safety rod drives are interlocked with a safety trip circuit which can prevent rod withdrawal or initiate an automatic scram.

2. Fine Control Rod and Mechanism

The fine control rod (see Fig. 26) has a poison section, fabricated from cadmium and clad with stainless steel, which measures 29.2 cm ($11\frac{1}{2}$ in.) long, 2.54 cm (1 in.) wide, and 0.020 cm (0.008 in.) thick. The cadmium is centered on the midplane of the core when the rod is in the full IN position. This rod controls only 0.15% Δk and is not interlocked with the safety trip circuit.

The fine control rod is manually operated from the control console through the actuation of a conventional rack-and-pinion drive mechanism shown in Figs. 26 and 27. Vertical motion is imparted to the control rod by a gear head motor (Globe Industries, Inc., No. 43A154, Type SS, 24-v dc) coupled directly to the pinion gear drive shaft. As in the case of the shim-safety rods, the gearing system limits the rate of rod withdrawal to 0.33 cm/sec (0.128 in./sec), corresponding to an average reactivity rate addition of $<0.003\%$ $(\Delta k/k)$/sec. In the event of a power failure, the rod will remain stationary until power to the drive motor is restored.

The position of the fine control rod over its total travel of 20 cm (8 in.) is indicated by a synchro transmitter geared directly to to the rod drive shaft and a set of cams that operate limit switches. The respective signals are transmitted to a corresponding receiver and position-indicating dial, calibrated in increments of 0.025 cm (0.01 in.), and to full IN and full OUT lights mounted on the control console.

Maintenance work can be performed on the fine control rod and drive mechanism after removal of the top section of the removable shield assembly.

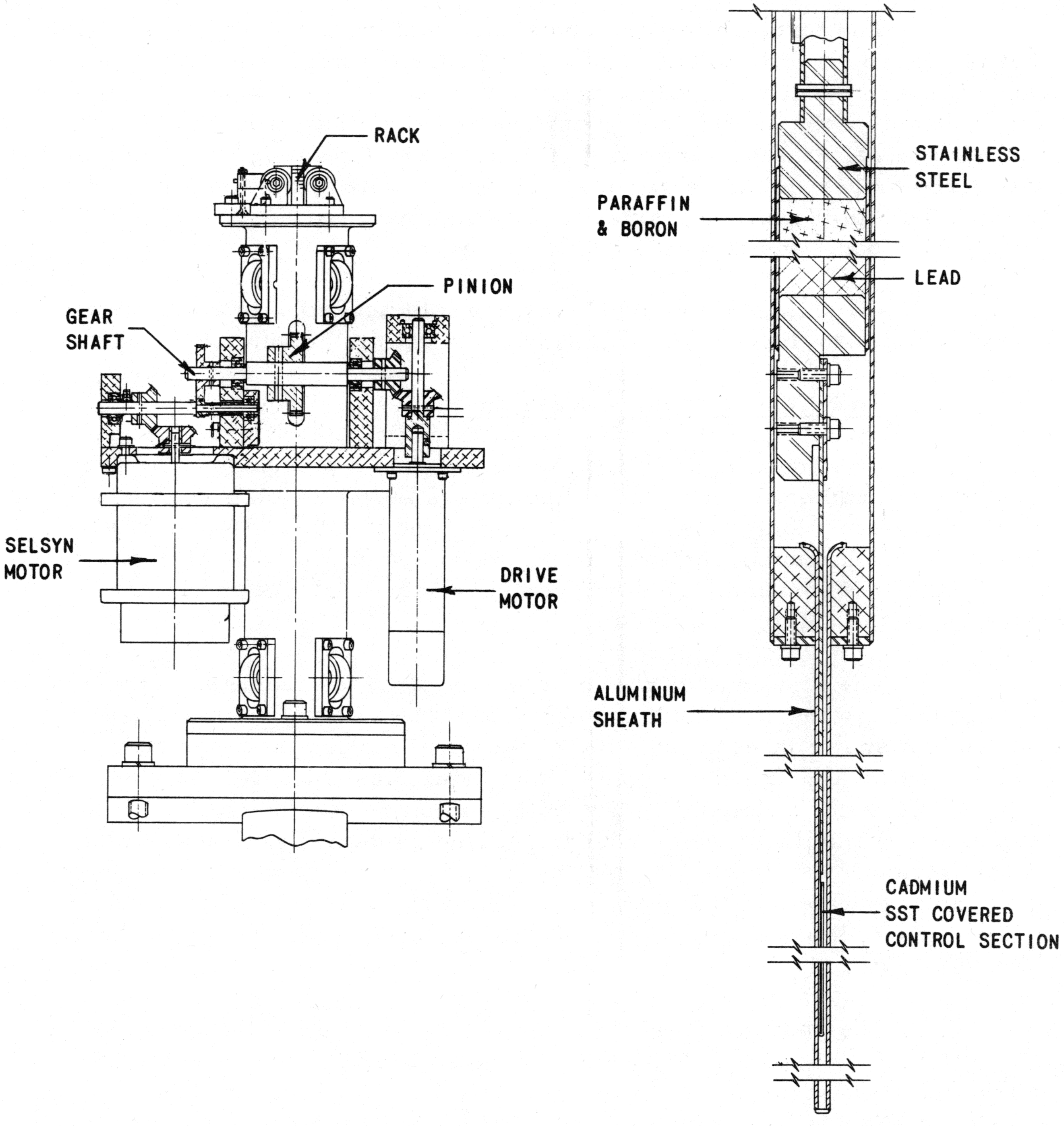


Fig. 26. Fine Control Rod and Mechanism - Details

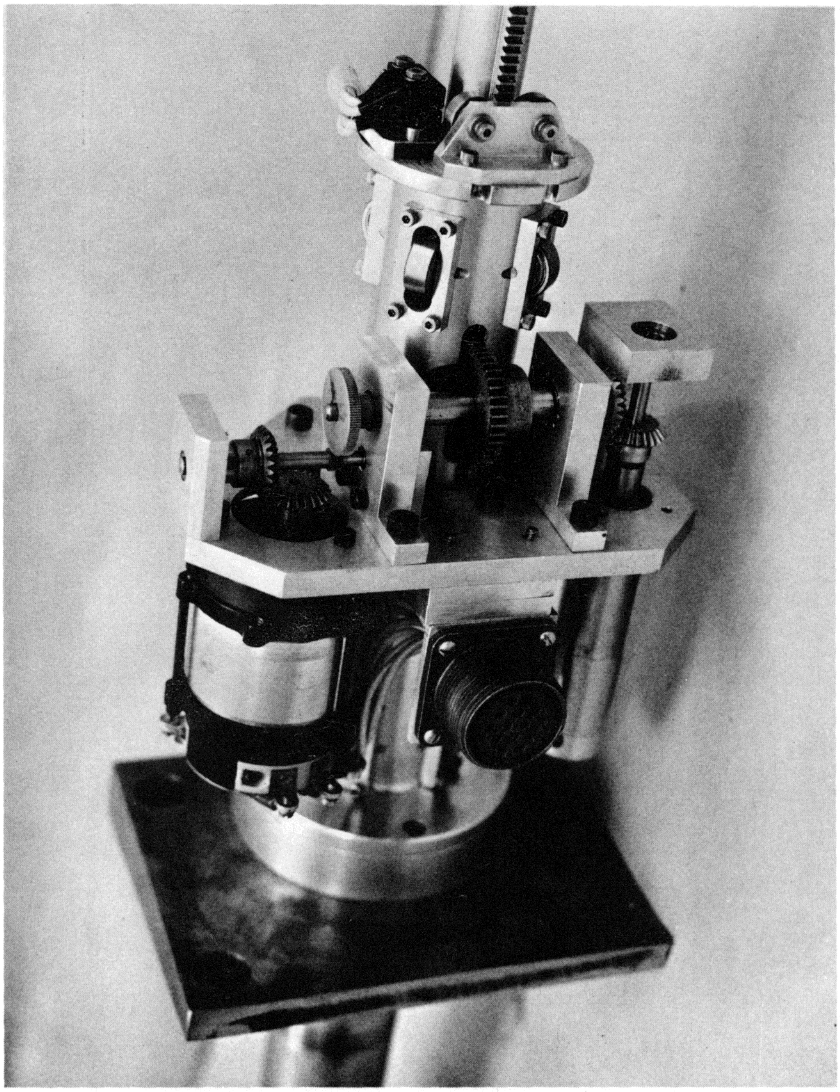


Fig. 27. Fine Control Rod Mechanism

G. Control and Instrumentation

The reactor is controlled at the control console through the manipulation of the control rods. Reactor response is obtained from both nuclear and non-nuclear instrumentation. Protection for both the plant and personnel is continuously maintained by systems of radiation monitoring and safety interlocks which provide warnings and/or prevent reactor startup or initiate reactor shutdown in the event of various malfunctions. Block diagrams showing the JUGGERNAUT electrical system overall are shown in Figs. 28, 29, and 30.

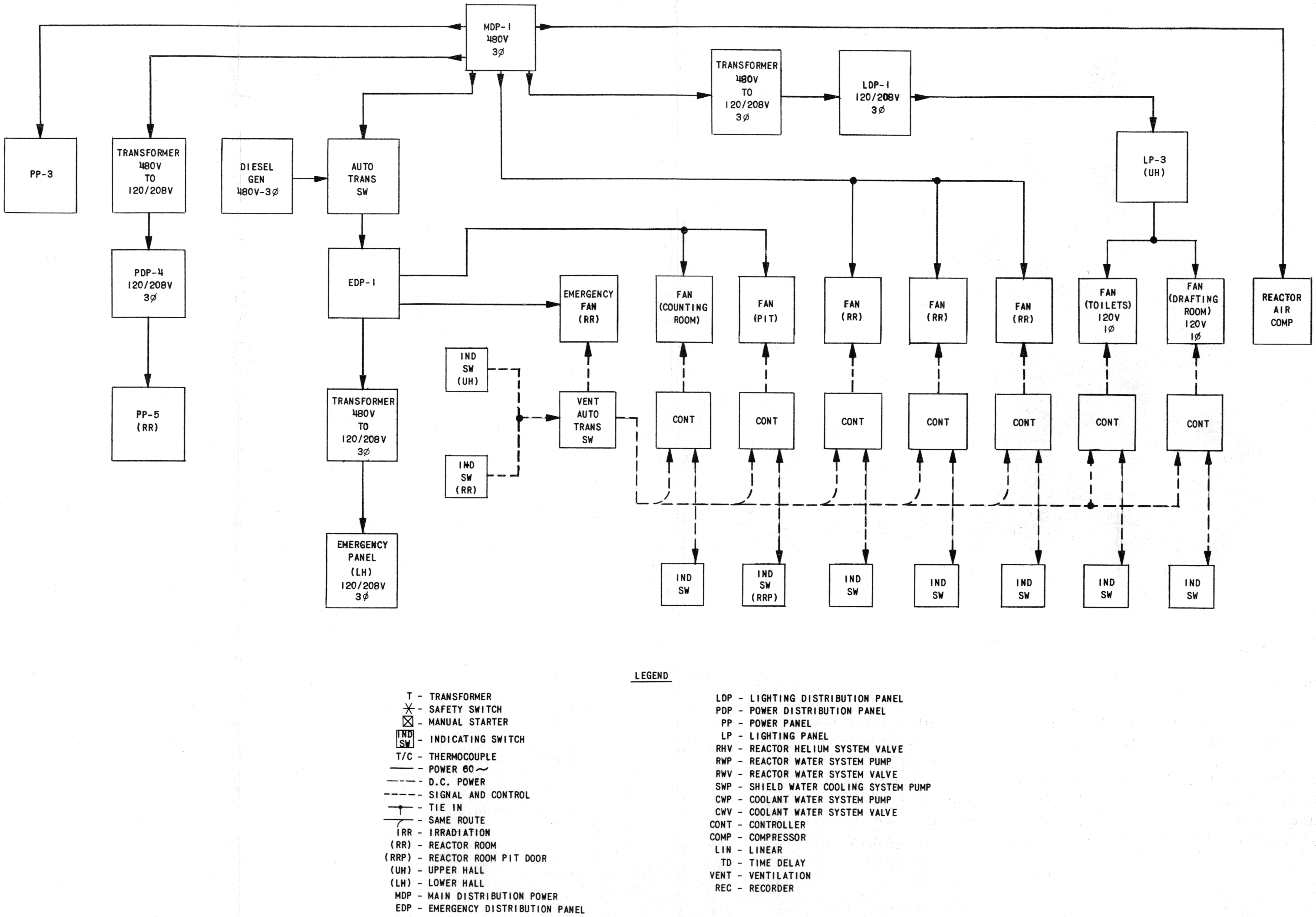
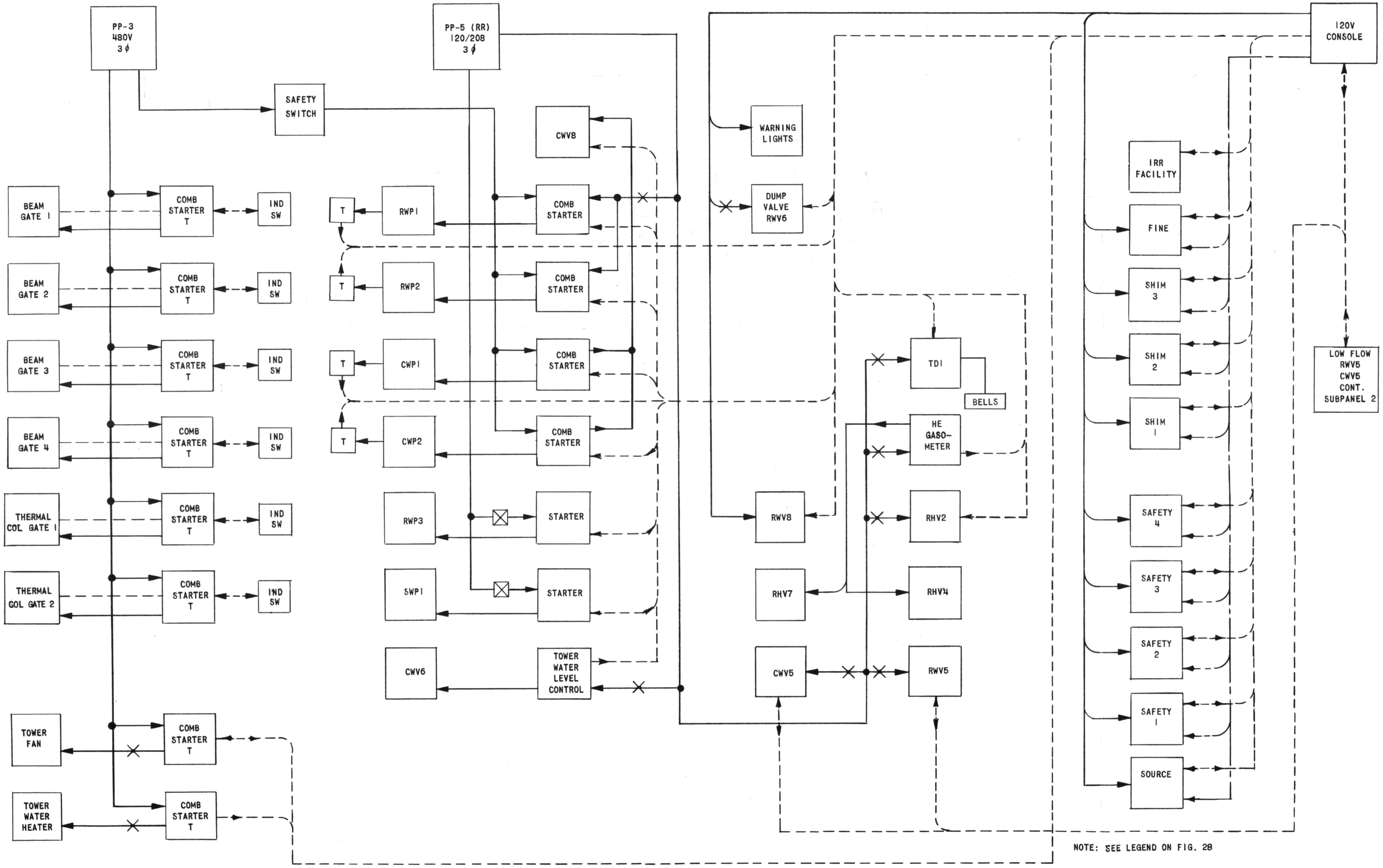
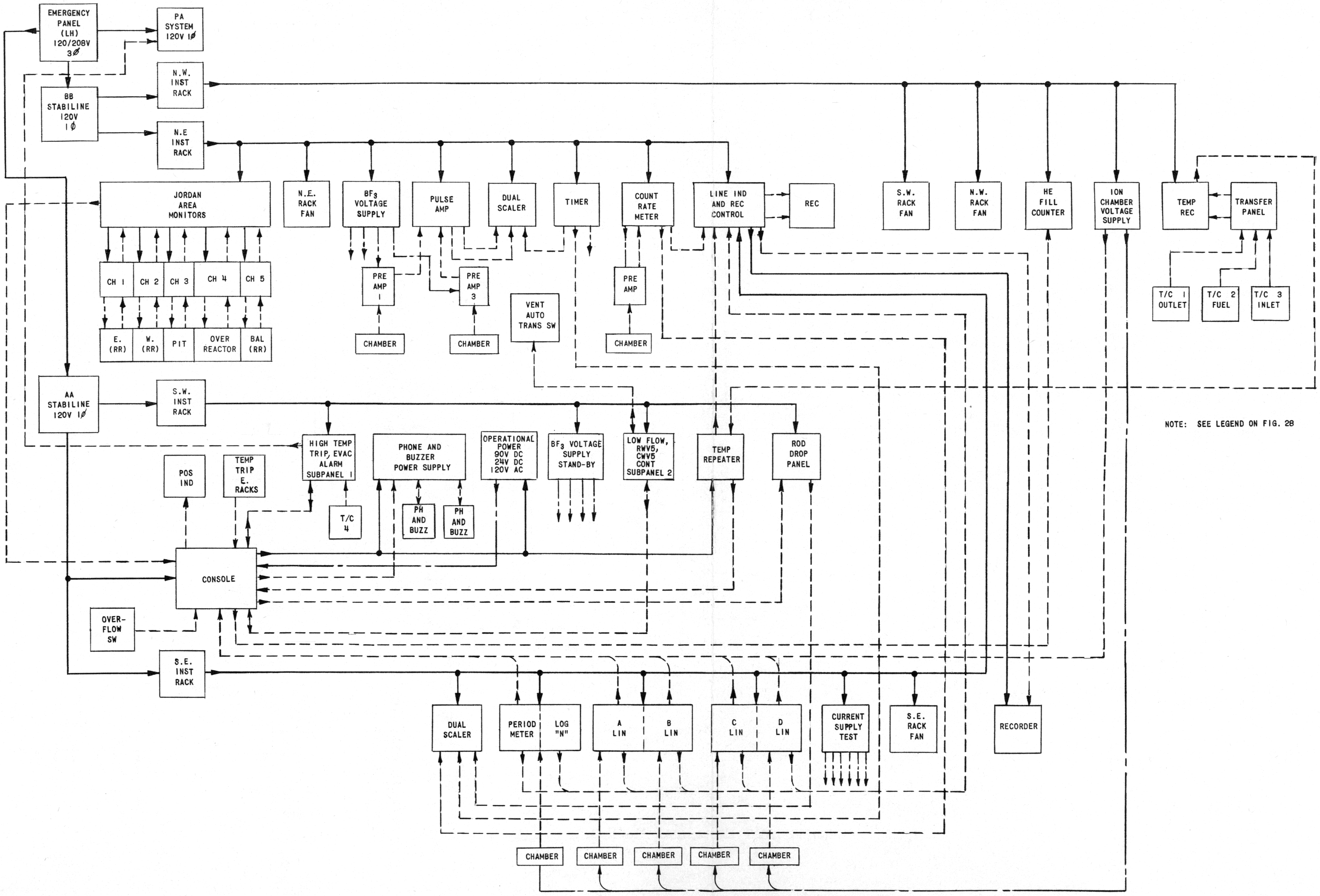


Fig. 28. JUGGERNAUT Electrical Block Diagram (Part I of III)



NOTE: SEE LEGEND ON FIG. 28

Fig. 29. JUGGERNAUT Electrical Block Diagram (Part II of III)



NOTE: SEE LEGEND ON FIG. 28

Fig. 30. JUGGERNAUT Electrical Block Diagram (Part III of III)

1. Control Console and Instrument Cubicle

All control switches, indicators, and recorders required for reactor startup, as well as for steady-state and emergency operations, are displayed on the control console and the four instrument racks to either side of the console which comprise the instrument cubicle. The control console and the instrument cubicle are located on the balcony of the reactor room (see Fig. 31).

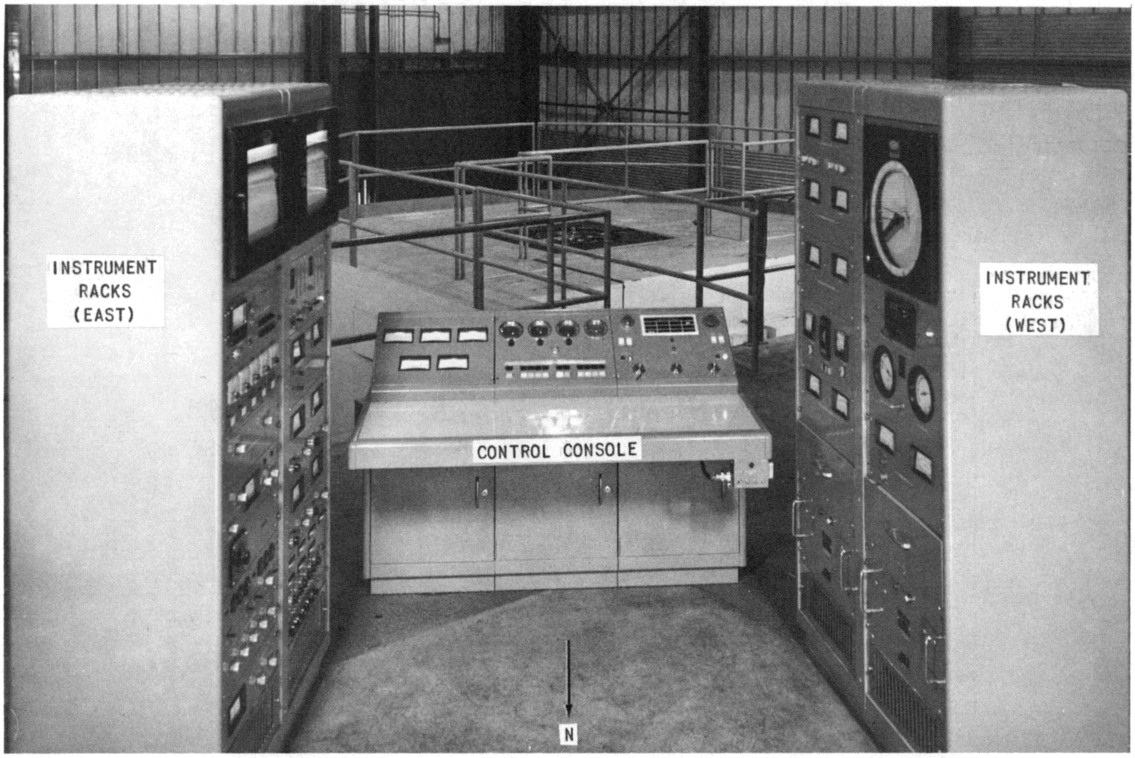
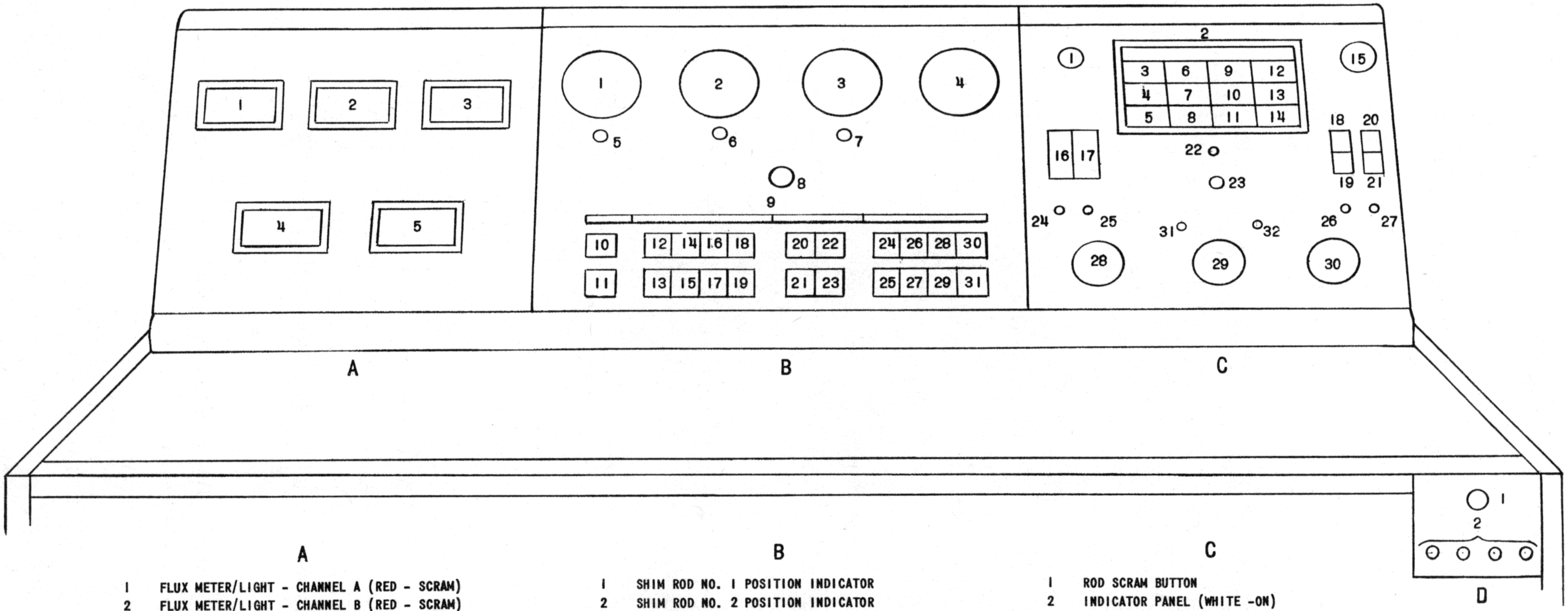


Fig. 31. Control Console and Instrument Cubicle

Primary instrumentation and controls for the reactor, and the annunciator alarm, are located at the control console (see Fig. 32). The safety trips, period trip, radiation-monitoring system, recorders, additional indicator lights, and the control switches for auxiliary equipment are located in the instrument cubicle (see Figs. 33 and 34, and Tables IV and V).

The control console is designed as a separate unit with 24 feed-in plugs. The various cables feeding information to the control console are:

(a) Cables from the top of the reactor, which include those for the temperature sensors; limit switches for safe positioning of the top removable shield assembly, the center, 15-cm (6-in.) plug, and the fuel plug; rod drive mechanisms; and, most importantly, the neutron-sensing instruments.



A

1 FLUX METER/LIGHT - CHANNEL A (RED - SCRAM)
2 FLUX METER/LIGHT - CHANNEL B (RED - SCRAM)
3 FLUX METER/LIGHT - CHANNEL C (RED - SCRAM)
4 RW TEMPERATURE METER/LIGHT (GREEN - Δt; YELLOW -t)
5 PERIOD METER/LIGHT (RED - SCRAM)

D

1 ANNUNCIATOR ALARM AND TELEPHONE LIGHT/BUZZER
  (a) ALARM - STEADY GREEN LIGHT AND STEADY BUZZ
  (b) PHONE - FLASHING GREEN LIGHT AND INTERMITTENT BUZZ
2 TELEPHONE STATION BUTTONS

B

1 SHIM ROD NO. 1 POSITION INDICATOR
2 SHIM ROD NO. 2 POSITION INDICATOR
3 SHIM ROD NO. 3 POSITION INDICATOR
4 FINE CONTROL ROD POSITION INDICATOR
5 SHIM ROD NO. 1 DROP (SCRAM) BUTTON
6 SHIM ROD NO. 2 DROP (SCRAM) BUTTON
7 SHIM ROD NO. 3 DROP (SCRAM) BUTTON
8 ROD SPEED CONTROL SWITCH
9 READY INDICATOR BAR/LIGHT (WHITE - ON)
10 SOURCE SWITCH/LIGHT - CSW1 (GREEN - IN)
11 SOURCE SWITCH/LIGHT - CSW2 (YELLOW - OUT)
12 SAFETY ROD NO. 1 SWITCH/LIGHT - CSW4 (GREEN - OUT)
13 SAFETY ROD NO. 1 SWITCH/LIGHT - CSW3 (YELLOW - IN)
14 SAFETY ROD NO. 2 SWITCH/LIGHT - CSW6 (GREEN - OUT)
15 SAFETY ROD NO. 2 SWITCH/LIGHT - CSW5 (YELLOW - IN)
16 SAFETY ROD NO. 3 SWITCH/LIGHT - CSW8 (GREEN - OUT)
17 SAFETY ROD NO. 3 SWITCH/LIGHT - CSW7 (YELLOW - IN)
18 SAFETY ROD NO. 4 SWITCH/LIGHT - CSW10 (GREEN - OUT)
19 SAFETY ROD NO. 4 SWITCH/LIGHT - CSW9 (YELLOW - IN)
20 DUMP VALVE SWITCH/LIGHT - CSW12 (GREEN - CLOSED)
21 DUMP VALVE LIGHT ONLY (YELLOW - OPEN)
22 RW LEVEL LIGHT ONLY (GREEN - UP)
23 RW LEVEL LIGHT ONLY (YELLOW - DOWN)
24 SHIM ROD NO. 1 SWITCH/LIGHT - CSW16 (GREEN - OUT)
25 SHIM ROD NO. 1 SWITCH/LIGHT - CSW15 (YELLOW - IN)
26 SHIM ROD NO. 2 SWITCH/LIGHT - CSW18 (GREEN - OUT)
27 SHIM ROD NO. 2 SWITCH/LIGHT - CSW17 (YELLOW - IN)
28 SHIM ROD NO. 3 SWITCH/LIGHT - CSW20 (GREEN - OUT)
29 SHIM ROD NO. 3 SWITCH/LIGHT - CSW19 (YELLOW - IN)
30 FINE CONTROL ROD SWITCH/LIGHT - CSW22 (GREEN - OUT)
31 FINE CONTROL ROD SWITCH/LIGHT - CSW21 (YELLOW - IN)

C

1 ROD SCRAM BUTTON
2 INDICATOR PANEL (WHITE -ON)
3 DETECTOR HIGH VOLTAGE INDICATOR (RED - SCRAM)
4 CONTROL RELAYS POWER INDICATOR (RED - SCRAM)
5 LOW FLOW INDICATOR (RED - SCRAM)
6 GAMMA MONITOR INDICATOR (WHITE - ALARM)
7 HELIUM FILL INDICATOR (WHITE - ON)
8 HELIUM BLOW-OFF INDICATOR (WHITE - ON)
9 INSTRUMENT RACK TEMPERATURE INDICATOR (WHITE - ALARM)
10 DISASTER MONITOR INDICATOR (RED - SCRAM)
11 PIT DOOR INDICATOR (WHITE - ALARM)
12 TOWER WATER INDICATOR (WHITE - ON)
13 IRRADIATION FACILITY (RED -SCRAM)
14 TOWER HEATER INDICATOR (WHITE - ON)
15 SCRAM BUTTON (WATER DUMP AND ROD SCRAM)
16 SWP1 SWITCH/LIGHT (WHITE - ON)
17 RWP3 SWITCH/LIGHT (WHITE - ON)
18 RWP1 SWITCH/LIGHT (WHITE - ON)
19 RWP2 SWITCH/LIGHT (WHITE - ON)
20 CWP1 SWITCH/LIGHT (WHITE - ON)
21 CWP2 SWITCH/LIGHT (WHITE - ON)
22 HELIUM PURGE LIGHT (GREEN - ON)
23 HELIUM PURGE SWITCH
24 RW TEMPERATURE LIGHT - HIGH (RED - SCRAM)
25 RW TEMPERATURE LIGHT - LOW (GREEN - ON)
26 RWV8 SWITCH/LIGHT - ENERGIZING (WHITE - ON)
27 RWV8 SWITCH/LIGHT - DEENERGIZING (WHITE - ON)
28 CONTROL POWER KEY SWITCH - KSW1
29 DUMP VALVE POWER KEY SWITCH - KSW2
30 MAIN POWER KEY SWITCH - KSW3
31 ANNUNCIATOR ALARM - STOP
32 ANNUNCIATOR ALARM - RESET

Fig. 32. Control Console

These instruments include the startup channel counters and the power-level ionization chambers. Because of extremely weak signals, the preamps for the startup channels are located at the reactor top, about 15 cm (6 in.) from the chambers. The signal cables are shielded to reduce electrostatic pickup.

(b) Cables from the pump room, referred to as pit cables, which include those for the pump controls; solenoid controls; and limit switches.

(c) Cables from the reactor area which include those for gamma area monitoring and reactor operational light control.

2. Nuclear Instrumentation

Nuclear instruments use both transistorized circuits and electromechanical relays to provide monitoring and safety control for the reactor. The transistorized circuits were compensated to operate at temperatures up to 50°C (122°F). These circuits have a fail-safe feature which indicates a high temperature, above 50°C (122°F), so that corrective action can be taken without affecting reactor operation. Other safety features included in the nuclear control system are: the use of monitoring and test circuits; and the use of duplicate channels. Duplicate channels, measuring the same variable, initiate individual signals that may be used to check one channel against the other in prestartup and intermediate-power ranges.

The nuclear instrumentation system consists of eight channels of information (see Fig. 35). Three channels are used for startup since a startup accident is the most serious probable type of accident. The remaining five channels include the period channel and the high-flux channels. Reactor shutdown trip signals are derived from four of these five channels, as shown in Fig. 35. Each channel overlaps the previous one to the extent that information is displayed on the instrumentation panel at all times for any point within the operating neutron-flux range (see Fig. 36). Figure 36 is based on ionization current chambers having a sensitivity of 10^{-14} amp/nv, and a neutron density in the instrument tube of 5×10^9 n/(cm^2)(sec) at 250 kw.

As a precaution against complete loss of nuclear instrumentation in the event of failure of a voltage regulator, power to the instrumentation cubicles, which hold the various amplifiers and power supplies, is distributed between two voltage regulators (see Fig. 30).

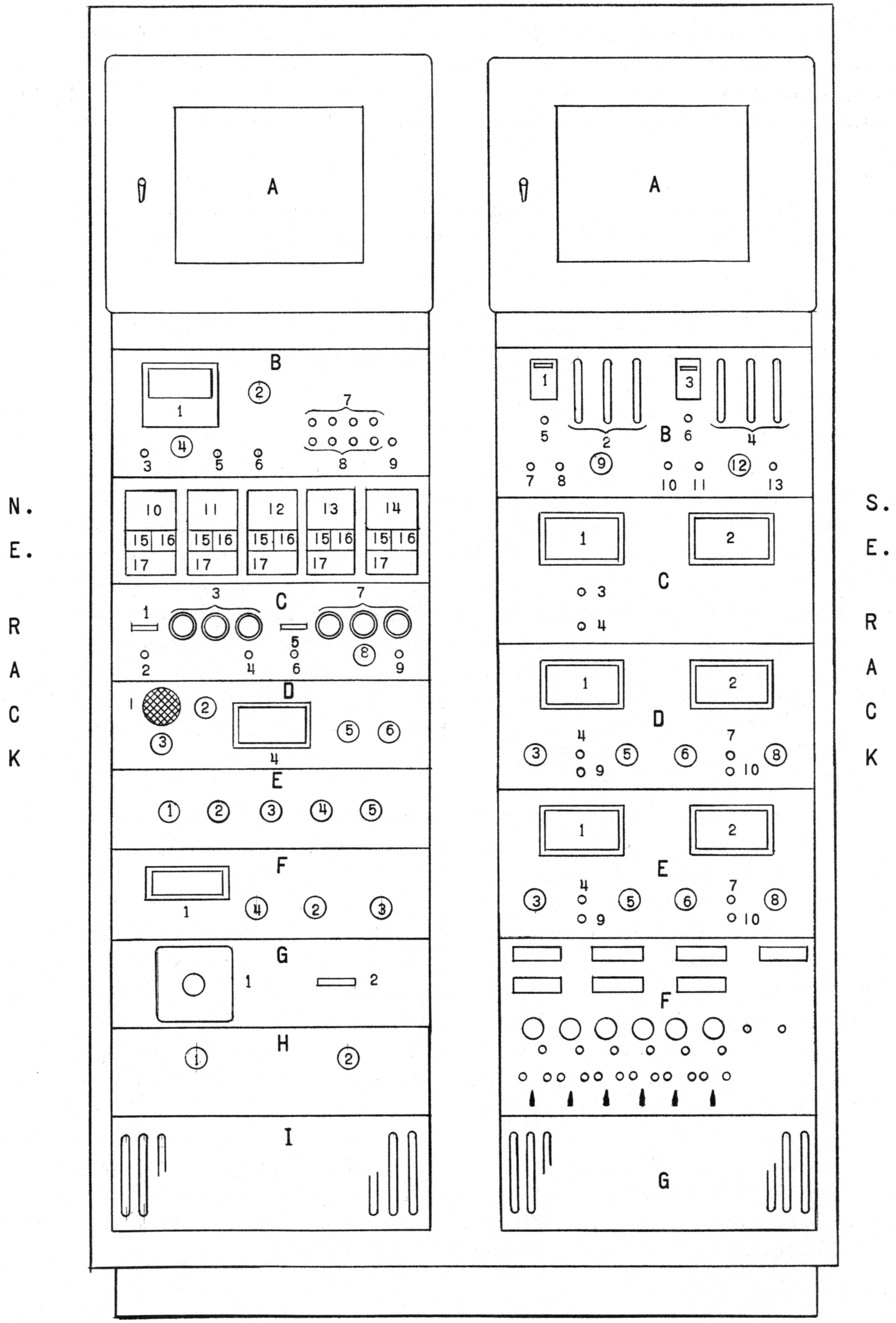


Fig. 33. Instrument Racks (East) (See Table IV)

Table IV

INSTRUMENT RACKS (EAST)-PANEL DESCRIPTION

N. E. RACK	A - LINEAR FLUX LEVEL RECORDER		
	B - REMOTE AREA MONITORING SYSTEM		
		1	PANEL AND VOLTAGE CHECK METER
		2	TWO POSITION SELECTOR SWITCH (OPERATE - CHECK)
		3	PHONE OUTLET (TEST PURPOSE ONLY)
		4	SYSTEM ON LIGHT (ORANGE)
		5	PUSHBUTTON ALARM-RESET
		6	PUSHBUTTON MONITORING CLEAR
		7	FUSES
		8	SPARE FUSES
		9	POWER SWITCH (ON - OFF)
		10	GAMMA DOSE RATE INDICATOR, STATION I REACTOR ROOM WEST
		11	GAMMA DOSE RATE INDICATOR, STATION II PUMP ROOM
		12	GAMMA DOSE RATE INDICATOR, STATION III REACTOR ROOM EAST
		13	GAMMA DOSE RATE INDICATOR, STATION IV REACTOR ROOM OVERHEAD
		14	GAMMA DOSE RATE INDICATOR, STATION V REACTOR ROOM BALCONY
		15	PANEL METER LIGHT (GREEN - READING ON NO. 1)
		16	ALARM LIGHT (RED - TRIPPED OUT)
		17	PUSHBUTTON TRANSFER SWITCH (SIGNAL TRANSFER FROM INDIVIDUAL INDICATOR TO NO. 1)
	C - SCALER FOR STARTUP COUNTER NO. 2		
		1 & 5	FOUR DIGIT SODECO REGISTERS - COUNT LIGHTS (RED-ON; WHITE -OFF)
		2 & 6	RESET SWITCHES
		3 & 7	COUNTING UNITS - SET OF THREE GC10D TUBES (DECIMAL)
		4	THREE POSITION SWITCH (COMMON - OFF - COUNT)
		8	OVERFLOW SELECTOR SWITCH
		9	SELECTOR SWITCH (TIMER - OFF - COUNT)
	D - COUNT RATE METER FOR STARTUP COUNTER NO. 3		
		1	SPEAKER
		2	DETECTOR GAIN HIGH VOLTAGE SELECTOR SWITCH
		3	VOLUME CONTROL
		4	COUNT-RATE METER (COUNT/sec)
		5	MULTIPLIER SELECTOR SWITCH
		6	TIME CONSTANT SELECTOR SWITCH (NORMAL - FAST)
	E - PULSE AMPLIFIERS		
		1 TO 4	GAIN AND DISCRIMINATOR SWITCHES
		5	SELECTOR SWITCH FOR DIFFERENT MODES
	F - RECORDERS & VOLTAGE INDICATOR		
		1	METER FOR A-C LINE VOLTAGE
		2 & 3	INSTRUMENT CHANNEL SELECTOR SWITCHES
		4	VOLTAGE CHECK SWITCH (AA STABILINE - OFF - BB STABILINE)
	G - TIME		
		1	TIMER (1 sec - 1 hr)
		2	CLOCK (24 hr)
	H - BF_3 VOLTAGE SUPPLY		
		1	DETECTOR GAIN HIGH VOLTAGE SELECTOR SWITCH
		2	DETECTOR GAIN HIGH VOLTAGE SELECTOR SWITCH
	I - AIR BLOWER AND FILTER		
S. E. RACK	A - LOG FLUX LEVEL RECORDER		
	B - DUAL SCALER FOR STARTUP COUNTERS AND ROD DROP TIME TESTS		
		1 & 3	FOUR DIGIT SODECO REGISTERS
		2 & 4	COUNTING UNITS - 705A COUNTERS (DECIMAL)
		5 & 6	COUNT LIGHTS (YELLOW - MANUAL COUNT)
		7 & 10	RESET PUSHBUTTON
		8	THREE POSITION SWITCH (COMMON - OFF - COUNT)
		9 & 12	SCALE FACTOR SELECTOR SWITCHES
		11	THREE POSITION SWITCH (TIMER - OFF - COUNT)
		13	A-C POWER ON LIGHT (YELLOW)
	C - REACTOR PERIOD METER		
		1	PERIOD METER (sec)
		2	CURRENT METER (POWERS OF TEN)
		3	RESET PUSHBUTTON
		4	RECOVERY PUSHBUTTON
	D - LINEAR TRIPS A & B		
		1 & 2	CURRENT INDICATORS (FULL SCALE = 1 MA)
		3 & 6	TRIP LEVEL SET DIALS
		4 & 7	RESET PUSHBUTTONS
		5 & 8	MULTIPLIER SELECTOR SWITCHES
		9 & 10	TRIP BYPASS BUTTONS FOR CURRENT RANGES OF 10^{-12} & 10^{-11} amp
	E - LINEAR TRIPS C & D		
		1 & 2	CURRENT INDICATORS (FULL SCALE = 1 MA)
		3 & 6	TRIP LEVEL SET DIALS
		4 & 7	RESET PUSHBUTTONS
		5 & 8	MULTIPLIER SELECTOR SWITCHES
		9 & 10	TRIP BYPASS BUTTONS FOR CURRENT RANGES OF 10^{-12} & 10^{-11} amp
	F - SEVEN CURRENT SOURCES (TEST EQUIPMENT)		
	G - AIR BLOWER AND FILTER		

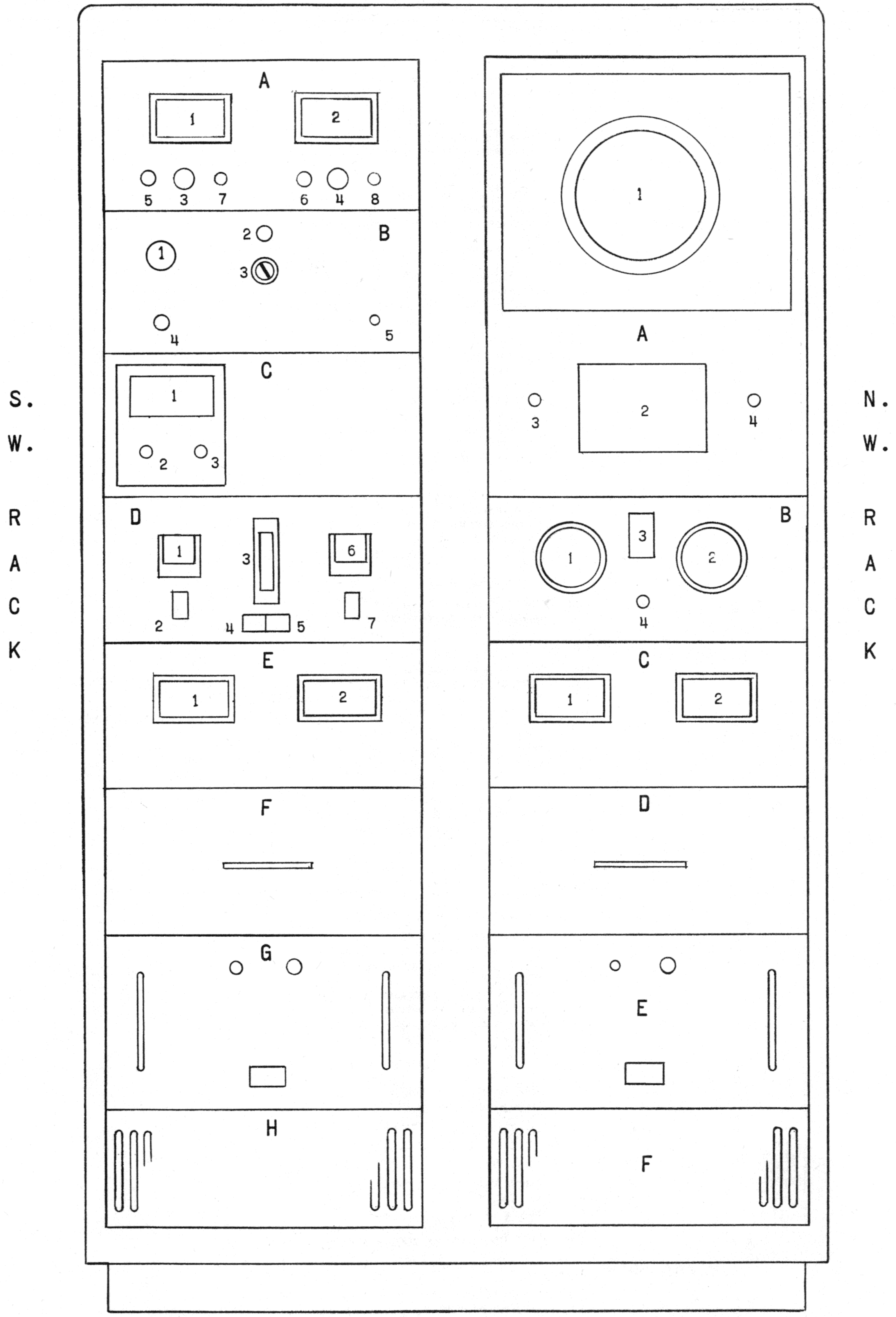


Fig. 34. Instrument Racks (West) (See Table V)

Table V

INSTRUMENT RACKS (WEST)-PANEL DESCRIPTION

S.W. RACK

A - DUAL BF_3 VOLTAGE SUPPLY

1 & 2	VOLT METERS (0 - 2 KILOVOLTS)
3 & 4	STEP SELECTOR SWITCHES (100 VOLTS/STEP)
5 & 6	COMMAND SWITCHES (SAFE - ON)
7 & 8	FINE ADJUSTMENT CONTROLS

B - ROD DROP TEST

1	ROD DROP SELECTOR SWITCH
2	ROD DROP TEST WARNING LIGHT (RED - REACTOR UNDER MANUAL SUPERVISION ONLY. NO INTERLOCK SEQUENCE REQUIRED.)
3	ROD DROP TEST CONTROL KEY SWITCH - KSW
4	ROD DROP PUSHBUTTON
5	POWER ON LIGHT (YELLOW)

C - HIGH TEMPERATURE TRIP

1	TEMPERATURE TRIP SETTING
2	TEMPERATURE LIGHT (GREEN - LOW)
3	TEMPERATURE LIGHT (RED - HIGH)

D - THROTTLE VALVE

1	REACTOR THROTTLE VALVE POSITION INDICATOR
2	REACTOR THROTTLE VALVE POSITION SELECTOR (OPEN - OFF - CLOSE)
3	FLOWMETER (FLOW IN GPM)
4	TOWER FAN PUSHBUTTON/LIGHT (GREEN - ON)
5	TOWER FAN PUSHBUTTON/LIGHT (YELLOW - OFF)
6	TOWER THROTTLE VALVE POSITION INDICATOR
7	TOWER THROTTLE VALVE POSITION SELECTOR (OPEN - OFF - CLOSE)

E - OPERATIONAL POWER

1	ROD DROP VOLTAGE METER/LIGHT - SCALE COLORS (RED - OPERATING VOLTAGE ABNORMAL; GREEN - SAFE)
2	CLUTCH VOLTAGE METER/LIGHT - SCALE COLORS (RED - OPERATING VOLTAGE ABNORMAL; GREEN - SAFE)

F - RECORDS DRAWER

G - AA STABILINE (S.W. AND S.E. RACKS)

H - AIR BLOWER AND FILTER

N.W. RACK

A - REACTOR WATER TEMPERATURE

1	MULTI-RANGE TEMPERATURE RECORDER (SELECTOR SWITCH [t OR Δt] LOCATED BEHIND PANEL DOOR)
2	THERMOCOUPLE SELECTOR PANEL
3	RECORDING LIGHT (YELLOW - t)
4	RECORDING LIGHT (GREEN - Δt)

B - REACTOR ATMOSPHERIC CONDITIONS

1	HELIUM PRESSURE INDICATOR
2	VESSEL SEAL PRESSURE INDICATOR
3	HELIUM FILL CYCLE INDICATOR
4	VESSEL SEAL VALVE STEM

C - ION CHAMBER VOLTAGE SUPPLY

1	COMPENSATION VOLTAGE INDICATOR
2	COLLECTION VOLTAGE INDICATOR

D - RECORDS DRAWER

E - BB STABILINE (N.W. AND N.E. RACKS)

F - AIR BLOWER AND FILTER

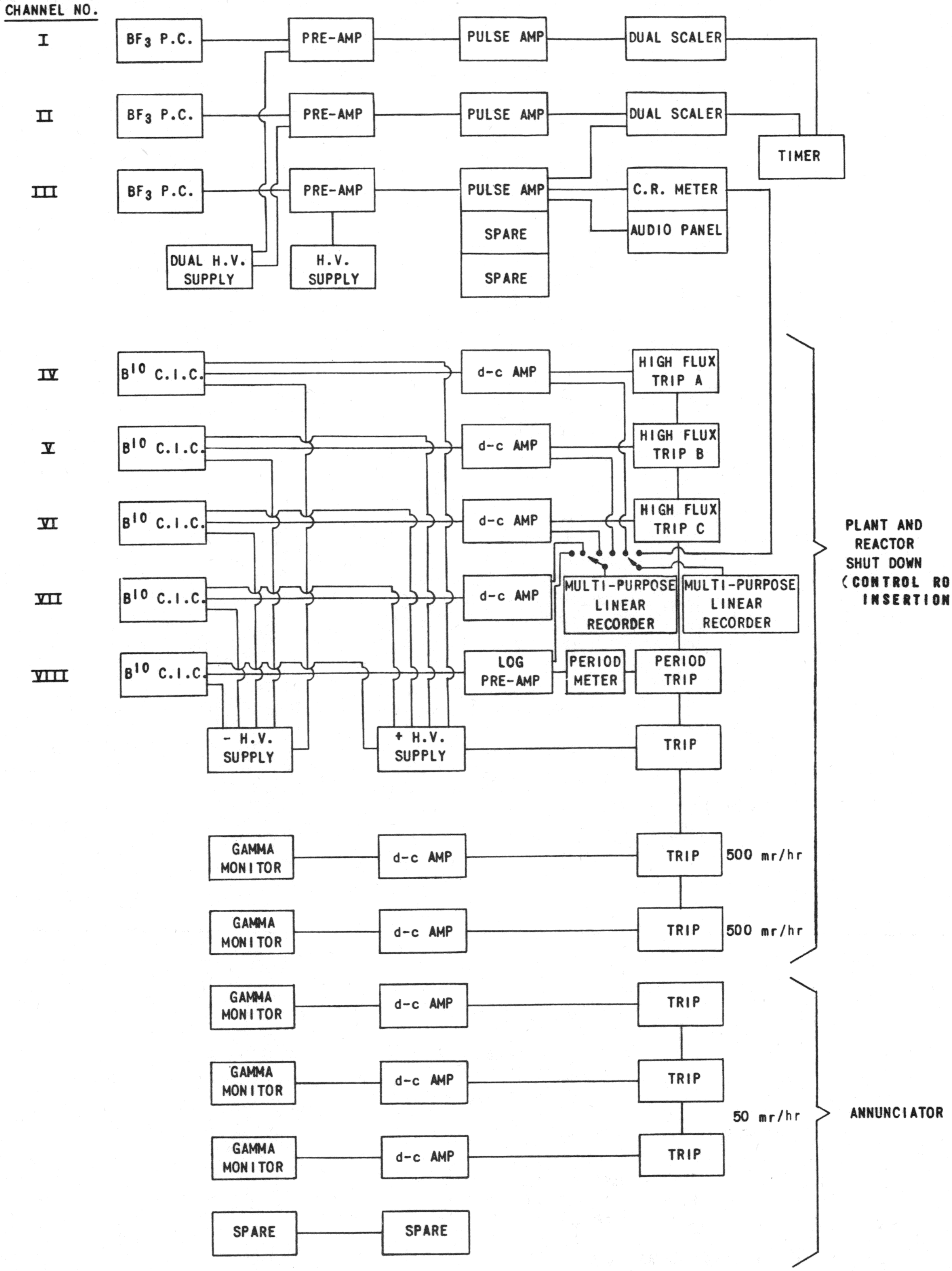
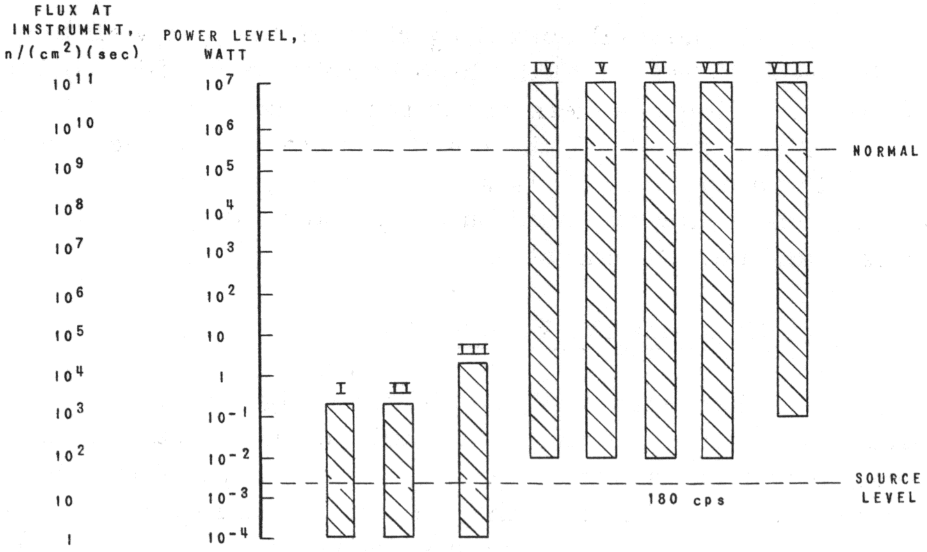


Fig. 35. Nuclear Instrumentation and Radiation Monitoring Circuitry



CHANNEL NO.	FUNCTION
I	COUNTER NO. 1 SCALER (12,000 cps)
II	COUNTER NO. 2 SCALER (12,000 cps)
III	COUNT-RATE METER (10^5 cps)
IV	SAFETY TRIP A
V	SAFETY TRIP B
VI	SAFETY TRIP C
VII	LINEAR LEVEL
VIII	LOG PERIOD

Fig. 36. Ranges of Nuclear Instrumentation

a. Channels I, II, and III - Startup

These channels are used primarily for startup and are invariably referred to as the pulse or the counting-rate channels (see Fig. 35). Each employs a BF_3 proportional counter (PC) (Westinghouse Electric Company, WL-6307) as a sensing element which transmits approximately four pulses per second per unit thermal-neutron flux. The pulse preamplifiers are located on the reactor top removable shield assembly to amplify the signals to be transmitted to the control console. At the console, the pulse is received by the pulse amplifier-discriminator circuit. The discriminator rejects pulses of small magnitudes, such as those caused by gamma flux or other spurious noises, and passes those pulses of large magnitude caused by neutron flux. These amplified pulses are fed to the dual scaler in Channel I, dual scaler-timer combination in Channel II, and to a log-count rate (CR) meter in Channel III. In the log-count-rate meter they are integrated, and their average counting rate is displayed on a meter on the N.E. instrument rack. The meter is calibrated for five decades (10-10^5 cps). The average counting rate can also be recorded on a recorder. The signal (amplified voltage pulses) is also fed to the audio panel (see Fig. 33) on the N.E. instrument rack for audible indication of up to 5×10^3 pulses.

The normal operating reactor level is well above the range of these channels. Therefore, the high voltage to the BF_3 counters is turned off before the counting channels reach their maximum counting rate. If the high voltage is not turned off, the counting rate will exceed the resolution capability of the amplifier. This will cause amplifier blocking due to pulse pile-up. The pulse pile-up could build up and collapse, to produce an erratic counting rate and period indication.

b. Channels IV, V, and VI

Channels IV, V, and VI (see Fig. 35) are used for power-level safety during intermediate- and full-power operation. Each uses a B^{10} neutron-sensitive, Argonne-type, gamma-compensated, boron-lined ionization chamber (CIC). The chamber output is fed to a high-gain dc amplifier, which, in turn, provides a suitable input signal to the 0-10-mv strip chart recorder (linear) and to a high-flux trip circuit. The high-level channels have a range of nine decades, including a one-and-one-half-decade overlap with the startup channels. The trip circuit is preset to effect reactor shutdown if the operating power level exceeds 120% of full power (250 kw). Calibration signals can be applied to supply currents above and below scram levels, thus checking the operating characteristics of the circuit. Each channel can be tested separately, including Channel VII.

c. Channel VII

Channel VII (see Fig. 35) differs from Channels IV, V, and VI in one respect: the output of the B^{10} gamma-compensated, boron-lined ionization chamber, after amplification, is fed only to the 0-10-mv strip chart recorder (linear). This channel does not feed into the high-flux trip.

d. Channel VIII

Channel VIII uses a B^{10} neutron-sensitive, Argonne-type, gamma-compensated ionization chamber with associated power supply, a log preamplifier, a reactor period (time rate of change of log n) meter, a log n recorder, and period trip circuitry (see Fig. 35). The compensated ionization chamber supplies current through a low-noise coaxial cable into the log preamplifier, which is proportional to the neutron flux at the chamber. In the preamplifier the current signal is fed into a circuit containing ten series-connected selected diodes to obtain an output voltage proportional to the logarithm of the input current (see Fig. 37).

This output voltage is the logarithm of the power level and is displayed on both an indicating meter (range: 10^{-3} to 10^{-11} amp) and on a log n recorder mounted on the S.E. instrument rack. The output is also fed to the period meter circuit which includes a cathode follower stage, the main amplifier, differentiation circuit, a period meter, and the period trip circuitry. The period trip circuit is preset to effect shutdown on a period less than 10 sec. A duplicate period meter unit is available to minimize reactor down-time in the event a malfunction should occur in the panel-mounted unit.

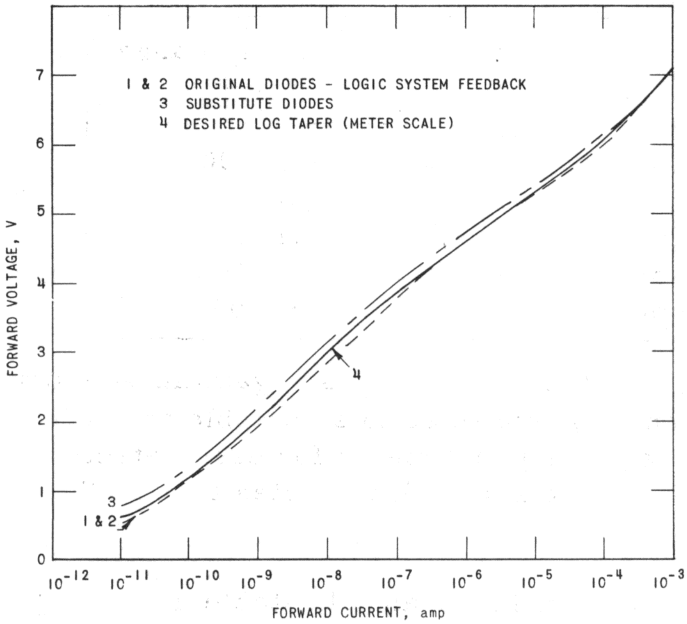


Fig. 37

Diode Characteristics of Type 1N137A Diodes Used in Period Meter Circuit

e. Chamber Location

The counting and current chambers are inserted into the vertical holes C1, C2, and C3 (see Fig. 22) from the top of the lower section of the removable shield assembly. Each hole is closed with a concrete shield plug for protection against radiation streaming. Each plug is pierced with a hole through its entire length to accommodate chamber leads. The chambers are free to move in the vertical direction. The final closure is provided by the upper section of the removable shield assembly surrounding the rotating shield.

The counting (BF_3 proportional counters) chambers (Channels I, II, and III) are lowered into the hole C3 alongside the compensated ionization chamber used for period measurement (Channel VIII). At full-power operation, the minimum flux is expected to be about 10^8 nv.

The current chambers (Channels IV, V, VI, and VII) are located in pairs in each of the vertical holes C1 and C2. The chamber flux at full-power operation is expected to be about 5×10^9 nv. Since the chambers can operate in a flux range of nearly 10^{10} nv for extended periods of time, no flux attenuation should be needed.

3. Radiation-monitoring System

Radiation monitoring is performed in five different locations by Jordan Electronics, Inc., Model "RAMS II" gamma monitors (see Table VI).

Table VI

LOCATION AND RANGE OF JORDAN GAMMA MONITORS

Station	Detector Location	Monitoring Range (mr)
1	Reactor Room West	0.1-100
2	Pump Room	0.1-100
3	Reactor Room East	0.1-100
4	Reactor Room Overhead	1-1000
5	Reactor Room Balcony	1-1000

The detector for each gamma channel is a gamma-sensitive ionization chamber (gamma monitor) connected to a portable amplifier unit located in the instrument cubicle. The panel meter for each detector, located on the N.E. instrument rack (see Fig. 33), indicates true radiation level at the detector location.

The monitoring system includes an adjustable level trip relay circuit with local reset control. The relay will initiate reactor shutdown, by rod insertion, for stations 4 and 5 if radiation levels exceed 500 mr. The audible and visual annunciator alarm and a visual indicator at the control console will be actuated. For the remaining three stations, the relay will operate the audible alarm at the control console, a visual alarm indicator on the N.E. instrument rack, and a visual indicator at the control console, if the radiation levels exceed 50 mr.

4. Non-nuclear Instrumentation

The non-nuclear data that are important for the safety and control of the reactor system are those connected with temperature, pressure, and flow effects. The pressure and flow data are transmitted to the console by pressure lines, and the temperature data are transmitted electrically.

a. Temperature

The reactor temperatures are measured by chromel-constantan thermocouples. These thermocouples are located at three different positions (see Fig. 17): (1) within the reactor water-inlet line

(T3); (2) within the reactor water-outlet line (T1); and (3) 25.4 cm (10 in.) above the core (T2).

The signals from these thermocouples can be recorded on a Thermo Electric Company circular chart recorder mounted on the N.W. instrument rack (see Fig. 34). At the recorder panel and behind the door which encloses the recorder, a selector switch is available by which either the temperature (as determined directly by the thermocouples) or the differential temperature (difference between two thermocouple signals) is recorded. A plug-in board is also available for the selection of either the specific thermocouple (T1, T2, or T3) or the specific temperature differential (T1T2, T2T3, or T1T3) to be recorded. Temperature indication (either temperature [direct] or temperature differential as determined at the recorder panel) is also provided in °C on a meter at the control console (see Fig. 32). The signal to the control console comes directly off the slide wire in the "Thermo Electronic" recorder.

A temperature trip circuit, located on the S.W. instrument rack (see Fig. 34), derives its signal from a fourth thermocouple (T4), an iron-constant thermocouple located in the same position as T2. This thermocouple will initiate reactor shutdown if the coolant outlet temperature at that location exceeds a set value of 50°C (122°F) higher than the temperature of the cooling tower water. Visual indicators at both the control console and the S.W. instrument rack will be actuated in addition to the audible alarm at the control console.

Small temperature switches (normally closed), located at the back and near the top of each of the east instrument racks, are preset to energize the audible and visual annunciator alarm and the applicable visual indicator at the control console if the instrument cubicle temperature exceeds 50°C (122°F). The purpose of these switches is to prevent a phenomenon called "thermal runaway" should transistor temperature increase too much. During a "thermal runaway" the current heats the junction, increasing the cut-off current, increasing collector current, raising junction dissipation, and increasing temperature again. Transistors tend to be very temperature drift sensitive, though reliable against outright failure.

b. Pressure

The pressure gauges that are of immediate interest to the reactor operator are those that indicate helium gasometer pressure and vessel seal pressure. These gauges are mounted on the N.W. instrument rack (see Fig. 33). The pressure ranges for these gauges are as follows:

(1) Helium gasometer pressure range: -1 to 3 in. of water.

(2) Vessel seal pressure range: -3.75 to 4.75 lb/in.^{2}.

System pressures for which only occasional checks are required are indicated locally in the pump room (see Fig. 17).

c. Flow

To monitor the flow rate of reactor water an orifice-plate-type flowmeter, in the outlet piping from the main reactor pumps, is pneumatically interlocked with a differential pressure transmitter which transmits differential equivalent signals to a direct-reading (0-150 gpm) drum indicator mounted on the S.W. instrument rack (see Fig. 33). If the flow rate decreases below 4 liters/sec (60 gpm), a low-flow safety trip will automatically initiate reactor shutdown (rod scram). The audible and visual annunciator alarm and a visual indicator at the control console (see Fig. 32) will be actuated.

Those flowmeters for which only occasional checks are required are the rotometer-type flowmeters which monitor the ion-exchange flow, the initial water-fill flow rate from the auxiliary pump, and the six shield-cooling system lines (see Fig. 17). These direct reading meters are located in the reactor pump room.

5. Control Systems

Each of the eight control rods is driven by an electrical-mechanical drive mechanism which permits slow-speed vertical motion (in both directions) for rod positioning and fast-speed downward motion for reactor scram. During normal operation only one shim-safety rod drive can be operated at a time, but all rods (except the fine control rod) can be dropped simultaneously to scram the reactor. All shim-safety rods can be dropped from any position in their operating stroke.

All shim-safety control rod circuits are interlocked to provide safe control sequences during calibration and operation. The control rods cannot be withdrawn until all safety conditions are satisfied. The basic startup and shutdown safety interlock system is shown in Fig. 38. When all startup conditions are satisfied as "safe," safety rods Nos. 1 and 3 may be pulled in sequence. Safety rods Nos. 2 and 4, however, cannot be pulled up until the core is filled up with water and overflow is achieved.

After the startup sequence has been completed, the operator is in full command of rod operation and can change reactor power at will within the limits of the shutdown interlocks.

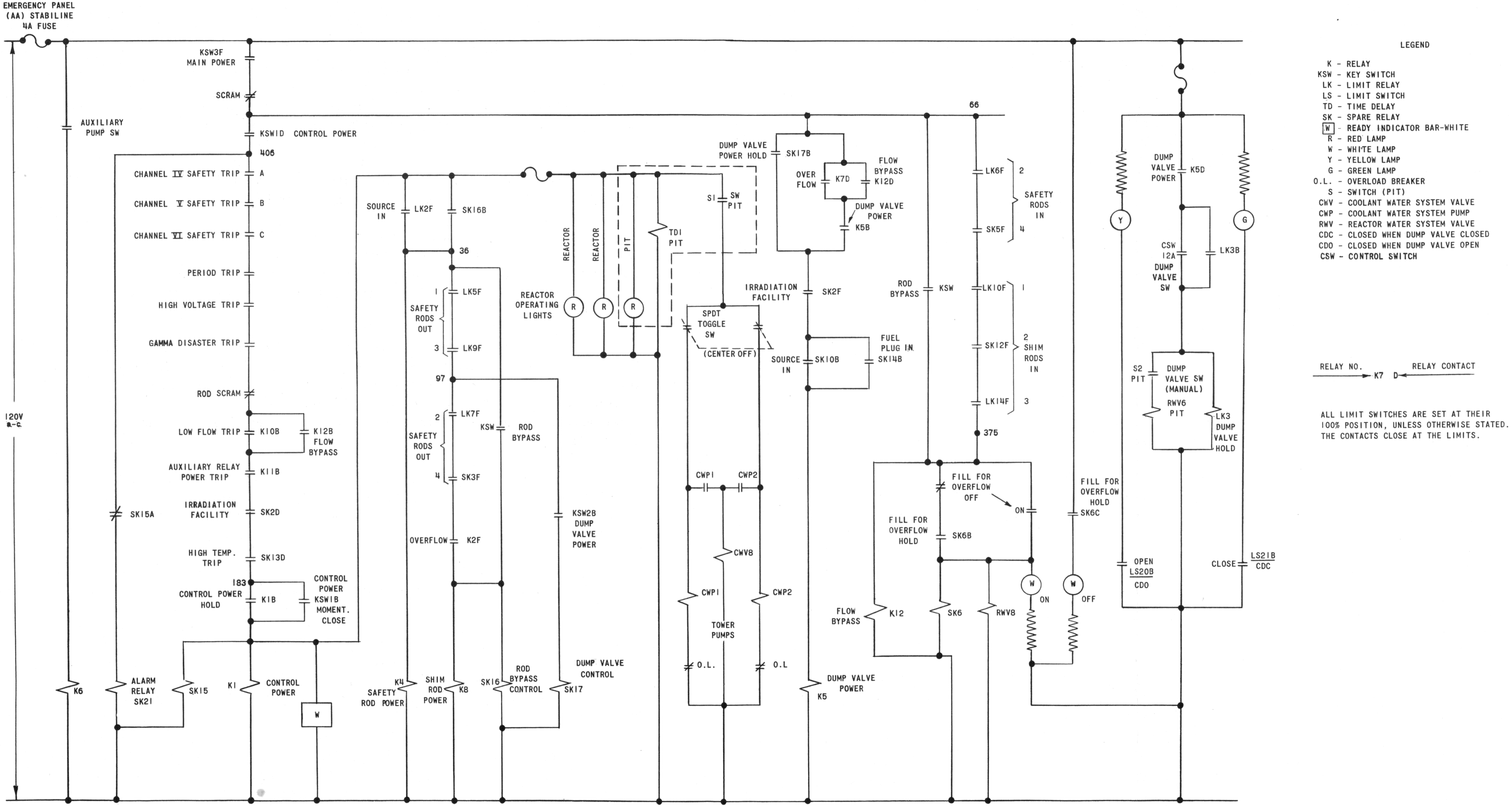


Fig. 38. JUGGERNAUT Startup and Shutdown Safety Interlock Diagram

a. Startup and Shutdown Interlocks

Specific startup conditions must be fulfilled in sequence before the safety rods can be withdrawn. In the event a condition is not fulfilled, startup will be prevented until the condition is cleared. Audible and visual indication of an interruption in the startup sequence is provided at the console. The startup conditions are as follows:

(1) All rods must be in their fully inserted positions. This condition is indicated by the rod position-indicator dials (see Fig. 32). Contacts between points 66 and 375 are closed (see Fig. 38).

(2) Main power key switch (KSW3, see Figs. 32 and 38) is turned on. This switch actuates operational warning alarms and lights on the reactor face. The audible alarm automatically shuts off, but the warning lights on the face of the reactor remain on during reactor operation.

(3) Shutdown conditions represented by the contacts between points 406 through 183 (see Fig. 38) must be cleared. A shutdown interlock can prevent startup and, after the safety rods are withdrawn, initiate a scram. A clear condition is indicated by the illumination of the first portion of the ready indicator bar light (see Figs. 32 and 38) when the control power is turned on.

(4) If the fuel plug is in position, the source can be raised into the reactor. This energizes the safety rod power relay (K4; see Fig. 38) to allow safety rods Nos. 1 and 2 to be raised. Points 36 through 97 are now closed.

(5) The dump-valve power key switch (KSW2; see Figs. 32 and 38) can now be operated to energize the dump-valve control relay (SK17; see Fig. 38) which in turn energizes the dump-valve power relay (K5; see Fig. 38). The dump valve can now be closed using the control switch (CSW12; see Figs. 32 and 38).

(6) The auxiliary pump and solenoid valve RWV8 can now be actuated from the console (see Figs. 32 and 38) and the reactor vessel filled with water until overflow is obtained. When overflow is achieved, the overflow switch actuates relays K7 and K2 (see Fig. 38), which results in the illumination of the RW level light UP. Safety rods Nos. 2 and 4 can now be raised to obtain control rod power. The operator is now in full command of the rod operation and can change reactor power level within specified limits.

The operator can also initiate a manual reactor shutdown by pressing either the rod scram or scram (water dump and rod scram) buttons on the console (see Fig. 32). Both buttons cause the rapid insertion of the shim-safety rods; however, the scram button also causes the removal of the core moderator (water dump). A partial rod scram can be initiated manually by pressing either the safety rod drop pushbutton, which drops all four safety rods simultaneously, in a bank, or by pressing the individual shim rod scram buttons which drop their respective rods individually (see Figs. 32 and 39).

After the startup sequence is completed, the shutdown interlocks automatically monitor plant operating parameters. In the event a plant parameter exceeds a preset interlock trip point, an automatic rod scram with or without a water dump will occur. In addition, audible and visual indication of the scram condition will be available at the console. The shutdown interlocks and the plant parameters which effect a scram are listed in Table VII. For additional protection, backup scram contacts are provided on the same bus as the clutch power circuitry (see Fig. 39).

Table VII

SHUTDOWN INTERLOCKS
(see Figs. 32 and 38)

Interlock*	Plant Parameter	Automatic Water Dump	Rod Scram
Channel IV Safety Trip A	Reactor power greater than 120% of normal operating power.	-	X
Channel V Safety Trip B	Reactor power greater than 120% of normal operating power.	-	X
Channel VI Safety Trip C	Reactor power greater than 120% of normal operating power.	-	X
Reactor Period Trip	Reactor period less than 10 sec.	-	X
High-voltage Trip	Loss of positive high-voltage supply to ion chamber.	-	X
Gamma Disaster Trip[†]	Radiation level equal to 500 mr/hr.	-	X
Low Coolant-flow Trip	Coolant flow less than 4 liters/sec.	-	X
Auxiliary Relay Power Trip	Relay power failure.	-	X
Irradiation Facility Trip	a. Nonpositioning of the center 15-cm (6-in.) plug in the rotating shield.	X	
	b. Nonpositioning of either section of the removable shield assembly.	X	
High-temperature Trip	Reactor coolant outlet temperature greater than preset level 50°C (122°F) above temperature of secondary coolant water.	-	X
Fuel Port (no panel identification)	Fuel port open when source is down.	X	X

*All shutdown interlocks actuate the annunciator alarm system, which includes both visual and audible indication. The visual and audible alarm system features a common buzzer, alarm stop, and reset buttons. Individual indicator lights are provided for each interlock; therefore, silencing an alarm caused by one input does not prevent a subsequent signal from actuating its respective indicator.

[†] Also actuates evacuation alarm (hooting sound) over public address system for building evacuation.

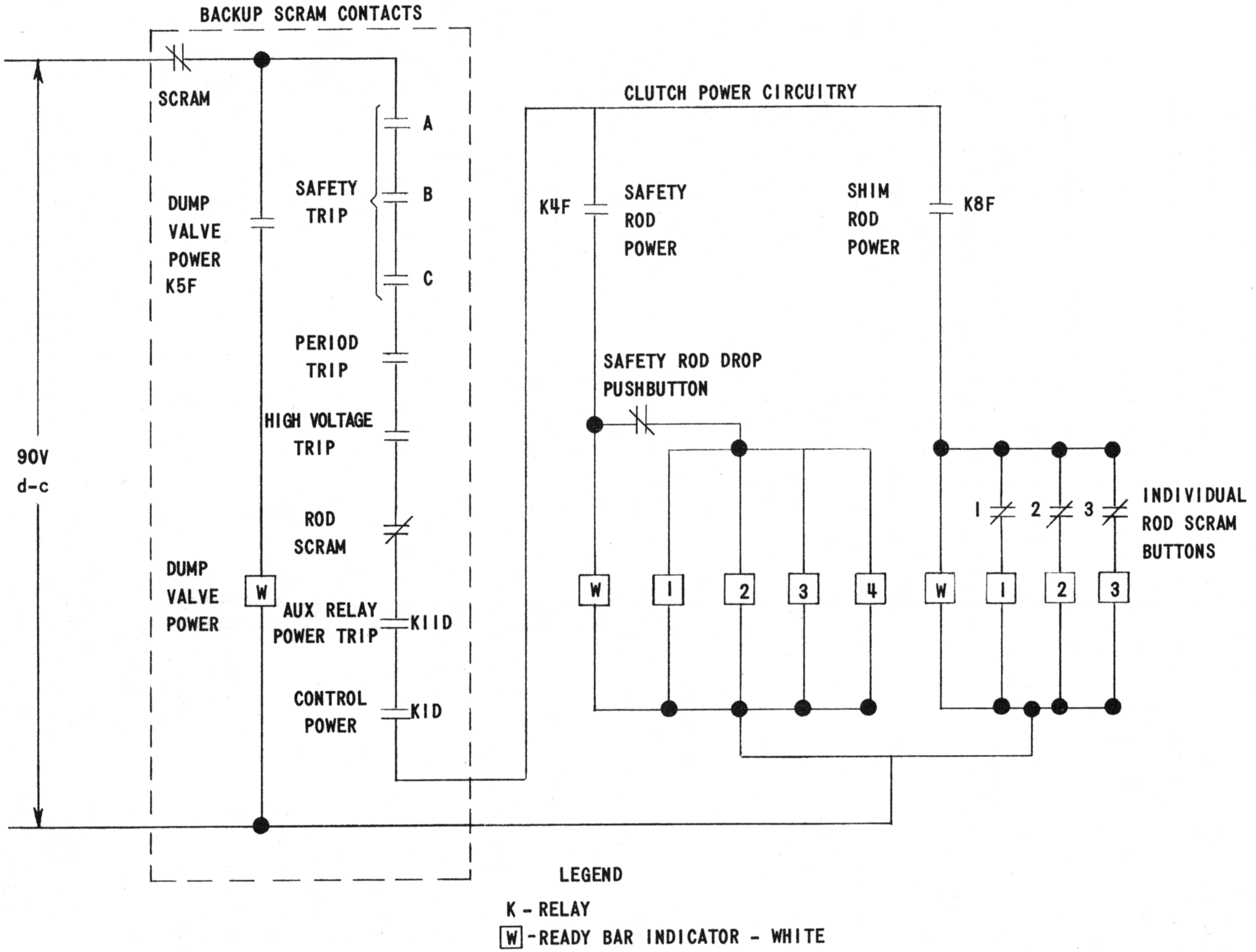


Fig. 39. Backup Scram Contacts and Clutch Power Circuitry

Visual and audible warning indications only are provided for the following plant conditions:

(1) instrument rack temperature above 50°C (122°F);

(2) reactor pump room (pit) door open; and

(3) gamma-monitor indication above 50 mr/hr.

b. Source, Safety Rod, and Shim Rod IN and OUT Control Circuits

Figure 40 illustrates the three control circuits. The source drive circuit is interlocked with the fuel plug so that the source cannot be lowered while the reactor is being loaded with fuel (fuel plug out), nor can the source be raised unless the fuel plug is in position.

The rod drive circuits are so designed as to allow only one rod to be raised at a time [maximum speed 0.3 cm/sec (0.118 in./sec)]. The rods can be lowered into or raised from the reactor by operating the IN or OUT control switches at the console. However, all the safety rods are interlocked with the safety rod power relay K4, which must be energized before the rods can be driven in or out. Similarly, the shim rod power relay K8 must be energized before the shim rods can be withdrawn or inserted. The fine control rod, however, is not interlocked and can be driven independently of the shim and safety rods.

For example (see Fig. 40), to lower safety rod No. 1, control switch CSW3 is operated. This closes the B and D contacts of the switch to provide a continuous path from points 17 to 278 and from 280 to 363. Since the rod is being driven down, the A contact of LK4 is closed to the motor armature. The second side of the armature is connected to the negative side of the dc supply through the D contact of CSW3. To raise safety rod No. 1 the control switch CSW4 is operated. This reverses the polarity of the armature.

c. Source and Rod IN and OUT Auxiliary Relays

Figure 41 illustrates the source and rod IN and OUT auxiliary relay circuits. These relays are independent of the reactor control power key switch KSW1. The limit switches close only if the rods are all the way IN or all the way OUT. Relay contacts light up the limit lights on the console.

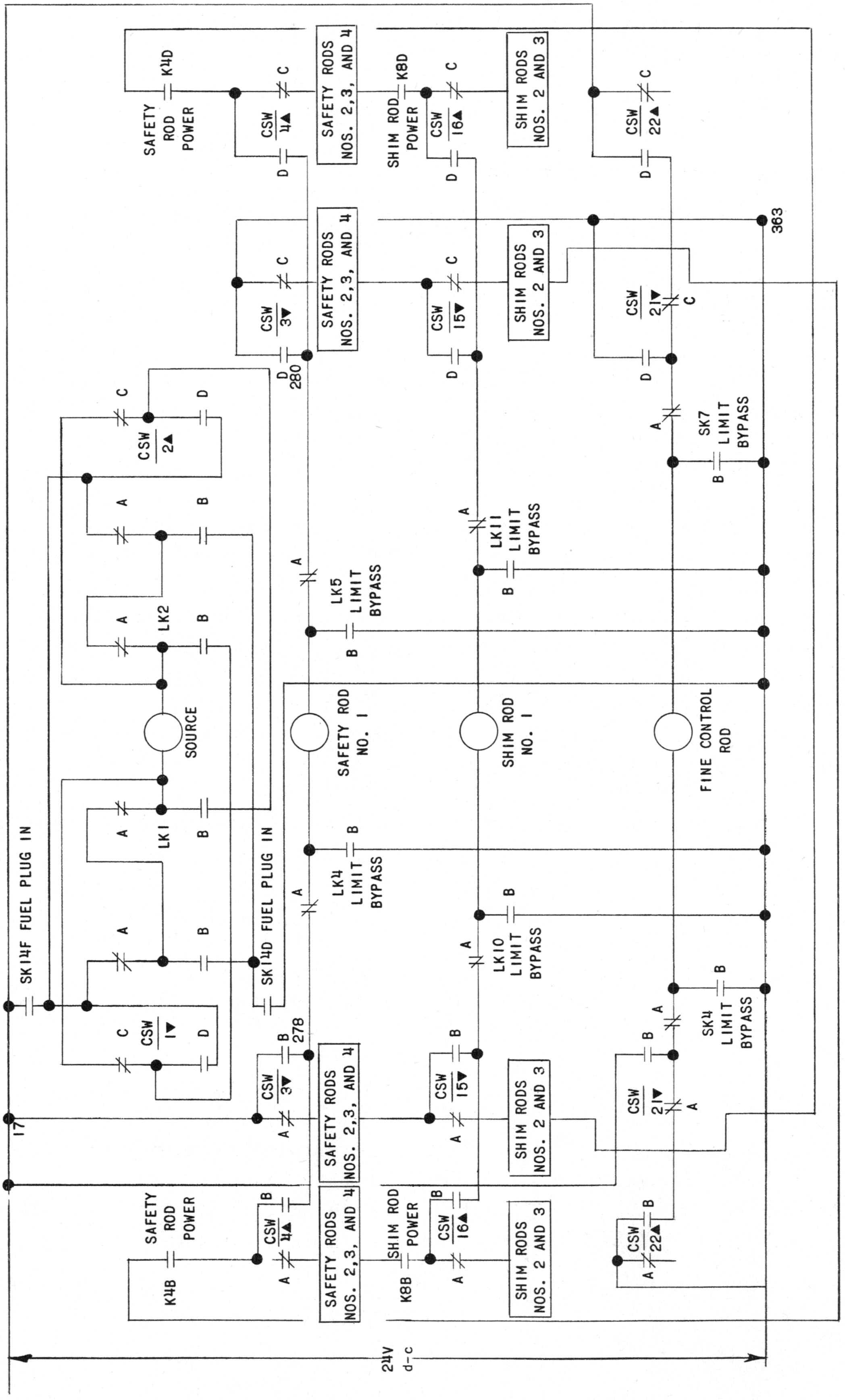


Fig. 40. Control Circuits

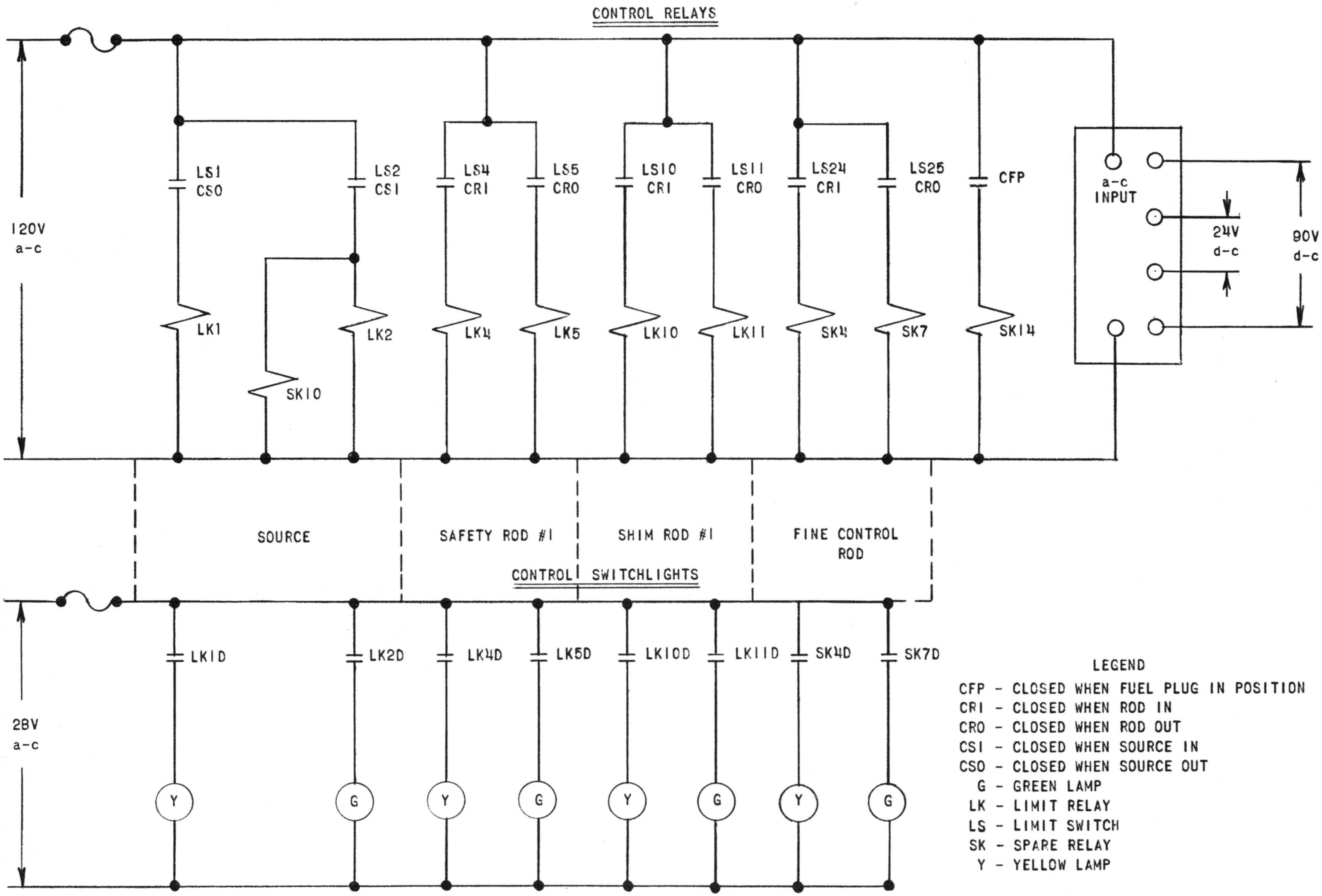


Fig. 41. Auxiliary Relay Circuits (Typical)

d. Rod Drop Test

With all rods in the full IN position, the shim-safety rod mechanisms can be checked for proper operation by performing rod drop tests. All rods are transferred from automatic to manual control by use of the rod-drop-test control key switch on the S.W. instrument rack (see Fig. 34). The rod to be tested is selected by means of the rod-drop selector switch. Only one rod can be tested at a time. By use of the console controls, the specific rod to be tested is raised to its full OUT position. Then the appropriate rod-release button is pressed to drop the rod, and a scaler on the S.E. instrument rack (see Fig. 33) counts the output of a 1000-cps pulse generator, as the rod drops, to determine the time it takes the rod to reach the IN limit. The average drop time must be below 0.50 sec.

As may be seen from Fig. 42, when the clutch in the rod drive mechanism is released, contact No. 1 is closed which starts the scaler. When the rod reaches the full IN microswitch, contact No. 2 is opened, which stops the scaler. The drop time is then read out from the scaler and the scaler is reset to zero for the next test.

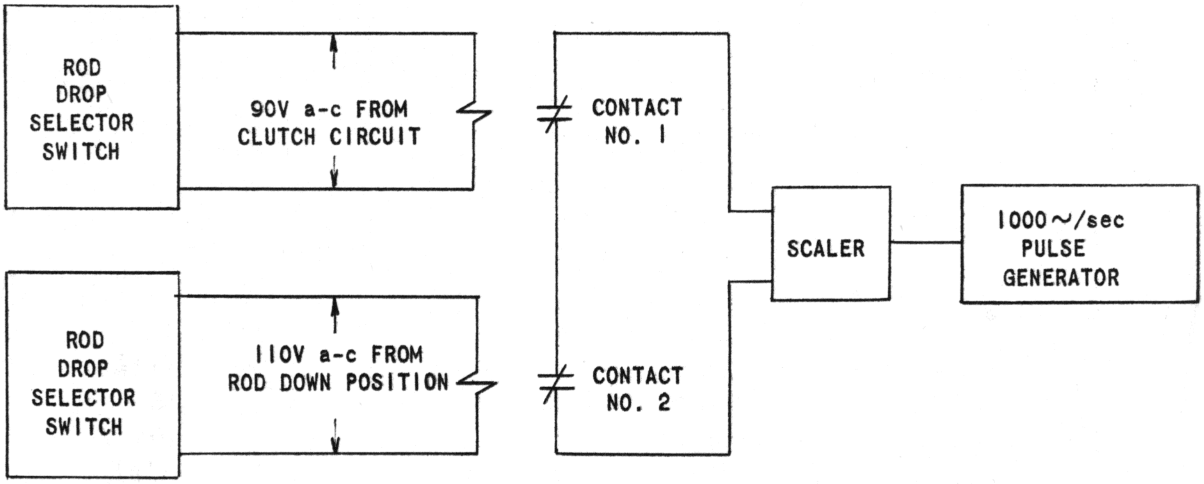


Fig. 42. Rod Drop Schematic

e. Ventilation System Shutdown and Emergency Exhaust Fan

During normal operation all building ventilation fans are operated manually in conjunction with their respective indicating switches (see Fig. 28). In the event of an evacuation alarm trip (gamma disaster relay in failed position; see Fig. 43), a control relay in the automatic transfer switch shuts off all ventilating-system fans and shuts all louvers and vents. The emergency exhaust fan can then be manually actuated from either of two switch locations (the upper hall or the reactor room). By use of the emergency fan, building air is exhausted to the atmosphere through high-efficiency filters and a roof vent in the reactor building.

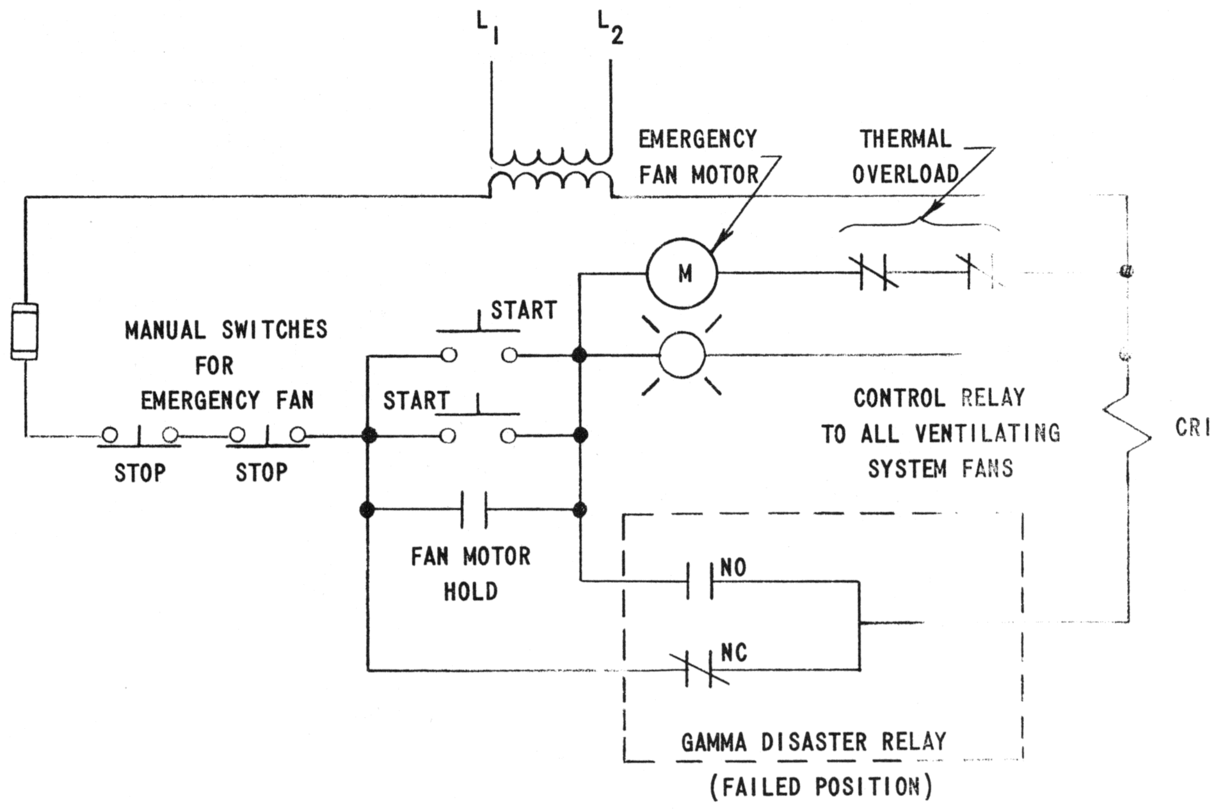


Fig. 43. Ventilation System Shutdown and Emergency Exhaust Fan Circuits

H. Reactor Graphite Assembly and Experimental Facilities

1. Reactor Graphite Assembly

All the graphite external to the lead thermal shield constitutes the reactor graphite assembly (see Fig. 44). In this assembly the graphite to the east and west of the lead thermal shield is designated the east and west thermal columns; to the north and south, the universal test facility and the test cave, respectively. The large graphite blocks, 38.2 cm (14 in.) square by 122 cm (48 in.) high, used in the thermal columns are AGOT reactor-grade graphite. The smaller bricks (the balance of the graphite), 10 cm (4 in.) square and random lengths, used in the thermal columns and the test facilities, are the original graphite bricks from the CP-1 and CP-2 reactors.

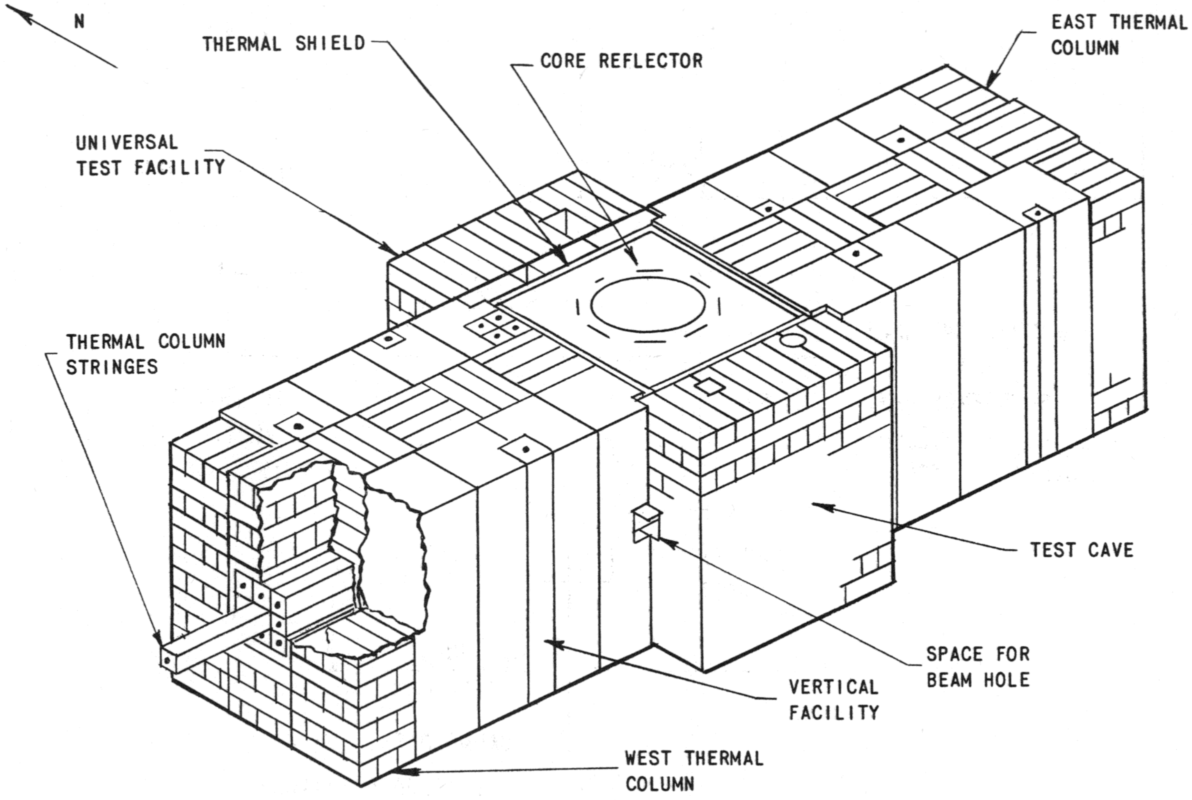


Fig. 44. Reactor Graphite Assembly

2. Experimental Facilities

There are 22 experimental facilities (see Fig. 45) located as follows:

(1) Horizontal ports:

East thermal column - 1

West thermal column - 1

(2) Vertical ports:

Internal thermal column - 3

East thermal column - 5

West thermal column - 5

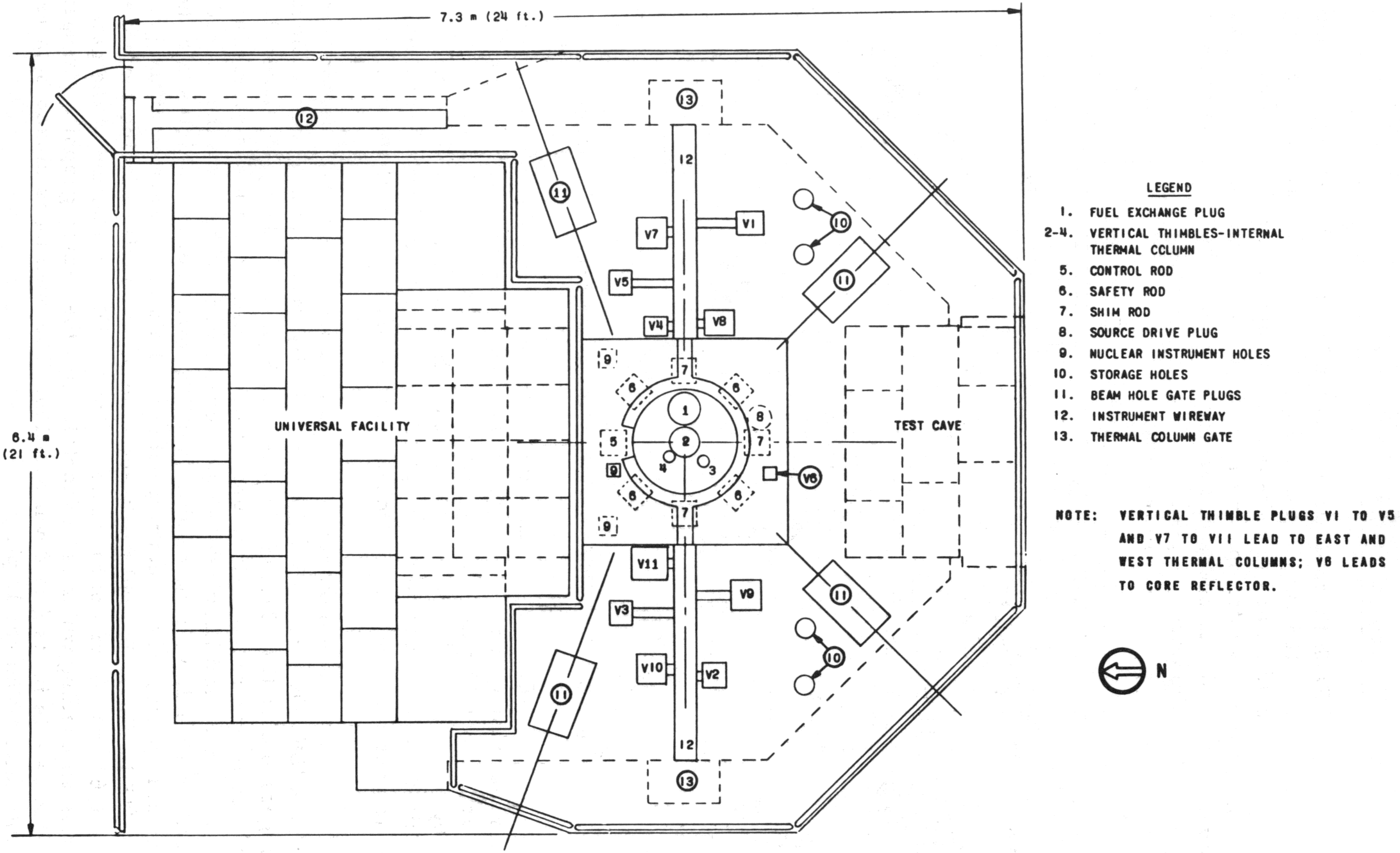
Core reflector - 1

(3) Test facilities:

Universal test facility - 1

Test cave - 1

(4) Horizontal beam holes - 4



LEGEND

1. FUEL EXCHANGE PLUG
2-4. VERTICAL THIMBLES-INTERNAL THERMAL CCLUMN
5. CONTROL ROD
6. SAFETY ROD
7. SHIM ROD
8. SOURCE DRIVE PLUG
9. NUCLEAR INSTRUMENT HOLES
10. STORAGE HOLES
11. BEAM HOLE GATE PLUGS
12. INSTRUMENT WIREWAY
13. THERMAL COLUMN GATE

NOTE: VERTICAL THIMBLE PLUGS V1 TO V5 AND V7 TO V11 LEAD TO EAST AND WEST THERMAL COLUMNS; V6 LEADS TO CORE REFLECTOR.

Fig. 45. Plan View of Experimental Facilities and Shield Plugs

a. Horizontal Ports

Each thermal column has a horizontal opening, 30.5 cm (12 in.) square and 183 cm (72 in.) deep, which extends through the length of the thermal column and terminates at the lead thermal shield (see Fig. 46). Each horizontal opening is filled with nine 10 cm (4 in.) square, removable graphite stringers of random lengths. The center stringer of the group is on the core midplane.

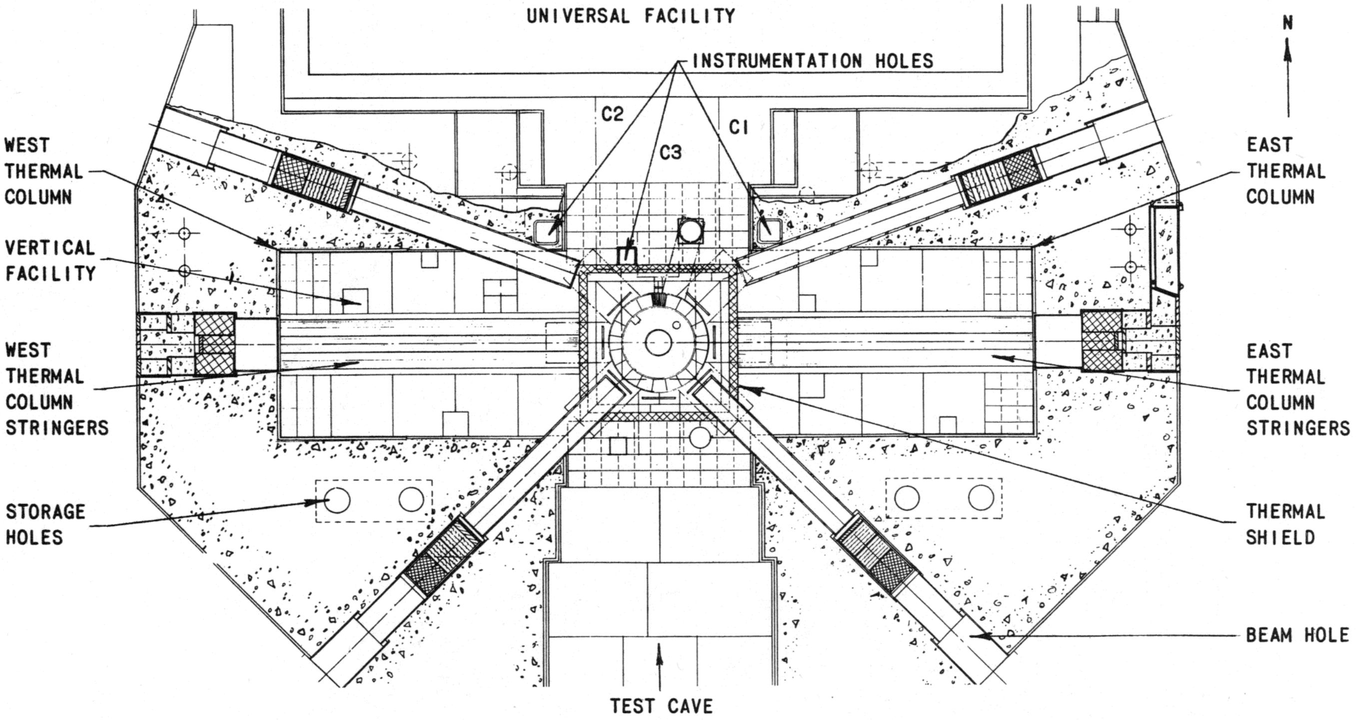


Fig. 46. JUGGERNAUT Section at 63.5-cm Elevation

Between the horizontal opening in each thermal column and the corresponding access opening in the face of the reactor there is a void, a motorized shield gate (rectangular in cross section, 35.6 cm [14 in.] wide by 23 cm [9 in.] deep, with a vertical height of 152.4 cm [60 in.]), two shield blocks, and two shield plugs (see Fig. 47). Operation of the gates is controlled by lock switches mounted on the face of the reactor.

Each motorized gate is suspended by a Duff-Norton worm-gear jack (SK2004-R-17-15 in.) and vertically driven by a General Electric $\frac{3}{4}$-hp gear motor (No. 045119, 220/440-V, 3-phase). The jack assembly is supported by the reactor structure. Each gate is of stainless steel clad, 0.63 cm ($\frac{1}{4}$ in.), and heavy-density concrete, compatible with the poured monolithic shield, with the exception of the lower section which seals the horizontal opening of the thermal column. This lower section of the gate, 38 cm (15 in.) high, is lead filled and clad on the surface facing the core with a 0.63-cm ($\frac{1}{4}$-in.) boral plate. This lead-filled section of the gate contains an opening which is concentric with the center graphite stringer when the gate is in its full-down position. The opening is closed by a removable lead-filled shield plug.

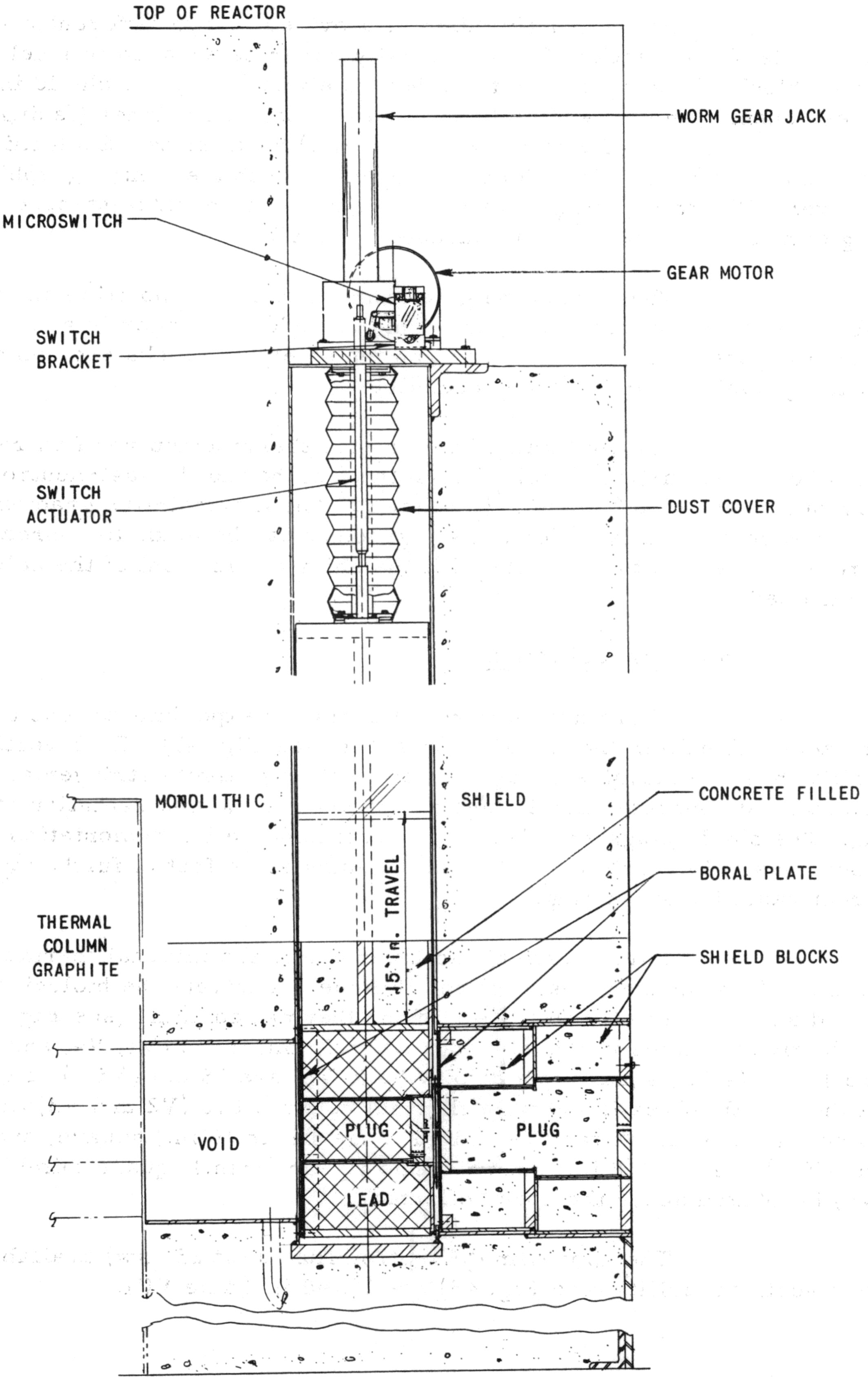


Fig. 47. Thermal Column (West) Gate Assembly

Additional shielding is provided by two differently sized removable shield blocks of heavy-density concrete encased in steel. The larger block is placed behind the other to effect a stepped shield in the access opening in the reactor face. The surface of the inner (facing the core) block is covered with a 0.63-cm ($\frac{1}{4}$-in.) boral plate. Each shield block contains an opening which is concentric with the center graphite stringer. The two openings are closed with one removable stepped shield plug of heavy density concrete encased in steel.

Thus, when the gate is in its full down position and the two shield plugs are removed, the center graphite stringer is accessible. When the gate is in its up position and the shielding blocks are removed all the graphite stringers are accessible.

In each thermal column the thermal-neutron flux ranges from 10^{12} to 10^{9} n/(cm^2)(sec) through the length; and the fast-neutron flux ranges from 10^{12} to 10^{3} n/(cm^2)(sec). The thermal-flux gradient within each column is 3%/cm. This gradient can be made to approach zero near the lead thermal shield if the shim rod in front of the column is inserted.

b. Vertical Ports

There are 14 vertical ports for experimental use, and all are accessible from the top of the reactor (see Fig. 45). Each vertical facility has a removable square-cross-section graphite stringer and two stepped concrete shield plugs for protection against radiation streaming. The shield plugs are pierced to accommodate instrumentation leads from installed experiments. These openings are offset to further prevent direct radiation streaming.

Three vertical facilities are in the internal thermal column. Ten square-cross-section thimbles penetrate the biological shield and extend to the full depth of the thermal columns (see Fig. 44). Of the five thimbles in the east thermal column, three (V1, V4, and V5) are 10 cm (4 in.) square, and two (V7 and V8) are 15 cm (6 in.) square. Of the five thimbles in the west thermal column, two (V2 and V3) are 10 cm (4 in.) square, two (V9 and V10) are 15 cm (6 in.) square, and one (V11) is 20 cm (8 in.) square. One 10-cm (4-in.) square thimble (V6) is located above the core reflector.

The approximate neutron fluxes (at 250 kw) available in each vertical facility (see Fig. 45) are listed in Table VIII.

Table VIII

APPROXIMATE MAXIMUM NEUTRON FLUXES IN VERTICAL FACILITIES

(see Fig. 45)

Facility No.	Neutron Flux, n/(cm²)(sec)		Facility No.	Neutron Flux, n/(cm²)(sec)	
	Thermal	Fast		Thermal	Fast
V-1	1×10^{10}	5×10^{4}	V-7	3×10^{10}	2×10^{4}
V-2	1×10^{10}	2×10^{4}	V-8	3×10^{11}	5×10^{9}
V-3	5×10^{10}	2×10^{6}	V-9	2×10^{11}	2×10^{8}
V-4	3×10^{11}	5×10^{9}	V-10	1×10^{10}	5×10^{4}
V-5	1×10^{11}	2×10^{7}	V-11	3×10^{11}	5×10^{9}
V-6	1×10^{12}	5×10^{11}			

c. Test Facilities

A universal test facility, 50 cm (20 in.) deep, filled with ordinary and heavy concrete blocks, is located in the north face of the reactor (see Fig. 45). The blocks can be removed to make an opening, 112 x 122 cm (44 x 48 in.) in vertical cross section, for the irradiation of bulky apparatus adjacent to the face of the reactor graphite, approximately 68 cm (27 in.) from the core face. The thermal-neutron flux at the external face of the reactor graphite is approximately 2×10^{11} n/(cm²)(sec) at 250 kw.

Diametrically opposite the universal test facility is a test cave, 40 cm (16 in.) deep, shielded with removable, heavy-concrete blocks (see Fig. 45). The inner opening of the test cave also faces the reactor graphite assembly, 112 x 122 cm (44 x 48 in.) in vertical cross section and approximately 60 cm (24 in.) from the core face. The thermal flux at the external face of this graphite section is approximately 2×10^{11} n/(cm²)(sec) at 250 kw.

d. Horizontal Beam Holes

Four 15-cm (6-in.)-diameter horizontal beam holes are installed on a level corresponding to the core midplane, a distance of 63.5 cm (25 in.) above the reactor room floor level. Two of the beam holes (opening on the northwest and northeast faces of the reactor) extend to the corners of the lead thermal shield; the other two beam holes (opening on the southwest and southeast faces of the reactor) penetrate the corners of the lead thermal shield to within 7 cm (3 in.) of the face of the reactor vessel (see Fig. 46).

Between the outer opening of each beam hole in the reactor graphite and the corresponding access opening in the reactor face there is a motorized gate, rectangular in cross section, 21.6 cm ($8\frac{1}{2}$ in.) wide by 47 cm ($18\frac{1}{2}$ in.) deep, with a vertical height of 152.4 cm (60 in.), and two cylindrical shield plugs (see Fig. 48). The outer shell of each gate is fabricated from stainless steel plate, 0.63 cm ($\frac{1}{4}$ in.) by 1.27 cm ($\frac{1}{2}$ in.), and 2.54 cm (1 in.) thick. Each gate is filled with heavy-density concrete with the exception of the lower, 22.9-cm (9-in.) section, which contains laminations of boral, mild steel, masonite, and a 18.4-cm ($7\frac{1}{4}$-in.) thickness of lead.

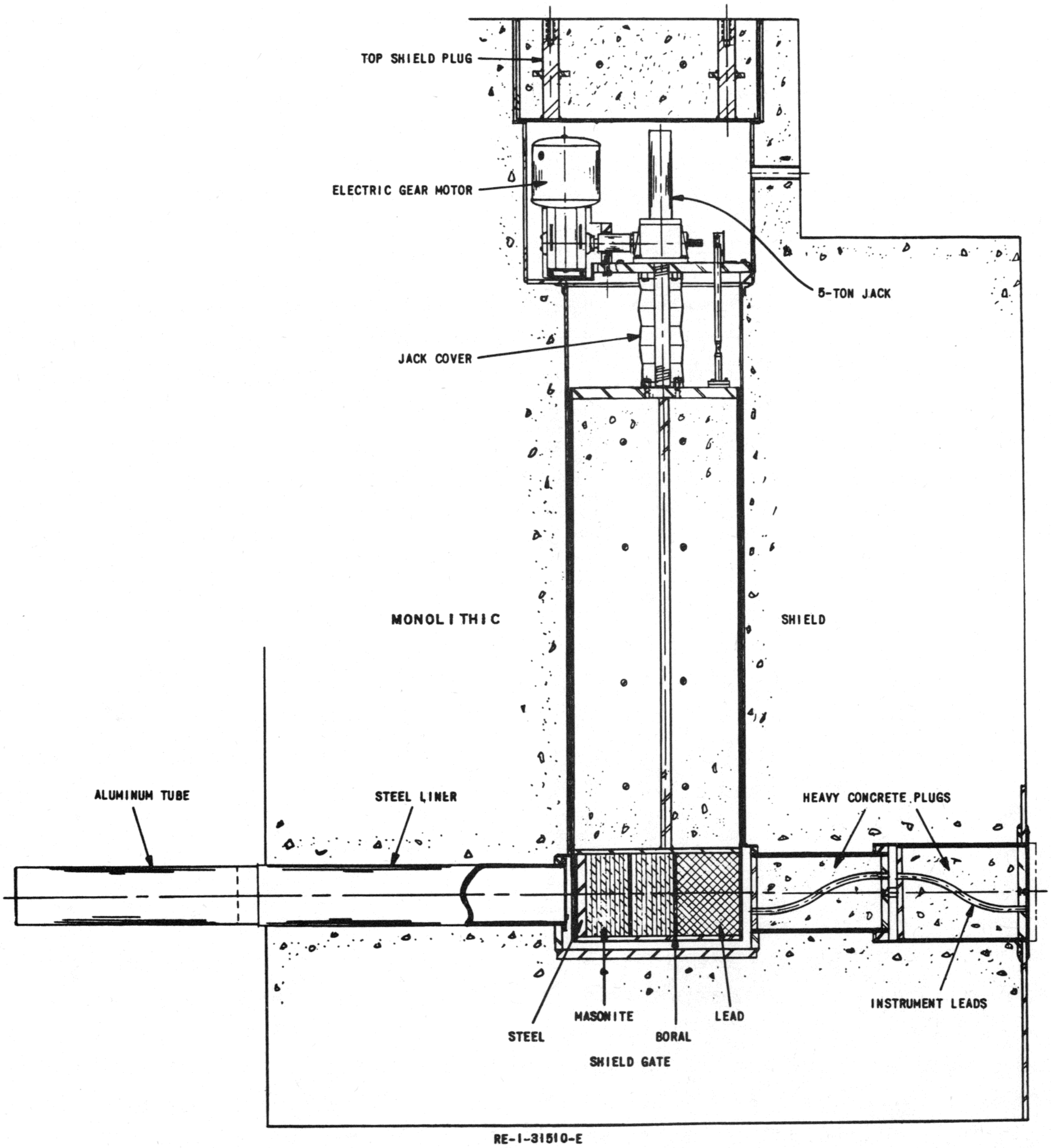


Fig. 48. Beam Hole Facility

Each motorized gate is suspended by a Duff-Norton worm-gear jack (SK2004-R-17-9 in.) and vertically driven by a General Electric $\frac{3}{4}$-hp gear motor (No. 045712, 220/440-v, 3-phase). The gear motor and jack are attached to a 1-in. plate located 61 cm (24 in.) below the top of the reactor shield. Directly above the gear motor and the screw jack drive are rectangular shield plugs clad with 0.63-cm ($\frac{1}{4}$-in.) steel plate and filled with heavy-density concrete to prevent direct radiation streaming. Operation of the gates is controlled by lock switches mounted on the reactor face.

Additional shielding is provided by two shielding plugs of different diameters filled with heavy-density concrete. The larger plug is placed behind the smaller plug to effect a stepped shield in the access opening of the reactor face. A stainless steel tube of 2.54-cm (1-in.) diameter is buried within each plug to serve as a wireway for installed experiments. This tube has an "S" bend to prevent direct radiation streaming.

Each of the beam holes extending to the southeast and southwest faces of the reactor describe a 45-degree angle with an east-west centerline. Both beam holes are constructed of 15-cm (6-in.)-diameter, Schedule 40, stainless steel pipe open at both ends to accommodate an aluminum liner. The liner, 121 cm (48 in.) in length, extends beyond the steel pipe toward the core. That end of the liner nearest the core is closed with the exception of a small hole. The liner was incorporated in the design solely for flexibility in the future removal of core reflector and thermal column graphite.

The other two beam holes, extending to the northeast and northwest faces of the reactor, describe a 20-degree angle with an east-west centerline. These beam holes are tangential to the core. Constructed of 15-cm (6-in.)-diameter, Schedule 40, stainless steel pipe, the beam holes extend 138 cm ($54\frac{3}{8}$ in.) in length and are closed, with the exception of a small hole, at that end of the pipe nearest the core. These beam holes do not have a liner, as they extend only to the corners of the lead thermal shield.

The maximum neutron current emerging from any beam hole will be of the order of 0.0001 ϕ_i n/(cm^2)(sec), where ϕ_i is the flux in a particular energy range at the end of the beam hole nearest the core. For example, the maximum thermal flux in the core reflector at an operating power level of 250 kw will approximate 10^{12} n/(cm^2)(sec); therefore, the maximum thermal-neutron current available at the outer face of the reactor will be 10^8 n/(cm^2)(sec).

I. Biological Shielding

1. Monolithic and Block Shielding

Stacked blocks of ordinary and heavy concrete comprise 60% of the radial biological shielding; the remainder is monolithic, poured heavy-density concrete, having a specific gravity of 3.77 gm/cm^3 (235 lb/cu ft). The aggregate of the heavy-density concrete is magnetite. The design calculations for the biological shielding are discussed in Appendix C.

Prior to the pouring of the heavy-density concrete for the monolithic shield, steel forms and encasements were constructed to make a protective outline over and in the reactor graphite assembly. The steel forms for the universal test facility, the test cave, the 1.5-m (5-ft) square opening for the top removable shield, the thermal-column vertical ports, and the steel encasements for the thermal columns were fabricated from 1.27-cm ($\frac{1}{2}$-in.) steel plate. These preconstructed sections were assembled at the reactor site after the reactor graphite assembly was in place (see Fig. 49).

The first sections to be positioned were the two thermal-column steel covers (each cover included a top, sides, and an end face) which contained cutouts for the vertical ports, the thermal-column horizontal openings, and the beam-hole horizontal openings. To reduce tolerances, the cutouts for the horizontal openings were deliberately made over-size with the intention of using steel flanges to fill in the gap between mating parts. The section or end face of each steel cover, which contained the cutout for the horizontal opening, was lined with a 0.63-cm ($\frac{1}{4}$-in.) boral sheet. This lining was then continued back from the end face along the top and sides of the steel cover, between the reactor graphite and the cover, to a length of 76 cm (30 in.). The boral sheet was used to reduce the thermal-neutron flux both at the steel and in the concrete of the monolithic shield, thus eliminating capture gamma rays which would have necessitated the use of a thicker monolithic shield. Once installed, the steel covers were secured to the floor with "Ackermans."

The ten thermal-column vertical port forms were lined up with their respective graphite holes by means of a jig which conformed to the specific hole shape and size. The steel port forms were then welded to the steel cover plates and supported at the top by tie rods. Aluminum liners were inserted in the port forms to maintain cleanliness. Two concrete-filled, stainless steel, stepped, shield plugs were provided for each vertical port.

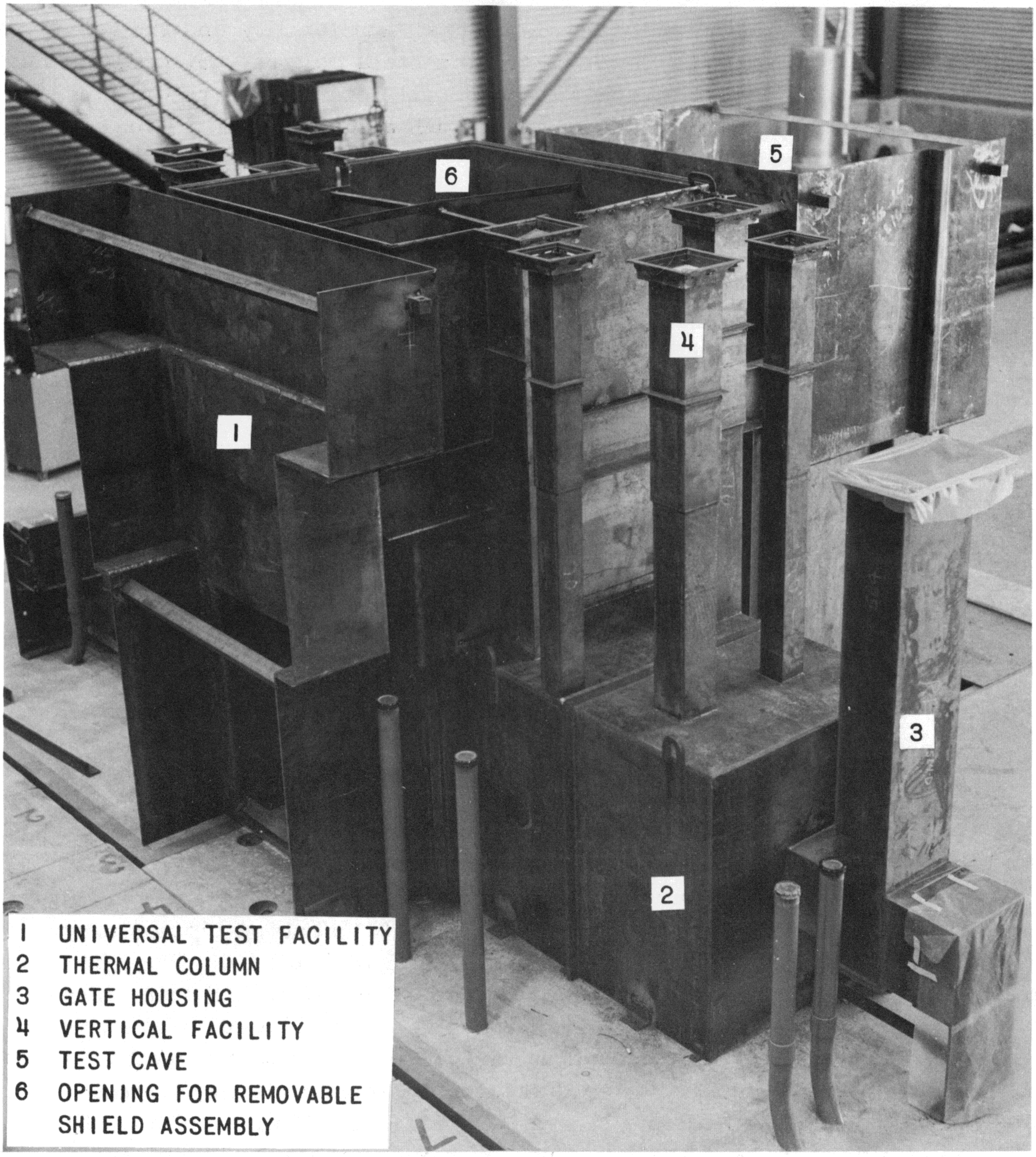


Fig. 49. Steel Encasements and Forms

The steel forms for the universal test facility and the test cave were positioned against the thermal-column steel covers. By design, the adjacent sides of the facilities and the thermal column covers did not meet. These sides were welded together with angle iron to fill the gaps. This design assured no interference between joining members and allowed the use of liberal tolerances.

The form for the 1.5-m (5-ft) square top opening was put in place and joined to the previously placed forms as described above. Steel supporting beams were then placed under the outer ledges of the form to help support the load of the shield plugs, coffin, and heavy sundry equipment expected to be used on the reactor top.

The two thermal-column gate housings were welded to the thermal-column steel covers. The four beam tubes with gate housings attached were also welded in place. Four storage tubes, to be used for the storage of low-level radioactive material, were positioned, two east and two west of the test cave, and secured to the floor.

Prior to the concrete pour, anchors and tie rods were welded to the steel forms (see Fig. 50). Concrete was then poured over the steel assembly to a depth of 86.5 cm (34 in.).

After the monolithic shield was poured, the test facilities to the north and south of the reactor were enclosed with shielding blocks, of various sizes and densities, to prevent direct radiation leakage into the reactor room and the surrounding area. The majority of the shielding blocks, 46 cm (18 in.) square in cross section by 46 cm (18 in.), 61 cm (24 in.), and 66 cm (26 in.) widths, were ARGONAUT-type blocks varying in specific gravity from 2.0 to 3.2 gm/cm^3 (125 to 200 lb/cu ft). The more dense blocks were located nearest the core. Nine shielding blocks, varying in weight from 1590 kg (3500 lb) to 8600 kg (19,000 lb), were fabricated at the site from the same mixture of concrete as used for the monolithic shield. Variously sized structural steel rods were buried within these blocks to be used for structural strength and lifting eyelets. The remaining blocks were made of standard mix concrete and steel punchings.

2. Top Removable Shield Assembly

The top removable shield assembly, of 1.5-m (5-ft) square horizontal cross section and 160 cm (63 in.) deep, is located directly over the core assembly. This shield assembly is the most complicated and important single item of the reactor as it shields and houses almost all of the reactor controls and instrumentation, and permits access to the reactor vessel and the core assembly, in addition to the controls and instrumentation.

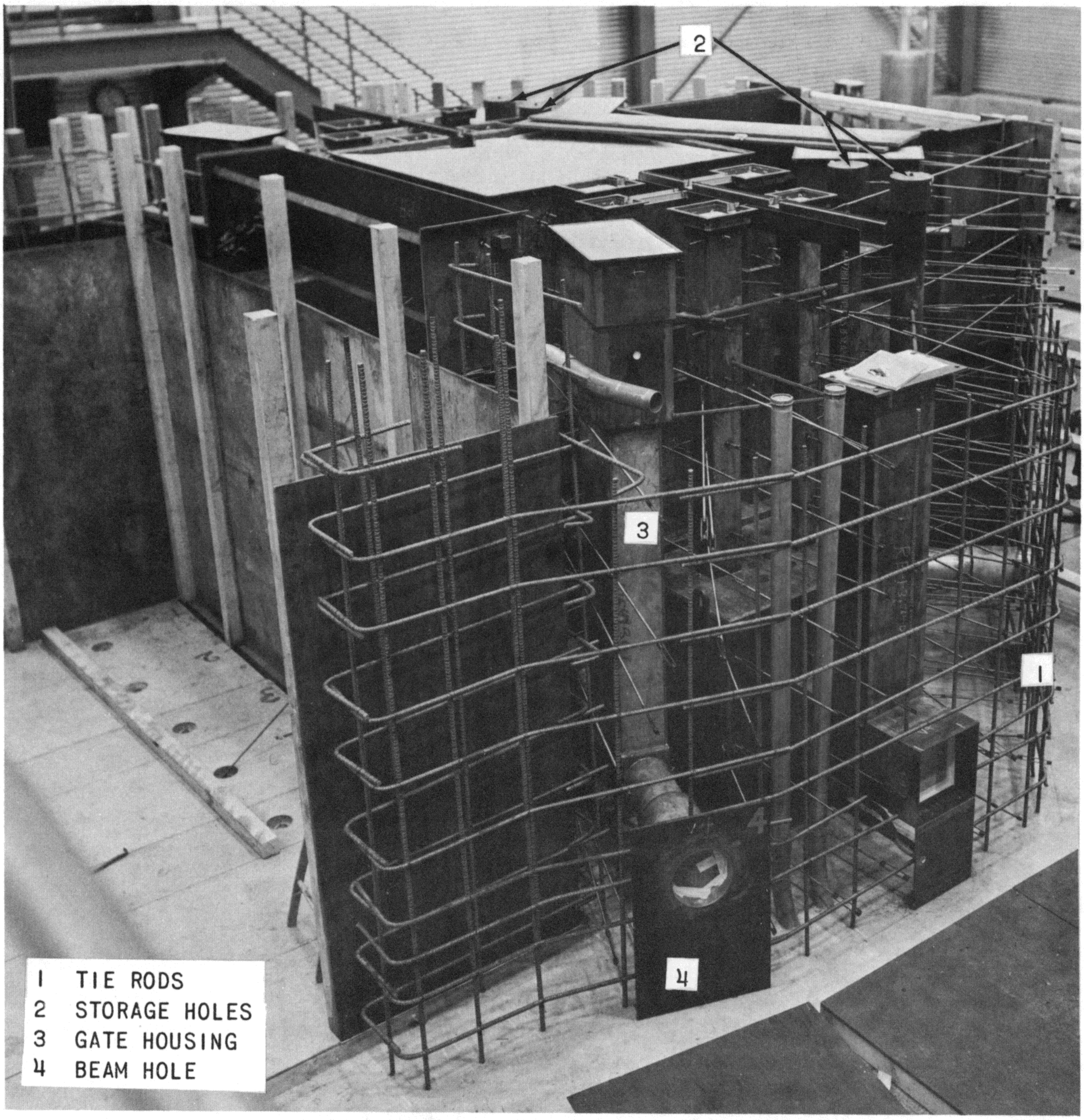


Fig. 50. Steel Encasements and Forms Prior to Concrete Pour

The shield assembly consists of two individually removable shielding sections which are placed one on top of the other (see Fig. 51). The upper section, 51 cm (20 in.) deep, shields the mechanical control rod devices and neutron detectors. The lower section, 109 cm (43 in.) deep, supports the control rod mechanisms and the top rotating shield, and houses the neutron detectors, the source hole, and a vertical experimental facility. Both sections of the removable shield assembly are interlocked with the safety trip circuitry (Irradiation Facility Interlock) either to prevent startup or to initiate a water dump (scram) if either section of the shield is not in position at the initiation of or during reactor operation.

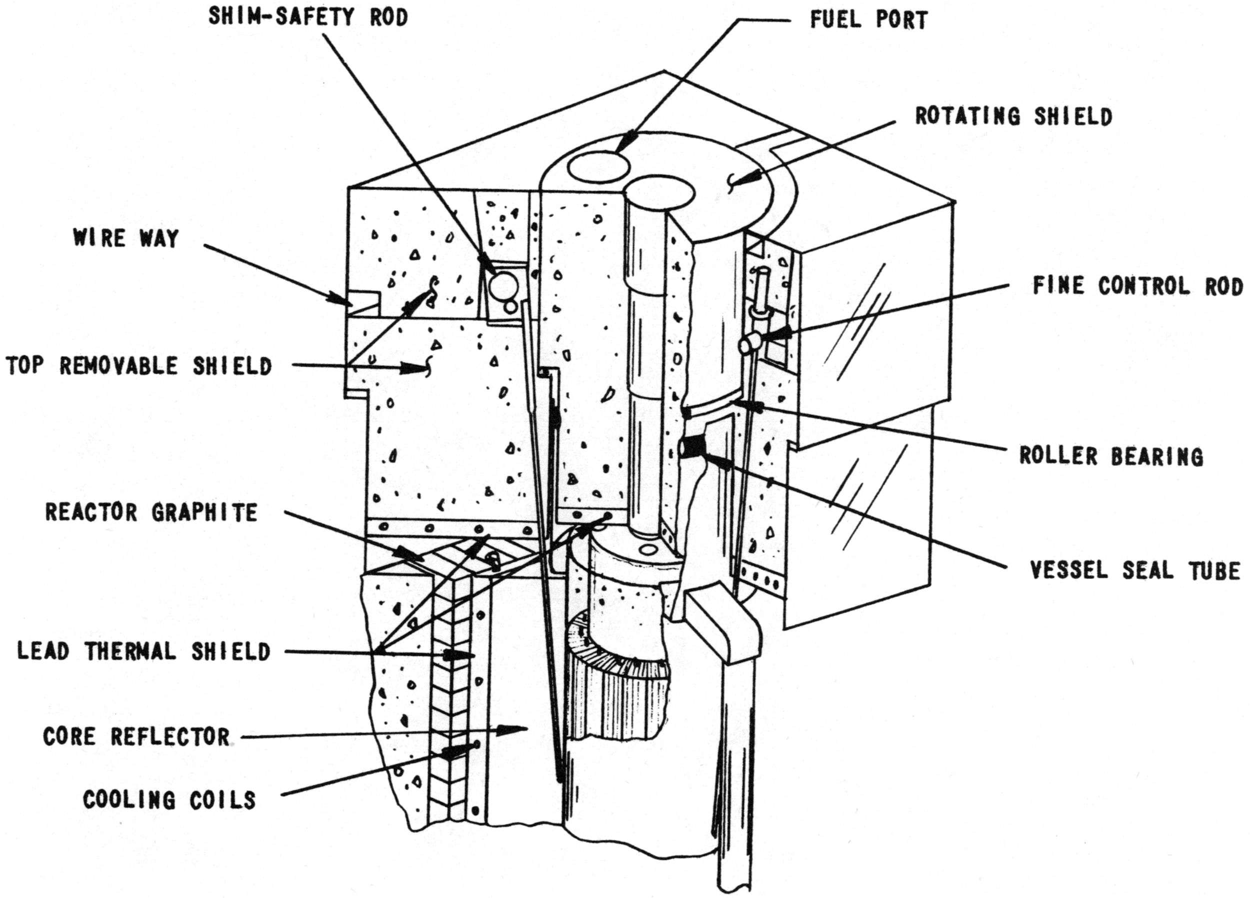


Fig. 51. Top Removable Shield Assembly in Relation to Core

During the initial installation of the shield, a steel shell of the lower section of the shield assembly was centered over and inserted into the 1.5-m (5-ft) square opening in the monolithic shield. This shell contained a boral sheet, 0.63 cm ($\frac{1}{4}$ in.) thick, an aluminum cover plate, 1.27 cm ($\frac{1}{2}$ in.) thick, attached to the bottom of the shell, and the necessary cutouts, the cylindrical stepped liner for the rotating shield, and the openings for the control rod sheaths. It was necessary to center the shell exactly to line up all the ports in the shell with their corresponding openings in the graphite core reflector and to center the opening of the liner on the vertical centerline of the core.

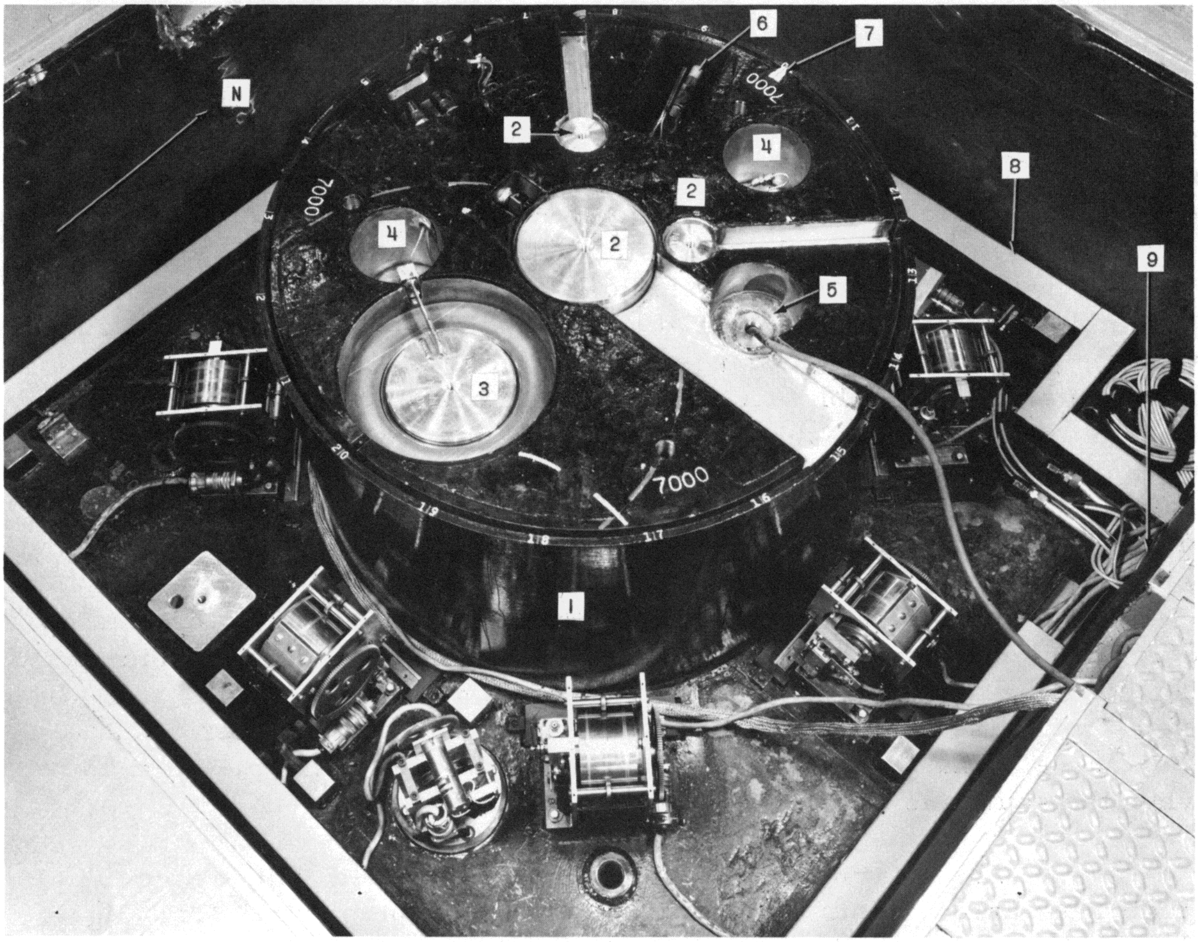
Centering the openings in the shell with those in the graphite core reflector was accomplished with the use of four bolts as screw jacks against each side of the steel-lined, 1.5-m (5-ft) square opening. When the shell was centered in the opening, by means of the screw jacks, a position-limiting nut was welded to each of the bolts; thus, returning the bolts to their original position would insure the return of the shield to its original position, thereby enabling the passing of the control rods through the shield and entry of the graphite core reflector without interference.

Following the centering procedure, the steel shell was removed from the reactor and stainless steel cooling coils, 1.27 cm ($\frac{1}{2}$ in.) in diameter, and component forms were installed. Lead was poured over the cooling coils to an overall depth of 7.6 cm (3 in.) in the bottom of the shell. The shell was then completely filled with high-density (specific gravity = 4.0 gm/cm^3) concrete to complete the lower section of the shield assembly. This completed section was then placed in the reactor (see Fig. 52), and the eight control rod mechanisms and the source mechanism were installed. These mechanisms, with the exception of those of the source and the fine control rod, were covered first with dust covers and then with encasement cans. The source and fine control rod mechanisms were covered with dust covers only.

The shell, including cutouts, for the upper section of the shield assembly was positioned next and lowered over the lower shield section. When this shell was centered, the mechanism encasement cans, which now protruded through the bottom of the upper section shell, were welded to the shell. The shell was then removed and, after the component forms were installed, filled with high-density (specific gravity = 4.0 gm/cm^3) concrete. Boron, paraffin and lead fill were used in nonremovable forms directly over the mechanism encasement cans. Removable plugs were inserted over the source and fine control rod mechanisms to shield against expected neutron and gamma streaming. A removable plug was also inserted in the opening over the vertical experimental facility. The total weight of the complete shield assembly is 8$\frac{1}{2}$ tonnes (9$\frac{1}{2}$ tons).

The wiring for the chambers, mechanisms, etc., enters the top of the lower section of the shield assembly from a large junction box (located under the monolithic shield) in the northeast corner of the steel form for the 1.5-m (5-ft) square opening (see Fig. 53). The wires were inserted into a wire-mold conduit and then distributed to the various devices. The Shield Water Cooling System lines were also arranged to enter the lower section of the shield from the large junction box. To remove the lower section of the shield assembly, the wiring, cables, and water lines must first be disconnected and put back into the junction box.

Fig. 52. Lower Section of Removable Shield Assembly Lowered into Reactor



1. Removable Shield Assembly Liner
2. Experimental Facilities
3. Fuel Port
4. Thermocouples
5. Vessel Seal Tube Air Line
6. Hand Brake
7. Indicating Arrow and Fuel Indexing Numbers
8. Wiremold Conduit
9. Junction Box

Fig. 53. Lower Section of Removable Shield Assembly with Components Installed (Rotating Shield in Position)

3. Rotating Shield

A rotating shield (see Figs. 53 and 54) with one recessed fuel port is used for access to the 20 fuel-assembly positions of the annular core. The 3.1-tonne ($3\frac{1}{2}$-ton), stepped shield is supported within the liner of the top removable shield assembly (see Fig. 54) and rotated on the supporting ledge of the liner by means of a roller bearing (see Fig. 55) of 76-cm (30-in.) diameter. The shield is rotatable by hand to the fuel-assembly position desired upon aligning the pointer on the rotating shield with the position-index markings on the edge of the liner of the top removable shield assembly. A hand-operated brake, which bears on the liner of the removable shield assembly, is used to hold the rotating shield stationary. Six roller bearings mounted in the outer wall of the rotating shield restrict the horizontal movement of the shield by maintaining rolling contact with the adjacent liner. The shield may be rotated with the 3.1-tonne ($3\frac{1}{2}$-ton) fuel-handling coffin in place. A recess, 28 cm (11 in.) in ID and 5 cm (2 in.) deep, in the shield around the fuel-loading port accommodates a steel adapter on the bottom of the coffin which both centers the coffin over the port and prevents gamma streaming at the base of the coffin (see Figs. 53 and 54). The fuel-port plug is interlocked with the source so that a water dump (scram) will occur if the plug is removed when the source is down.

The rotating shield is normally positioned at index number 10 (indicating arrow points to number 10) or facing due north. This aligns the two 5-cm (2-in.)-diameter experimental ports with their respective experimental openings in the internal thermal column. The 15-cm (6-in.) experimental port penetrates the center of the shield and is centered directly over the corresponding opening, and graphite stringer, in the internal thermal column. An interlock switch (Irradiation Facility) is provided for this center plug, which will either prevent startup or initiate a water dump (scram) if the plug is not positioned properly at the initiation of or during reactor operations.

Initially, the shield consisted of a steel form, stainless steel below the level of the rubber vessel seal and carbon steel above, containing the necessary cutout forms, a boral sheet, 0.63 cm ($\frac{1}{4}$ in.) thick, an aluminum cover plate, 1.27 cm ($\frac{1}{2}$ in.) thick, and stainless steel cooling coils. A layer of lead, 7.6 cm (3 in.) thick, was poured over the cooling coils at the bottom of the form. The form was then completely filled with high-density (specific gravity = $4.0\ \mathrm{gm/cm^3}$) concrete.

Since the reactor vessel, installed prior to the installation of the rotating shield, must accept the rotating shield, a liberal taper was used for lead-in at the bottom of the shield. This taper reduced the hazard of setting the rotating shield on the lip of the reactor vessel.

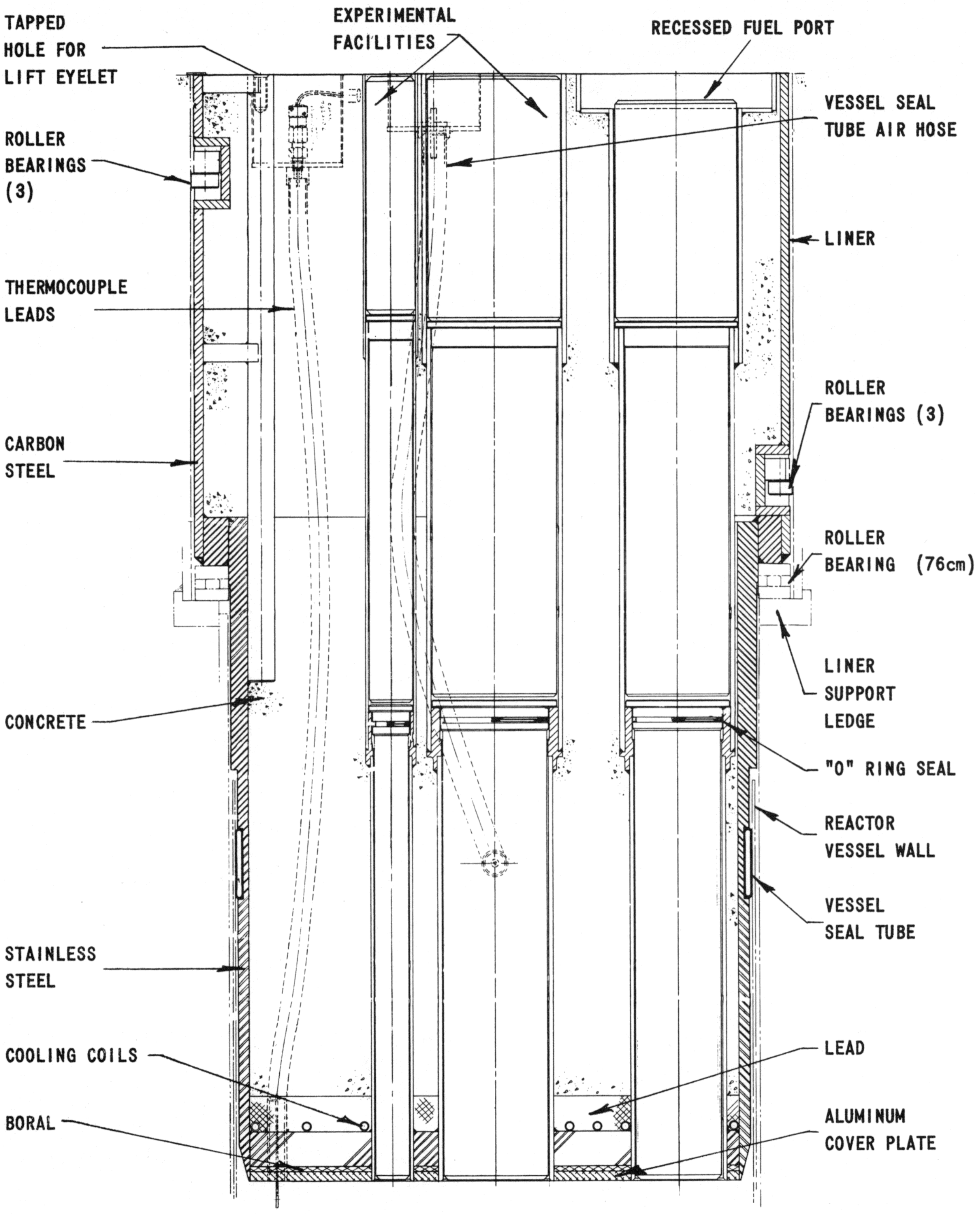


Fig. 54. Rotating Shield

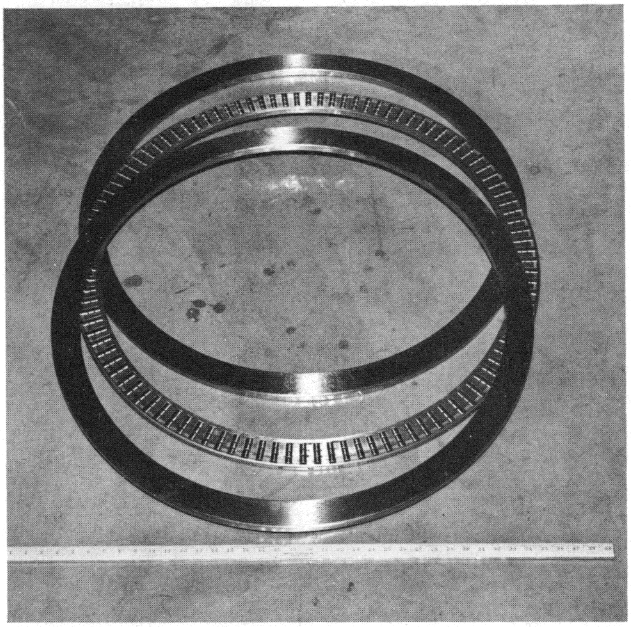


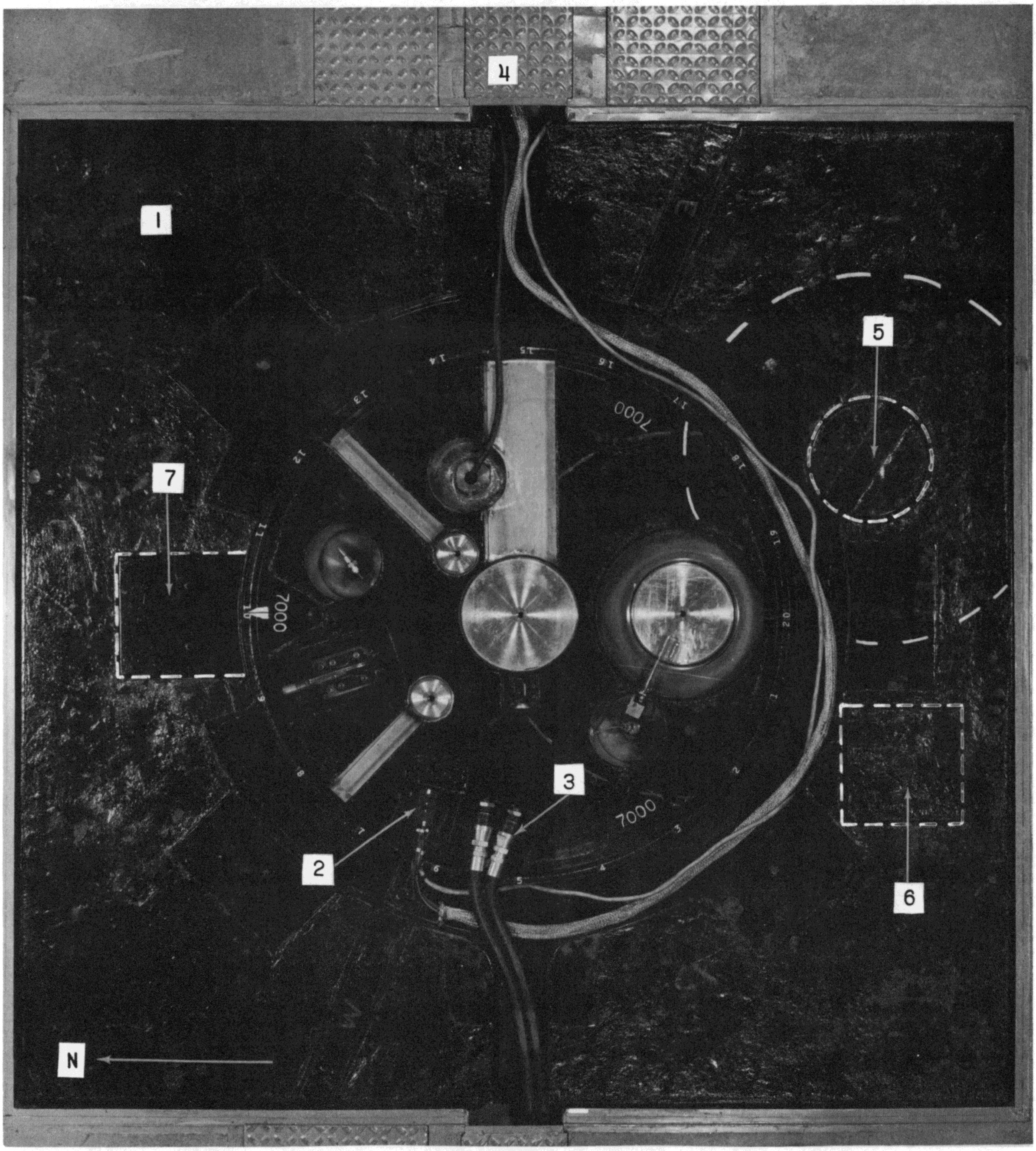
Fig. 55

Roller Bearing (76 cm Diameter)

As installed, two thermocouple wires pass through the rotating shield to allow measurement of the temperature of the core water (see Fig. 56). A third thermocouple wire is used in conjunction with the high water-temperature trip. All wires enter the shield at a common point (see Fig. 56) and are distributed to the proper terminals through buried conduit. All wires may be disconnected at the common point, if desired. Near the wire junction are the connections for the cooling system lines of the lead thermal shield. These water lines terminate in the pump room, and they must be disconnected before the shield is rotated. A rubber air hose passes through the shield (see Fig. 56) to the vessel seal tube. The wires and the air tube extend along the top of the reactor through a wire-way, covered by a tread plate, from the shield to the control console.

4. Surface Finish

When the biological shield was complete, the reactor surface, sides, and top were sealed and painted with "Neodry" concrete sealer. The openings on the reactor top, for experimental holes, wire-ways, etc., were covered with steel tread plates. The horizontal experimental openings (beam holes, etc.) were framed with sheet steel to provide a means of attaching apparatus to the face of the reactor (see Fig. 57).



1. Upper Section of Removable Shield Assembly
2. Thermocouple Wire Junction
3. Shield Cooling System Lines
4. Wire-way Covered by Tread Plate
5. Source Hole - Removable Shield Plug
6. Vertical Facility - Removable Shield Plug
7. Fine Control Rod Opening - Removable Shield Plug

Fig. 56. Top Section of Removable Shield Assembly (Rotating Shield in Position)

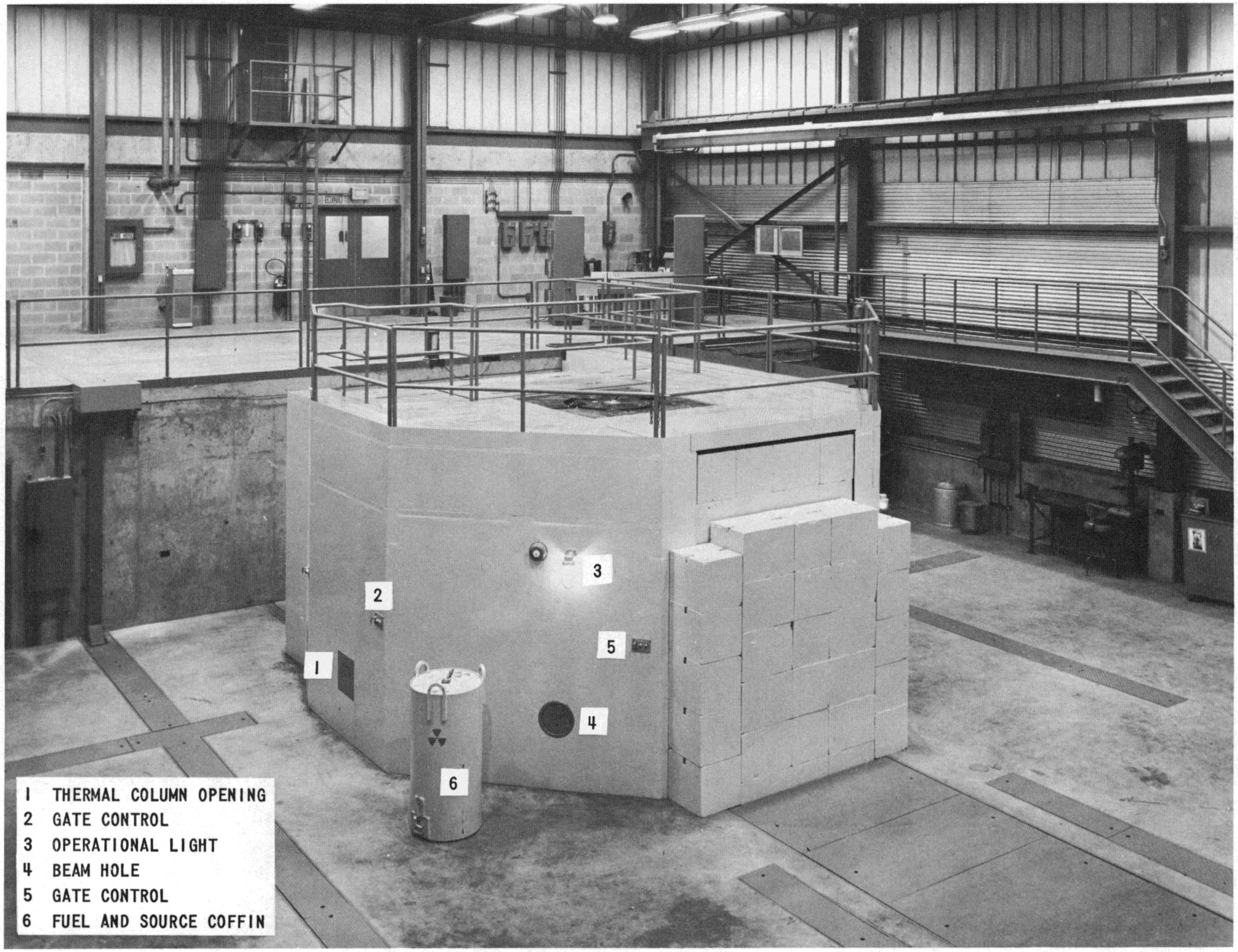


Fig. 57. Complete Reactor - JUGGERNAUT

J. Fuel and Source Handling

Fuel and source handling requires the use of a fuel and source coffin. Access to the reactor is provided via the fuel port or the source hole. Fuel loading is normally accomplished with the source in and the water up to provide radiation shielding for personnel. The source is interlocked with the fuel plug so that if the source is not up, a water dump (scram) will occur. An operator at the console observes the level of multiplied source neutrons at all times during loading operations. One safety rod is kept partially withdrawn to provide capability for emergency shutdown.

The unloading of spent fuel assemblies is to be initiated no less than one hour after reactor shutdown to afford a sufficient period for decay of fission products. The maximum time lapse will depend upon the history of reactor operations. The immediate vicinity of the fuel-exchange operations will be monitored continuously by radiological physics personnel.

The pre-unloading operations include: (1) removal of the top steel tread plate; (2) shutdown of the helium system; (3) deflation of the vessel seal tube between the rotating shield and the reactor vessel walls; and (4) turning of the rotating shield to index the fuel port over the fuel assembly to be unloaded.

1. Fuel and Source Coffin

Fuel and source loading and unloading will be effected with a lead-shielded coffin transported over the fuel port or the source hole by the overhead crane.

The coffin (see Fig. 58) is a lead cylinder, 122 cm (48 in.) high and of 61-cm (24-in.) OD, with a vertical hole, 12.7 cm (5 in.) in diameter, through the center. The vertical hole is locked closed at the top by a lead shield plug fitted with a locking latch. The plug has a small, centrally located hole which permits the vertical travel of a threaded cone-end fuel-gripper tool (see Fig. 59). This tool is fitted with a packing gland which prevents the tool from dropping into the reactor. When the coffin is used to transport the source, the fuel-gripper tool is replaced by a steel rod having a small centered through-hole for a wire rope which is used to lift the source container. A horizontal-sliding shield door is located at the bottom of the coffin. The door is locked closed, by means of a locking latch, and opened during loading and unloading operations to permit access to the bottom opening of the vertical hole in the coffin.

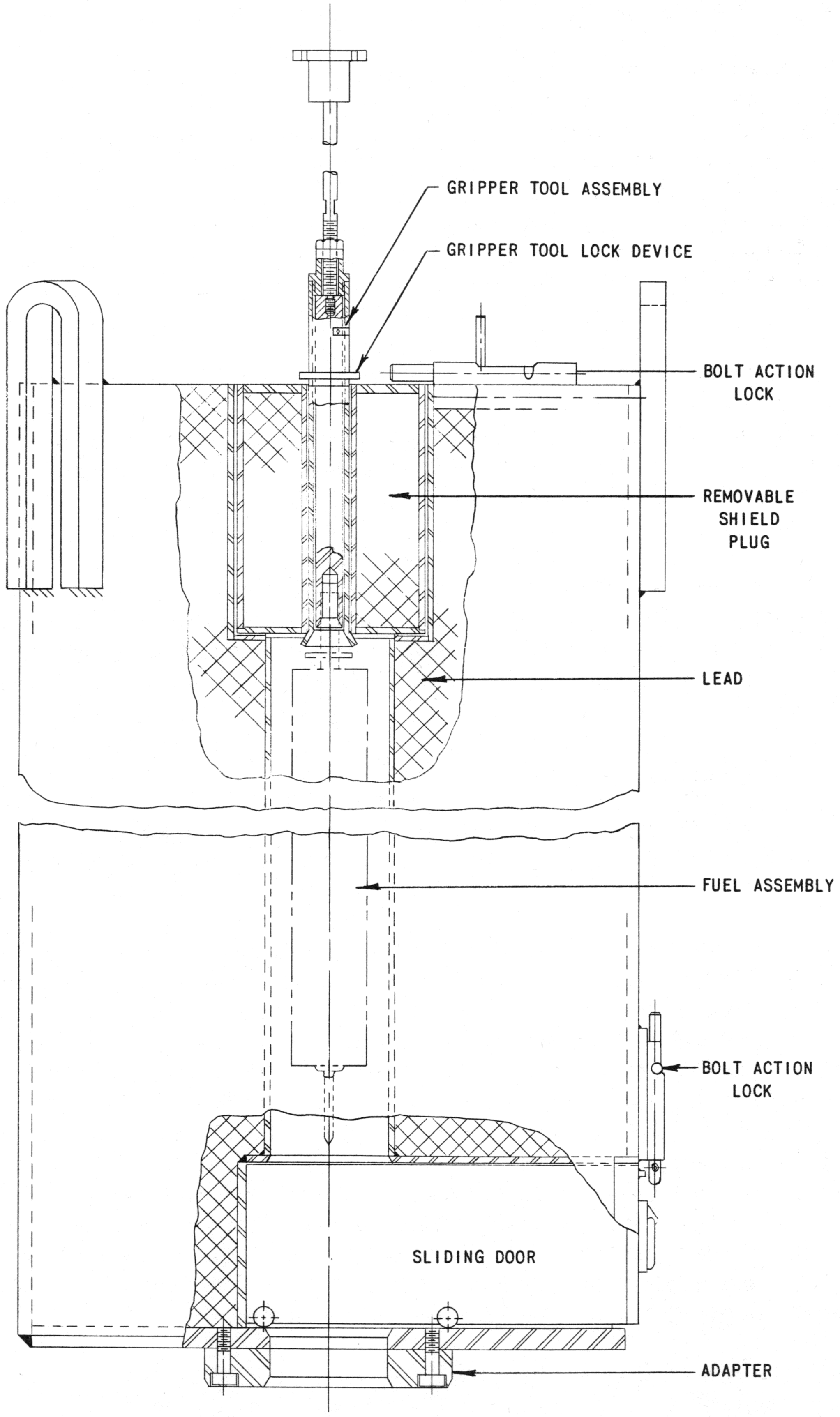


Fig. 58. Fuel and Source Coffin

During fuel-loading operations an aluminum fuel-guide tube, 200 cm ($78\frac{3}{4}$ in.) long and contoured to the shape of a fuel assembly, is used to position the fuel assemblies in the fuel grid correctly. The stepped tube or liner is inserted into the fuel port before the coffin is positioned. A flange of 23-cm (9-in.) diameter on top of the liner fits into the recess around the fuel port and supports the liner. If the liner is improperly lined up with the reactor core, the liner cannot be fully inserted.

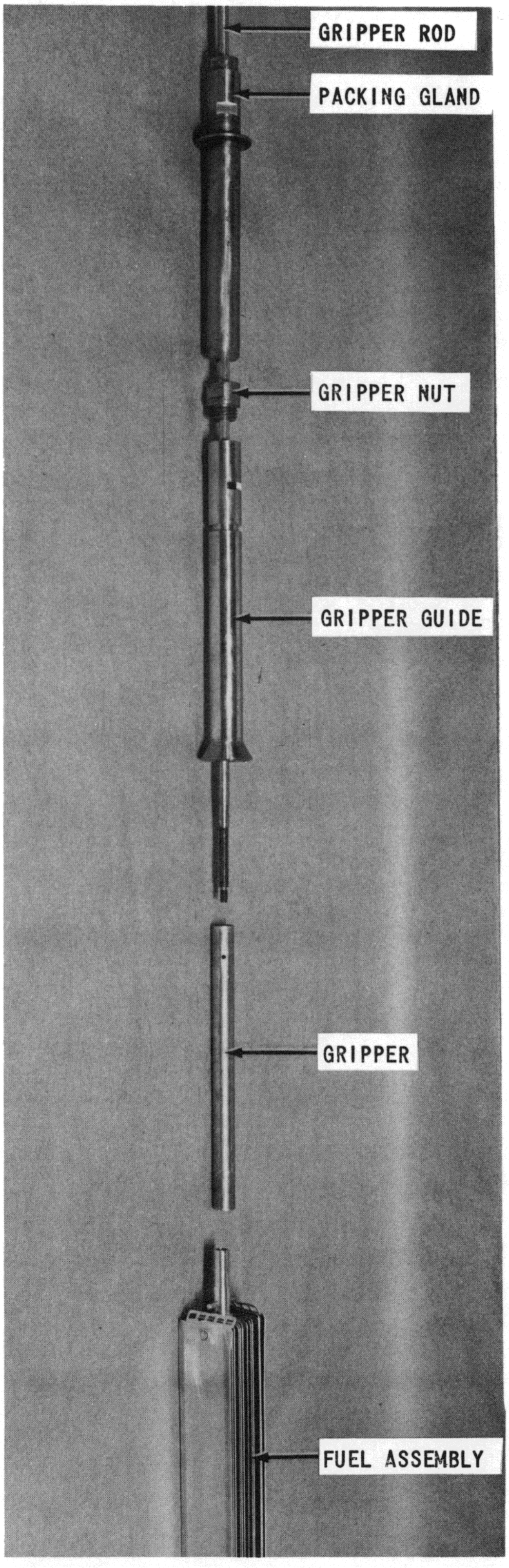


Fig. 59. Fuel Gripper Tool

During fuel-unloading operations the coffin is placed over the rotating shield, and an adapter on the bottom of the coffin is fitted into the recessed fuel port with or without the fuel-guide tube. The adapter in the recess acts as a stepped shield. The sliding door is opened and the fuel-gripper tool is lowered into the reactor and screwed onto the end fitting of the fuel assembly to be removed. The gripper is then raised, lifting the fuel assembly into the coffin. The sliding door is closed and locked. The gripper tool is disengaged from the assembly and replaced with a short end-threaded rod equipped with a wire rope. The coffin is then transported to the spent-fuel storage pit (see Fig. 60) where the fuel assembly is stored with the wire rope attached for future retrieving.

2. Storage Pit

Active fuel assemblies are stored in stainless steel tubes, 13.3 cm ($5\frac{1}{4}$ in.) in diameter, buried 3 m (10 ft) underground. Twenty-five of these tubes penetrate the floor in the southeast corner of the reactor room, and they constitute the storage pit (see Fig. 60). Each tube hole contains a shield plug and is counter sunk to provide a cavity which accommodates the coffin adapter, thus aligning the coffin over the hole. When a fuel assembly is lowered into a storage tube, the loose end of the wire rope (the other end is attached to the end-threaded rod and the fuel assembly) is secured to the bottom of the shield plug to be inserted in that hole. The entire storage area is covered with a sheet of steel to keep out dust and dirt.

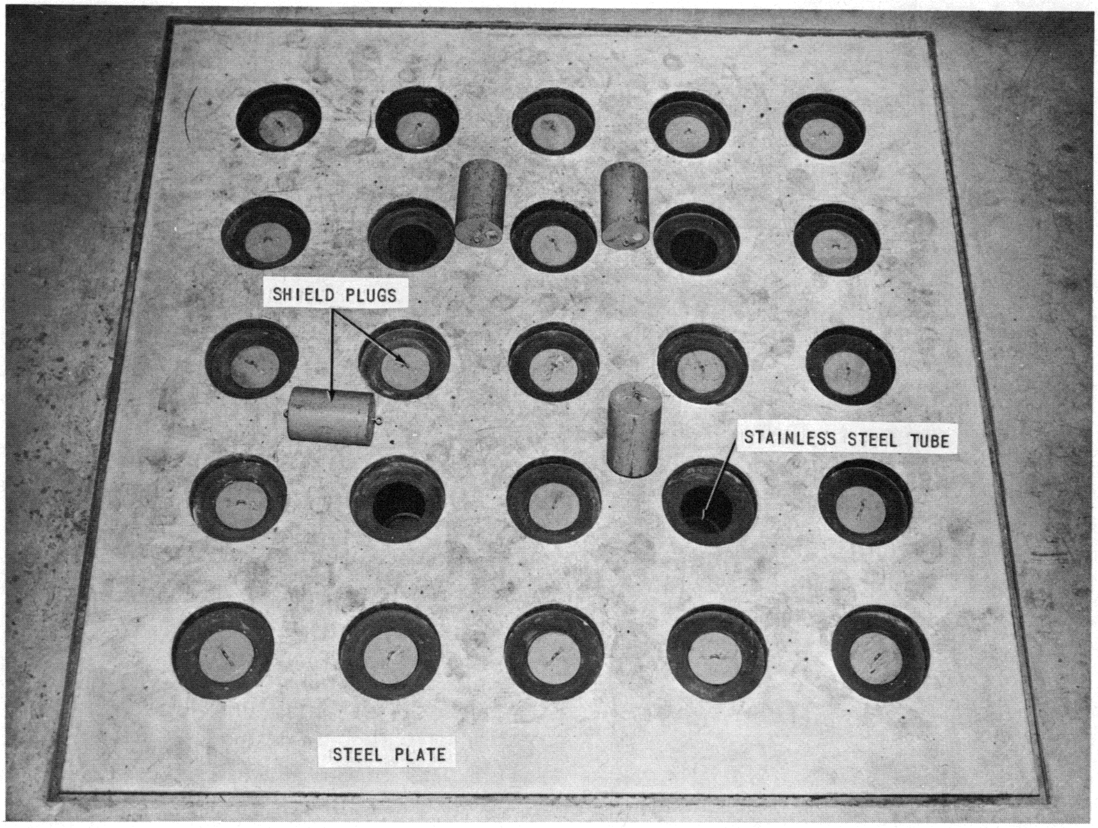


Fig. 60. Spent Fuel Storage Pit

3. Storage Holes

There are four storage holes, each 15 cm (6 in.) in ID, in the monolithic concrete shield. These storage holes, accessible from the top of the reactor, are to be used as temporary storage space for low-level radioactive materials removed from the reactor. Spent fuel will not be stored in these holes.

IV. COST ANALYSIS

The costs, including construction, fabrication, and assembly, for the reactor components as described in this report are listed as follows:

Internal Thermal Column			
Aluminum Container	$ 760.00		
Graphite	1,800.00		
Total Equipment		$ 2,560.00	
Drafting		782.00	
			$ 3,342.00
Core			
Fuel Plates (5.7 kg U^{235})	$10,000.00		
Shop Work	1,373.00		
Total Equipment		$11,373.00	
Drafting		732.00	
			$ 12,105.00
Fuel-assembly Grid			
Grid	$ 903.00		
Total Equipment		$ 903.00	
Drafting		525.00	
			$ 1,428.00
Reactor Vessel			
Vessel	$ 1,675.00		
Total Equipment		$ 1,675.00	
Drafting		200.00	
			$ 1,875.00
Core Reflector			
Graphite (Machined)	$ 2,600.00		
Total Equipment		$ 2,600.00	
Drafting		500.00	
			$ 3,100.00
Lead Thermal Shield			
Shield	$ 1,960.00		
Base	136.00		
Total Equipment		$ 2,096.00	
Drafting		300.00	
			$ 2,396.00
Cooling Systems			
Byron Jackson Cast Iron Pumps (100 gpm)	$ 554.00		
Byron Jackson Stainless Steel Pumps (125 gpm)	1,332.00		
Pipe Fittings	1,940.00		
Gaskets	155.00		

Cooling Systems (Cont'd.)			
Pipe	$ 216.00		
Valves (Ball and Check)	975.00		
Throttle Valves	1,276.00		
Strainers	233.00		
Solenoid Valves	372.00		
Brooks Flow Indicators	380.00		
Fisher and Porter Orifice Flow Meter	500.00		
Cooling Tower	1,275.00		
Temperature Recorder	1,018.00		
Pipe Shielding	537.00		
Helium Gasometer	1,045.00		
Ion-exchange Unit	800.00		
Dump-Storage Tank	600.00		
Eastern Industries Pumps	406.00		
Heat Exchanger	726.00		
Dump Valve	775.00		
Total Equipment		$15,115.00	
Drafting		2,651.00	
Pre-assembly		3,806.00	
			$ 21,572.00
Source			
Source Assembly	$ 1,488.00		
Total Equipment		$ 1,488.00	
Drafting		339.00	
			$ 1,827.00
Control Rods			
Motors	$ 1,065.00		
Gears	73.00		
Bearings	66.00		
Boron Steel	403.00		
Fabrication	5,806.00		
Total Equipment		$ 7,413.00	
Drafting		2,613.00	
			$ 10,026.00

Control Console and Instrumentation			
Cubical	$26,565.00		
Electrical Work	3,405.00		
Various Items	9,073.00		
Total Equipment		$39,043.00	
Drafting		1,823.00	
			$ 40,866.00
Thermal Columns			
Graphite (Machined)	$18,500.00		
Total Equipment		$18,500.00	
Drafting		682.00	
			$ 19,182.00
Test Facilities			
Graphite	$ 4,100.00		
Total Equipment		$ 4,100.00	
Drafting		330.00	
			$ 4,430.00
Horizontal Beam Holes			
Motors and Jacks	$ 1,666.00		
Four Beam Holes	7,206.00		
Four Gates	2,663.00		
Total Equipment		$11,535.00	
Drafting		1,873.00	
			$ 13,408.00
Steel Forms and Encasements			
Motors and Jacks	$ 866.00		
Boral Sheets	560.00		
East and West T.C. Encasements and Vertical Forms plus Gates	7,300.00		
Test Facilities and 1.5 m^2 (5 ft^2)	2,326.00		
Total Equipment		$11,052.00	
Drafting		2,569.00	
			$ 13,621.00

Monolithic and Block Shielding			
Monolithic Concrete Including Electrical Work	$25,943.00		
Steel Structure	1,946.00		
Block Shielding	9,641.00		
Total Equipment		$37,530.00	
Drafting		7,746.00	
			$ 45,276.00
Top Removable Shield			
Steel Forming	$ 7,248.00		
Concrete and Lead	1,485.00		
Total Equipment		$ 8,733.00	
Drafting		2,903.00	
			$ 11,636.00
Rotating Shield			
Steel Form	$13,454.00		
Bearing	514.00		
Concrete and Lead	635.00		
Total Equipment		$14,603.00	
Drafting		2,223.00	
			$ 16,826.00
Surface Finishing			
Steel Work	$ 735.00		
		$ 735.00	
Painting		500.00	
			$ 1,235.00
Fuel and Source Coffin			
Coffin and Fuel Gripper	$ 4,454.00		
Total Equipment		$ 4,454.00	
Drafting		990.00	
			$ 5,444.00

Storage Pit (Installed with Building)			
Material	$ 1,435.00		
Shop Work	1,393.00		
Total Equipment		$ 2,828.00	
Drafting		632.00	
			$ 3,460.00
Installation (Total)			13,586.00
Miscellaneous (Total)			7,286.00
	TOTAL		$257,721.00

APPENDIX A

OPTIMIZATION OF THE INTERNAL THERMAL COLUMN FOR THE HIGHEST THERMAL-NEUTRON FLUX

Two-group theory can be used to obtain that radius of the internal thermal column which will give the highest thermal-neutron flux at the center of the column for an idealized cylindrical-shell reactor. The fuel shell is assumed to be of infinitesimal thickness, but is considered to be black to thermal neutrons. An infinite reflector region of the same material as the internal column surrounds the shell.

There are two reasonable methods of normalizing the neutron flux at the center of the internal column. Normalization to one fission neutron emitted per centimeter of shell length per second would correspond to a constant-power condition for a given shell length as the radius is varied. Normalization to one fission neutron emitted per cm square of shell area per second corresponds to a constant power density. The optimum radius depends strongly upon the method of normalization. For a reactor in which the power is the limiting criterion, such as JUGGERNAUT, the first method is correct. For reactors with higher performance, in which the power density is the limiting criterion, the second method would be correct.

The two-group diffusion equation for the internal column (Region I) and the reflector (Region II) are given below with certain of the boundary conditions on the flux in each region.

Region I

$$-D_1 \nabla^2 \phi_1 + \Sigma_1 \phi_1 = 0 \quad ; \quad \left.\frac{d\phi_1}{dr}\right]_{r=0} = 0$$

$$-D_2 \nabla^2 \phi_2 + \Sigma_a \phi_2 = \Sigma_1 \phi_1 \quad ; \quad \left.\frac{d\phi_2}{dr}\right]_{r=0} = 0$$

Region II

$$-D_1 \nabla^2 \phi_1 + \Sigma_1 \phi_1 = 0 \quad ; \quad r \xrightarrow{\lim} \infty\, \phi_1 = 0$$

$$-D_2 \nabla^2 \phi_2 + \Sigma_a \phi_2 = \Sigma_1 \quad ; \quad r \xrightarrow{\lim} \infty\, \phi_2 = 0$$

where

D_1 = fast diffusion coefficient
Σ_1 = slowing-down cross section
D_2 = thermal diffusion coefficient
Σ_a = thermal-absorption cross section

Solving the set of equations above, we obtain

$$\phi_1^{I} = AI_0(\kappa_1 r)$$

$$\phi_2^{I} = CI_0(\kappa_2 r) + SAI_0(\kappa_1 r)$$

$$\phi_1^{II} = BK_0(\kappa_1 r)$$

$$\phi_2^{II} = FK_0(\kappa_2 r) + SBK_0(\kappa_1 r)$$

where

$$S = \frac{\Sigma_1}{D_2} \frac{1}{\kappa_2^2 - \kappa_1^2} \quad ;$$

$$\kappa_1^2 = \frac{\Sigma_1}{D_1} \quad ;$$

$$\kappa_2^2 = \frac{\Sigma_a}{D_2} \quad .$$

Boundary conditions must now be used to obtain the four unknowns in the set of equations above.

1. Normalization

a. The total number of neutrons from the shell is 1/(cm)(sec).

$$2\pi r_0 D_1 \left. \frac{\partial \phi_1^{I}}{\partial r} \right]_{r=r_0} - 2\pi r_0 D_1 \left. \frac{\partial \phi_1^{II}}{\partial r} \right]_{r=r_0} = 1 \quad .$$

b. Current density of neutrons from the shell is 1/(cm^2)(sec).

$$D_1 \left. \frac{\partial \phi_1^{I}}{\partial r} \right]_{r=r_0} - D_1 \left. \frac{\partial \phi_1^{II}}{\partial r} \right]_{r=r_0} = 1 \quad .$$

2. $\phi_1^{I}(r_0) = \phi_1^{II}(r_0)$.

Therefore,

$$AI_0(\kappa_1 r_0) = BK_0(\kappa_1 r_0) \quad .$$

3. Black boundary condition for both Regions I and II at the fuel shell.

Region I

$$- D_2 \left. \frac{\partial \phi_2^{I}}{\partial r} \middle/ \phi_2 \right]_{r=r_0} = 0.469$$

Region II

$$- D_2 \left. \frac{\partial \phi_2^{II}}{\partial r} \middle/ \phi_2 \right]_{r=r_0} = 0.469 \quad .$$

The curvature of the shell has been neglected in the black boundary condition. Four conditions are now available which enable us to solve for the four unknowns. Two other conditions are rejected as not valid or not necessary:

(1) Thermal fluxes are equal at the shell. This is not a valid condition, since the thermal fluxes in the two regions are independent because of the black boundary separating the regions.

(2) A criticality condition is not necessary since the flux shape is independent of this condition. Therefore, this condition would determine only the necessary multiplication properties of the fuel shell to obtain criticality.

Solving for the thermal flux in Region I at $r = 0$, we obtain

$$\phi_2^{I}(0) = \left(\frac{\Sigma_1}{D_2} \, \frac{1}{\kappa_1^2 - \kappa_2^2} \right) \frac{\left[\dfrac{D_2 \kappa_1 I_1(\kappa_1 r_0) + 0.469\, I_0(\kappa_1 r_0)}{D_2 \kappa_2 I_1(\kappa_2 r_0) + 0.469\, I_0(\kappa_1 r_0)} - 1 \right]}{2\pi r_0 D_1 \kappa_1 \left[I_1(\kappa_1 r_0) + \dfrac{I_0(\kappa_1 r_0)}{K_0(\kappa_1 r_0)} K_1(\kappa_1 r_0) \right]}$$

The factor $2\pi r_0$ in the denominator exists because of normalization to 1 n/(cm)(sec) from the shell. If normalization to 1 n/(cm^2)(sec) is used instead, the factor is replaced by the number 1.

In order to solve the above equation for the r_0 at which a maximum thermal flux is reached, $\phi_2^{I}(0)$ is differentiated with respect to r_0 and the resulting expression is equated to zero. The solution is straightforward.

Implicit in the previous solution is the assumption of an infinite cylinder. If a finite cylinder is assumed, two changes are evident: first,

κ_1^2 and κ_2^2 change, since the effect of the finiteness of the cylinder must be included by adding a term $D_i B_z^2$ to the absorption in both the thermal and fast groups. Hence,

$$\kappa_1^2 = \frac{\Sigma_1}{D_1} + B_z^2$$

$$\kappa_2^2 = \frac{\Sigma_a}{D_2} + B_z^2 \quad .$$

Secondly, the magnitude of the normalization factor is also affected; however, this does not change the solution.

Figure A-1 is a plot of δ vs r_0, where δ is proportional to $[d\phi_2^I(0)]/dr_0$. The r_0 for which δ becomes zero, under the given assumptions, is the optimum radius for maximum thermal-neutron flux. Since the JUGGERNAUT core is 60 cm in length and is power limited, the optimum internal thermal column radius would seem to be $1.03\sqrt{\tau}$ or 19.5 cm.

Although this is a good approximation, the finite thickness of the fuel shell must also be taken into account. This was achieved by solving several two-group three-region calculations in which a thin shell of water of varying thickness was inserted between the internal graphite column and the fuel shell. An optimum internal column radius was obtained for each thickness of water shell. The optimum radius for an H_2O internal thermal column was then compared with experimental data.[3] This comparison revealed that the effect of a 7-cm-thick Al-H_2O core could be accounted for by assuming a 1.4-cm-thick shell of H_2O between the internal column and the infinitesimal fuel shell. It was also found that for this shell thickness the optimum radius of a graphite internal column is approximately 15 cm (6 in.).

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[3] S. M. Feinberg *et al.*, *An Intermediate Reactor for Obtaining High Intensity Neutron Fluxes*, *Proceedings of the Second Geneva Conference on Peaceful Uses of Atomic Energy*, Geneva, Switzerland, *10*, 296 (1958).

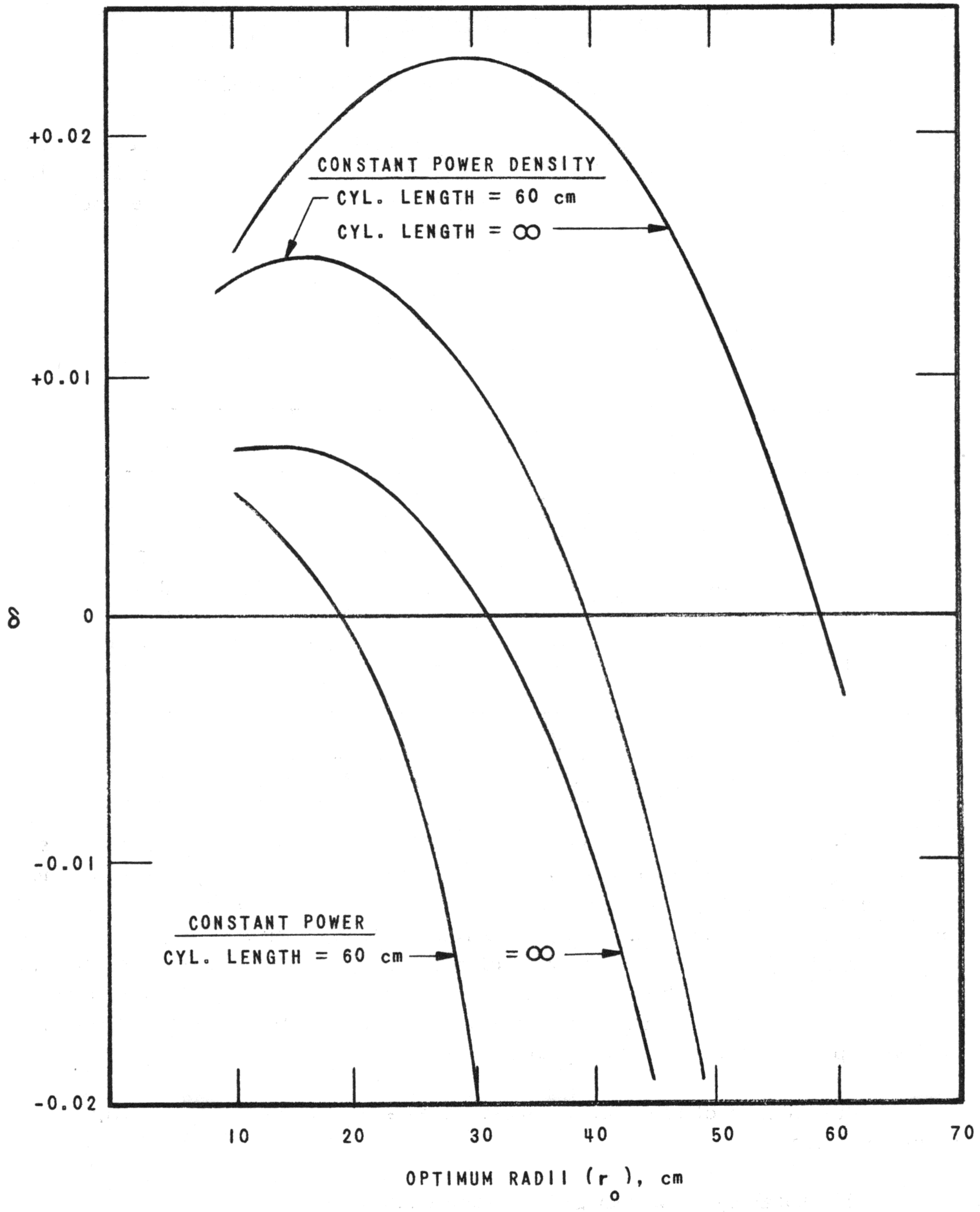

Fig. A-1. Optimum Internal Thermal Column Radii

APPENDIX B

REACTIVITY AND CONTROL REQUIREMENTS

The requirements of excess reactivity for JUGGERNAUT for two years of operation as a function of operating power are listed in Table B-I. Also included are the total requirements for operation during periods of one year and of three months.

Table B-I

EXCESS REACTIVITY REQUIREMENTS
(% Δk)

Operating Power (kw):	250	200	150	100
Experimental Apparatus (includes beam holes)	2.1	2.1	2.1	2.1
Xenon Poisoning	0.7	0.5	0.4	0.2
Samarium Poisoning	1.0	1.0	0.9	0.8
Temperature Rise	0.5	0.4	0.3	0.2
U^{235} Burnup	1.2	1.0	0.7	0.5
Two-year Totals	5.5	5.0	4.6	4.0
One-year Totals Only	4.5	4.1	3.7	3.3
Three-month Totals Only	3.7	3.3	3.1	2.8

Since the beam holes will remain open initially except for necessary shielding, the required shim system worth is 0.9% Δk less than the totals shown in Table B-I for any particular time and power level. To operate for two years at 250 kw (0.55 load factor) with no refueling would require an initial excess reactivity of 5.5% Δk and, therefore, a shim system worth 4.6% Δk. The total worth of the three-rod shim system has been calculated to be in the range from 3.2 to 3.9% Δk. The addition of fuel will probably be necessary once a year.

The design of the control system was based on the following requirements:

(1) total shim worth greater than 4.0% Δk;

(2) cold shutdown margin of approximately 3.0% Δk with water in the core;

(3) single rod worth no more than $2.0; and

(4) four-rod shutdown at any time.

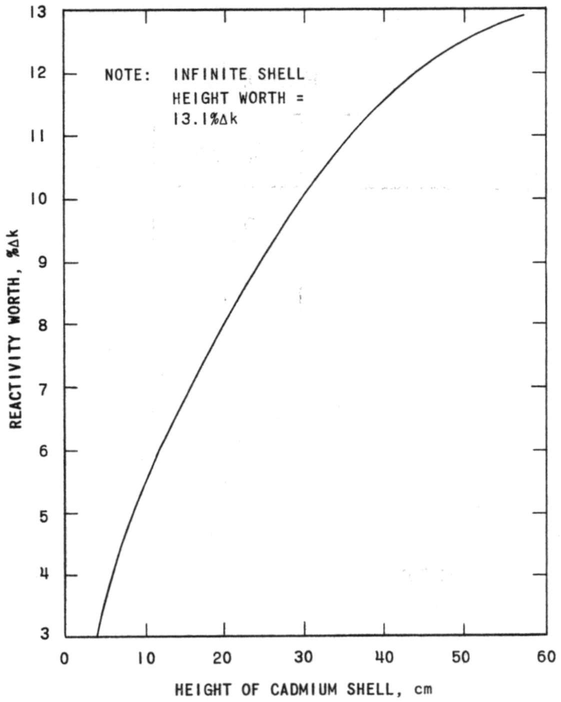

Fig. B-1. Worth of Cylindrical Cd Shell Versus Shell Height

In order to determine the individual worth of each control plate as a function of its length and width, a series of PDQ problems in R-O and X-Y geometry was analyzed. The control-element material was assumed to be black to thermal neutrons in each problem. Experiments with the ARGONAUT have indicated that the worth of 2 wt-% natural boron in steel plate of 0.108-in. thickness is 5% less than the worth of cadmium (40 mils thick).

The calculated worths of a complete cylindrical shell and of single plates as a function of height are shown in Figs. B-1 and B-2, respectively. These calculations were further analyzed to obtain the worth of the off-center and inclined type of plate used in the reactor. The results were then corrected by taking into account flux perturbations from beam tubes, control rod gaps, and the Al-H_2O shell surrounding the core. The final values for control rod worths are given in Table B-II.

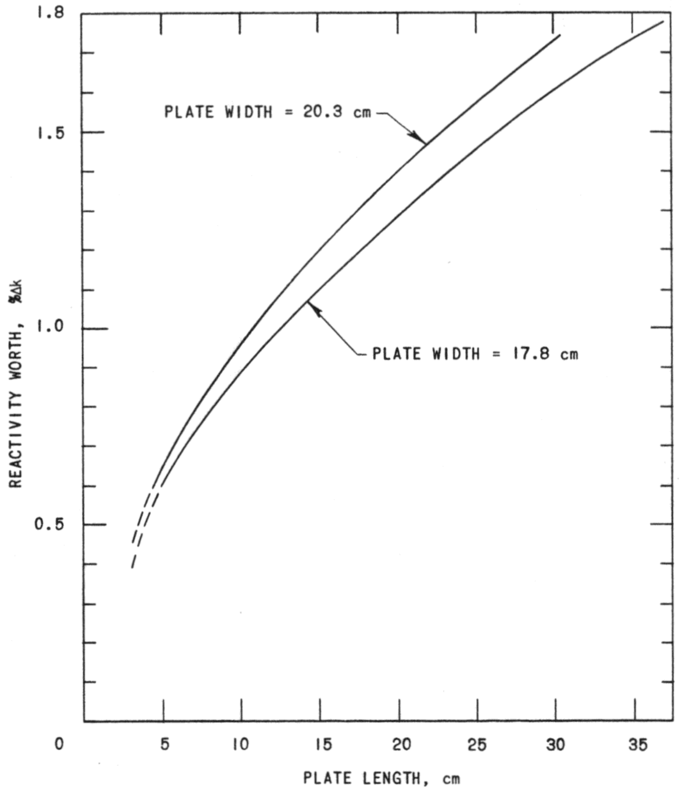

Fig. B-2

Worth of Single Cd Plate Versus Plate Length

Table B-II

CALCULATED WORTH OF CONTROL RODS

Control Rod(s)	% Δk
Fine Control Rod	0.15
Safety Rod No. 1 or No. 4	1.1
Safety Rod No. 2 or No. 3	0.9
Each Shim Rod	1.2
Combined Worth of Shim Rods	3.5
Combined Worth of Shim and Safety Rods	7.0

After ten years, the shim rods will have suffered a total atom transformation of only 0.3%, but a B^{10} burnup of 15%. This B^{10} depletion will lead to a 3-to-4% reduction in the total control system worth, or -0.3%Δk. Replacement of the rods may be necessary at this time even if their mechanical properties are unimpaired.

APPENDIX C

BIOLOGICAL-SHIELDING DESIGN CALCULATIONS

Two-group shielding calculations were made to determine the neutron and gamma fluxes penetrating (a) the top shield; (b) the thermal columns; (c) the cave facility; and (d) the concrete shield, assuming the existence of a power level of 250 kw. Other calculations were made to determine the plug and gate shielding requirements for the beam tubes, and the type and amount of shielding needed above the control drive mechanisms.

The first step of each computation was the determination of the neutron distribution throughout a hypothetical shield. The assumed shield was similar to that of the ARGONAUT reactor but increased in density and thickness. A modified one-group approach was used to obtain the distribution of thermal neutrons in the shield. In this model, the fast (uncollided) flux distribution is found by integrating a point kernel over the source volume, and then making use of the removal-cross-section concept to obtain the attenuation of the fast flux by the biological shield. The thermal-neutron flux is obtained from a one-group diffusion approximation with the source term defined to be the loss from the fast-neutron group. The form of the diffusion equation is

$$D_s V^2 \phi_s(x) - \Sigma_a \phi_s(x) + \Sigma_r \phi_f(x) = 0 \quad .$$

If it is assumed there is a single exponential form for the fast neutron flux $\phi_f(x)$ in each region, the thermal-neutron flux in slab geometry is obtained as a sum of exponentials.

The calculation of the prompt fission product and the equilibrium fission product gamma-ray-flux distributions was accomplished in much the same manner as for the uncollided neutron flux, except that the total gamma-attenuation coefficient replaced the removal cross section and an appropriate buildup factor was used.

The problem of determining the gamma-ray-flux distribution due to capture gamma rays was approached by assuming the shield to be effectively broken into regions containing only one material, in which the thermal flux can be represented by a sum of exponentials. The kernel approach was used with appropriate attenuation coefficients and buildup factors to obtain the gamma flux at the outside of each region. The gamma flux at the outside of each of these regions was then treated as a plane source to be attenuated through the remainder of the shield.

The distribution in gamma-ray energy was taken into account by approximating the true energy spectrum by discrete energy groups. From the gamma distributions, heating and temperature distributions through the shield were obtained.

The initial results indicated that more shielding was needed; this was added in the form of a lead thermal shield and by increasing the density of some of the shielding blocks.

The gamma-ray fluxes predicted outside of the biological shield are listed in Table C-I. The dose rate due to the neutron flux is negligible in all cases.

Table C-I

GAMMA-RAY FLUXES AT THE OUTSIDE OF THE BIOLOGICAL SHIELD ON THE CORE CENTERLINE

Direction	Source	E (Mev)	$\phi\sigma$ (Mv/hr)
Thermal Column	Graphite Capture	5	4.63
	Core Gamma Rays	6	0.81
	Other	-	0.02
	Total		5.46
Top of Reactor	Concrete Capture	8	0.211
	Concrete Capture	6	0.190
	Concrete Capture	4	0.055
	Al and Fe Capture	8	0.020
	Al and Fe Capture	6	0.028
	Other	-	0.075
	Total		0.579
220 Concrete Shield	Concrete Capture	8	0.115
	Concrete Capture	6	0.028
	Concrete Capture	4	0.006
	Reflector Capture	5	0.006
	Other	-	nil
	Total		0.155
Cave Facility	Concrete Capture	8	~1.1
	Concrete Capture	6	~1.1
	Concrete Capture	4	~0.2
	Reflector	5	~0.1
	Other	-	nil
	Total		~2.5

The calculated temperature distributions in the thermal column, the top shield, and the concrete shield are shown in Figs. C-1, C-2, and C-3 respectively.

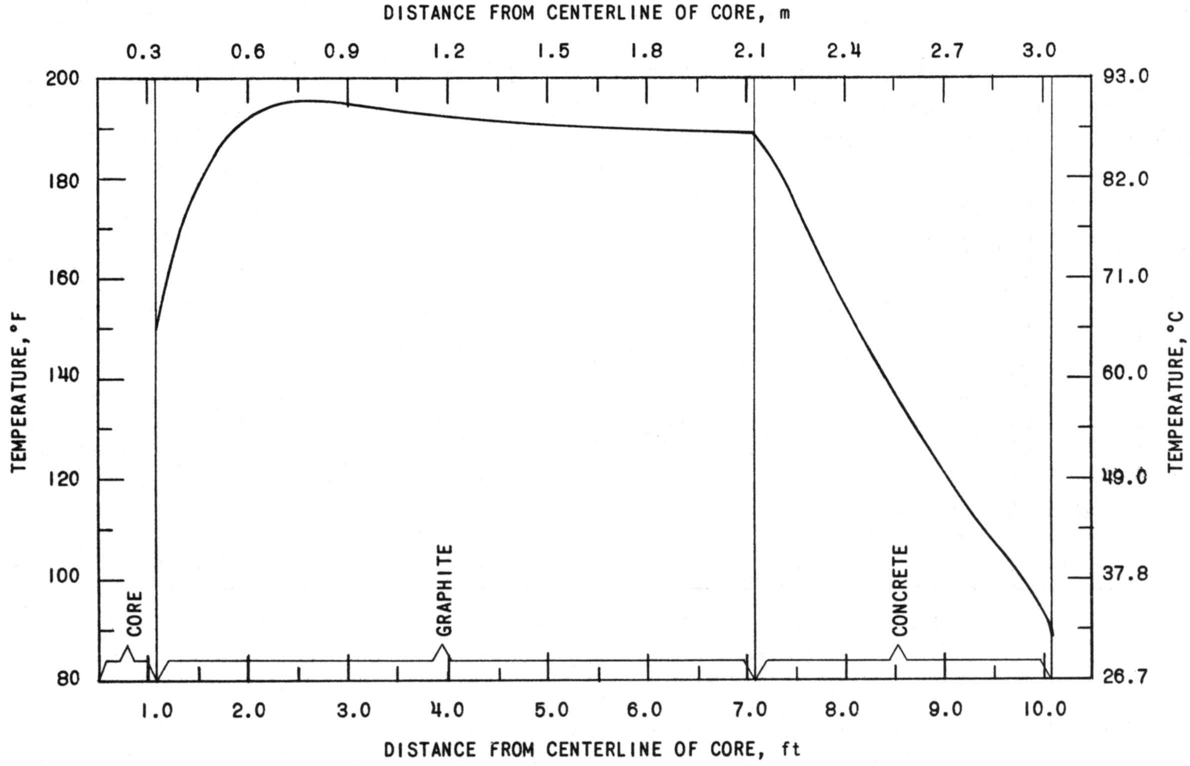

Fig. C-1. Temperature Distribution in Thermal Column

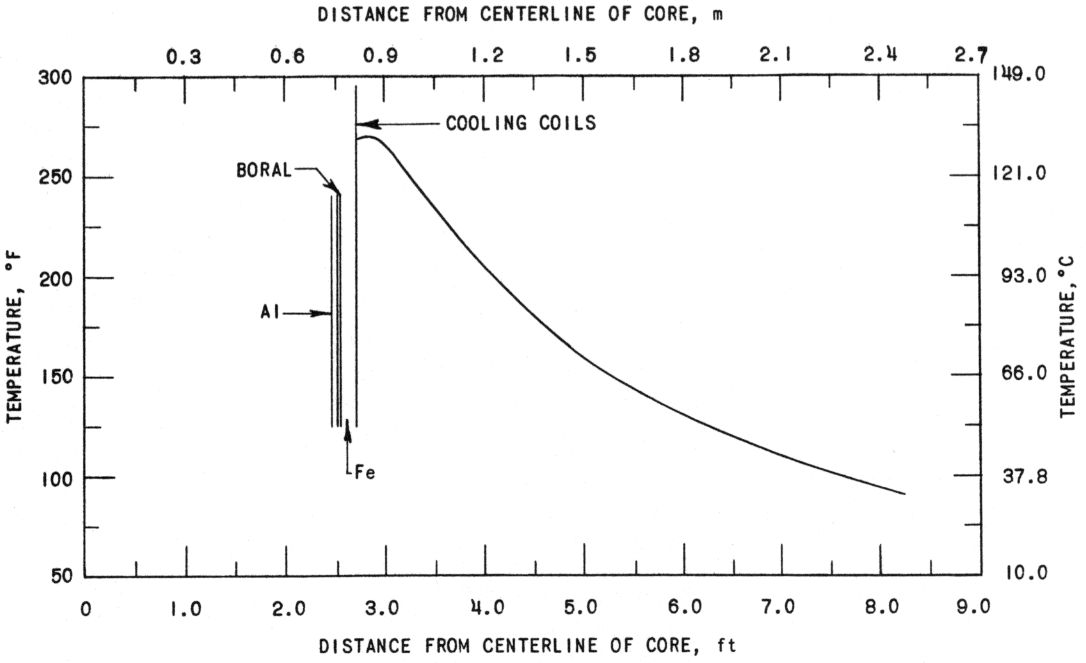

Fig. C-2. Temperature Distribution in Top Shield

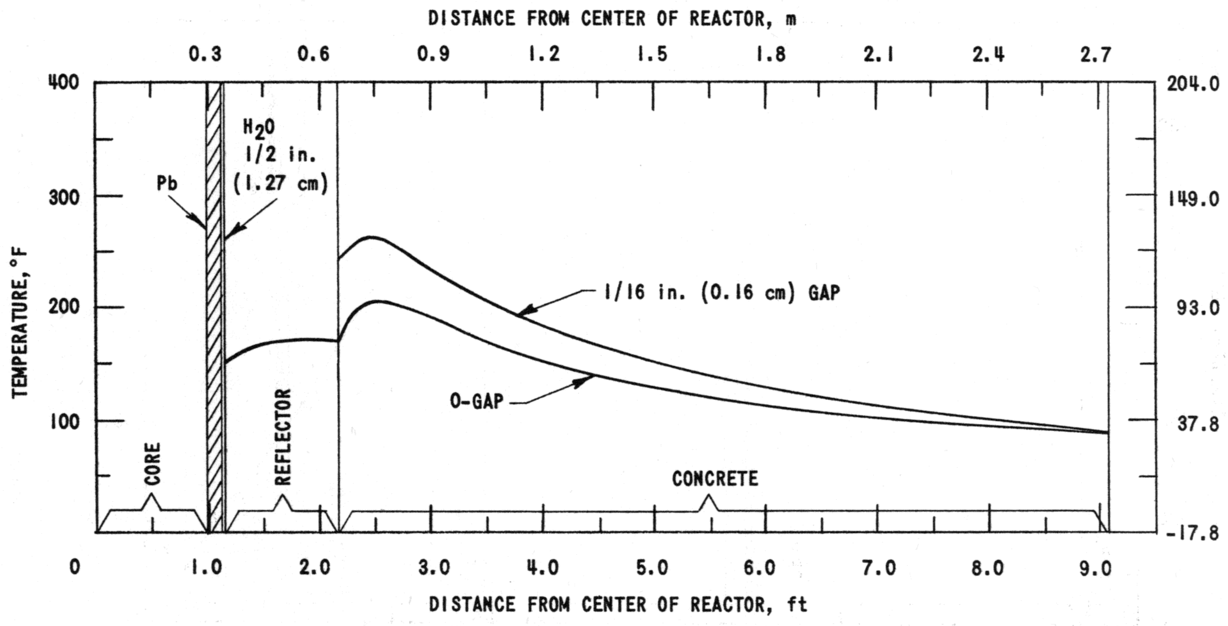

Fig. C-3. Temperature Distribution in 220-lb/ft^3 Concrete Shield with 2-in. Lead Gamma Shield

APPENDIX D

HEAT TRANSFER CALCULATIONS

Core - Steady State

Assumptions

Maximum total power	250 kw
Number of fuel plates in core	240
Flow rate	7.9 liters/sec (125 gpm)
Axial maximum/average flux ratio	1.3
Hot spot factor	1.5
Water-inlet temperature	32°C (90°F)

Using the above assumptions and the appropriate core dimensions, the following core characteristics were calculated:

h_c (heat transfer coefficient)	$0.114\ w/(cm^2)(°C)$
Average heat flux	$1.37\ w/(cm^2)$
Bulk-fluid temperature rise	8°C
Maximum Δt between fuel-plate surface and coolant	25°C
Maximum Δt between fuel-plate surface and inlet	35°C

The power output would have to be more than doubled before local boiling would occur at the hottest spot in the core. Even if the plates were to warp so that heat was to be removed from only one surface, no local boiling would occur.

Removal of Core Decay Heat

Emergency shutdown of the reactor can be effected by rapid drainage of the moderator-reflector-coolant water from the core to the dump-storage tank. The decay heat from the core will then be removed by the combined process of (1) natural convection of the helium (or air) atmosphere; (2) conduction through the helium into the graphite reflector; and (3) radiative transfer from the core to the reactor vessel wall and thence to the graphite reflector. Calculations have indicated that under normal conditions the core temperature will never rise above 200°C after removal of the coolant. Conservative calculations,[4] in which heat transfer by radiation only was assumed, indicate that the maximum possible core temperature is 450°C (assuming 24-hr/day operation at 250 kw).

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[4] J. R. Folkrod, D. P. Moon and J. K. Saluja, Hazards Summary Report on the JUGGERNAUT Reactor, ANL-6192 (Feb 1961) Appendix A.

Temperature of Control Rods

During full-power (250-kw) operation, the maximum temperature of a control rod will be 300°C. This estimate is based on a conservative calculation which considered the internal heat generation resulting from the capture of gamma rays and neutrons, and heat removal by conduction through air gaps and graphite to coolant water in the core and in the thermal shield.

The linear coefficient of expansion of steel is 12×10^{-6} cm/(cm)(°C) and that of aluminum is 27×10^{-6} cm/(cm)(°C). At 20°C the clearance between a steel control blade and its aluminum sheath is 0.16 cm on each of the four sides. If it is assumed that the control blade heats up to 300°C and the aluminum does not expand, the clearance at the blade edges is reduced to 0.13 cm. All other clearances remain the same. The melting point of the rods is above 1400°C.