ANL-6408 ANL-640

Argonne National Laboratory

HAZARD EVALUATION REPORT ON THE FAST REACTOR ZERO POWER EXPERIMENT ZPR-III

by

R. O. Brittan, B. Cerutti,
H. V. Lichtenberger, J. K. Long,
R. L. McVean, M. Novick,
R. Rice, and F. W. Thalgott

Robert - Thalgott

LEGAL NOTICE

ANL-6408
Reactor Technology
(TID-4500, 16th Ed.,
Amended)
AEC Research and
Development Report

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois

HAZARD EVALUATION REPORT ON THE FAST REACTOR ZERO POWER EXPERIMENT (ZPR-III)

by

J. K. Long, R. L. McVean, F. W. Thalgott, and M. Novick

October 1961

Operated by The University of Chicago
under
Contract W-31-109-eng-38

ACKNOWLEDGEMENT

This report is a revision of ANL-FWT-105 by R. O. Brittan, B. Cerutti, H. V. Lichtenberger, R. E. Rice, and F. W. Thalgott (April 1955). In the original report the authors acknowledged the direct contributions of data and information by the following people:

H. A. Bethe	H. I. Kraig
R. A. Cameron	W. B. Loewenstein
M. Grotenhuis	D. Okrent
R. O. Haroldsen	H. J. Wheeler

TABLE OF CONTENTS

LIST OF FIGURES

HAZARD EVALUATION REPORT ON THE FAST REACTOR ZERO POWER EXPERIMENT (ZPR-III)

by

J. K. Long, R. L. McVean, F. W. Thalgott, and M. Novick

SUMMARY

The fast zero power reactor experiment (ZPR-III) is planned to obtain neutron physics information necessary for the design of fast power breeder reactors. Although provisions for handling plutonium have been included in preparing the facility, this report deals only with the phase of the program in which U^{235} is used.

The systems to be studied are blanketed cores having a range of compositions in which the volume fractions of U^{235}, U^{238}, Fe and Na (simulated by reduced-density Al) are varied.

This is accomplished by assembly of small pieces in drawers which are placed in an array of square tubes mounted on two carriages so that two half-critical sections initially separated may be brought together in a carefully controlled manner.

The reaction is controlled by inserting or removing drawers from the back of each half with drives which are continually activated for scram under air pressure. Five control-safety drawers are associated with each half and may operate either in the core or blanket.

Each half is protected by a strong Po-Be source which must be in to operate. The assembly is protected against excessive power level or rate of rise by neutron and gamma monitoring circuits. Protection against accident or damage is afforded by physical limitations on the speed of motion of the halves of the machine, and the control rods. Reactivity changes are limited to rates of insertion of 0.05% dk/k per second. Further protection is provided by interlocks which prevent or curtail operation if:

1) neutron level is below a prescribed range on the monitor (source out)
2) the required number of monitor circuits are not working
3) the air pressure to the control-safety rods is below the prescribed limit
4) the air lock door is open
5) the personnel counter is not at zero

6) the gap between halves is less than maximum

7) two control-safety rods are not out

8) eight control-safety rods are not in

9) the atmospheric pressure in the assembly room is not sufficiently below ambient

10) both key locks are not open

11) the loading platform is not removed.

Some things cannot be physically restricted. Management of the fissionable material, of operations, and of access has been planned to restrict action of personnel which might lead to damage of the facility. A rather complex method of fissionable material management is necessary because enough U^{235} for several minimum critical masses is available. Each constituent material of a loading is differentiated by color from every other constituent, and so stacked to permit visual check on the loading. The operations are managed to command control of interlock overrides which are necessary for maintenance and component checking. Access is restricted to reduce probability of sabotage and protect experimenters from annoyance during crucial periods of operation.

This experiment has the following characteristics which govern the severity of an excursion. 1) The U^{235} pieces are out of thermal contact with other materials in fast transients. 2) Only axial expansion of the U^{235} causes a reduction in reactivity initially. 3) The use of low density aluminum introduces a large void fraction which must be filled before volumetric expansion can be taken advantage of. 4) The inertia of blanket material acts as a tamper inhibiting expansion after vaporization in fast transients. 5) There is no surrounding shield mass to absorb the energy release in an excursion. 6) The neutrons have a short lifetime. 7) There are no physical restrictions on concentration of U^{235} other than the total amount available. 8) The assemblies have no inherent means of reducing reactivity other than by expansion coupled with small reactivity coefficients. 9) Assemblies are autocatalytic if a net positive prompt temperature coefficient exists or a central void is available.

As a first step in reducing the recognized hazards, the experiment has been located at NRTS.

Secondly, the design and management have been arranged in such a way that if there is no malfunction of safety mechanisms, no damaging excursion can occur. Properly operating safety rods protect against any feasible rate of addition of reactivity made mechanically. ($<\$50/\text{sec}$)

In the unlikely event that the safety mechanisms do not operate, it may be possible to have excursions resulting in a temperature rise of as much as several hundred degrees. If this is further coupled with the presence of an unpredictably large positive Doppler coefficient ($50 \times 10^{-6}/°C$ dk/dT as opposed to a calculated $4 \times 10^{-6}/°C$ dk/dT, the latter being less than the expansion coefficient) or with assembly through mismanagement or sabotage of a supercritical core with an empty central matrix element, the consequences could be more severe. By pessimistic postulation the resulting excursion might result in violent disassembly and even destruction of the building.

For such an improbable case it is postulated that the safety rods fail to operate, allowing the power level to rise until sensible heating begins. The U^{235} expands axially, but a Doppler effect or later expansion into a central void yields a net positive change in reactivity, so that the reactivity is above prompt critical. Axial expansion continues, but melting of the U^{235} without heat transfer occurs before reactivity is noticeably reduced. Further shutdown cannot occur before the U^{235} has vaporized to fill the voids, then presses against the blanket as the core tries to expand. The energy release is so rapid that the blanket inertia inhibits the expansion, and shutdown does not occur until several e-fold times after initial vaporization of the U^{235}. This tamping effect enhances the severity by a factor of 10 over that for a bare core. There is no bulk shielding material to absorb the energy release and blanket sections move with high velocity. Vaporized U^{235} will burn in the air, causing a chemical energy release equal to the nuclear energy release. The integrity of the building is destroyed by missile penetration and gross overpressures resulting from heating of the air in the room.

If one considers such an unlikely accident possible, one makes the following estimates of upper limits on severity:

10^{20} fissions occur during burst.

8×10^8 cal of nuclear energy are released.

3×10^8 cal of chemical energy are released.

1500 ft/sec velocity of blanket pieces is realized.

~3000 ft exclusion radius is necessary for 300 roentgens.

The usual operating level will be less than a few watts. It may be necessary to operate at one kilowatt. Operation will be planned so that no undue exposure of personnel ensues.

INTRODUCTION

As a part of the program to establish the feasibility of a sodium-cooled, unmoderated power breeder reactor (PBR) for the production of economic power, and to facilitate the design, construction, and operation of a prototype reactor, the Experimental Breeder Reactor (EBR-II), Argonne National Laboratory has constructed a critical assembly facility located at the National Reactor Testing Station as a test of the engineering and operational feasibility of PBR. The facility is designed to accommodate experiments investigating the nuclear characteristics of both EBR-II and PBR with either U^{235} or plutonium, or a mixture of both, as fuel materials. The current program covers the use of U^{235} as fuel in studies aimed primarily at the design of EBR-II. This report is an evaluation of the hazards associated with these studies. An additional program which includes the use of plutonium or plutonium-U^{235} fuels will be covered in a separate report.

The EBR-II as presently conceived (see Figures 1 and 2) consists of an annular core of approximately 60 liters of volume in the form of a right cylinder. The center of the annulus is filled with blanket material, and the core is fully blanketed both radially and axially. Control as here illustrated is accomplished by movement of fuel elements.

Typical dimensions and volume composition fractions are:

			Volume Percent			
Region	Outer Radius, cm	Length, cm	Meat(1) U^{235} + U^{238}	Fertile Material U^{238}, Depleted	Structure (SS)	Coolant Na
Central Blanket	8	36	-	55	13	31
Core	24	36	32	-	17	51
Blanket above and below core	24	66	-	32	17	51
Inner radial blanket	35	168	-	55	13	31
Outer radial blanket	78	168	-	80	8	12

(1)The term meat denotes the mixture of U^{235} and U^{238} in the fuel elements.

Typical ratios of fissile to fertile material in the core are in the range of 1:1 to 2:1.

Aluminum of reduced density will be used in the critical assembly to simulate the sodium coolant of EBR-II. Correspondence of aluminum and sodium will be established by danger coefficient tests.

The experimental program to be followed in investigating EBR-II is based on the following consideration:

A fundamental characteristic of unmoderated dilute reactors is the wide range of neutron energies over which those reactions important to the maintenance of the neutron chain take place. Hence, the variation of neutron cross sections with energy makes it important to know accurately, not only the cross sections as a function of neutron energy, but the energy spectrum of neutrons (itself, a function of cross section) existing in the assembly. Present knowledge of cross sections in the energy range of interest, a few kilovolts to a few megavolts, is inadequate to assure prediction, by calculation, of the nuclear characteristics of such fast neutron assemblies. Coupled with the lack of information of cross sections is the difficulty of predicting, by calculation, the effects of the rather complex geometries of practical reactor systems on the neutron population.

The program for the critical facility is thus aimed at establishing, primarily by integral experiments, the effective cross sections and neutron energy spectrum existing in the assembly, and the effects of reactor geometry on nuclear performance. More specifically, the program for the critical facility includes:

1) Investigation, in various geometries, of the effects of U^{235} to U^{238} ratio.

2) Investigation of the effects of simple geometrical changes (i.e., length to diameter ratio for cylinders, etc.).

3) Investigation of the effectiveness of blanket composition and thickness.

4) Mock-up of EBR-II design, and proof test of the nuclear design.

Measurements to be made include:

1) Critical mass.

2) Neutron distribution in space and energy in core and blanket. Space distribution from activation and counter measurements. Energy distribution primarily by activation and fission ratios, and possibly by beam methods under development.

3) Effectiveness of control methods (fuel motion, absorber motion, reflector motion).

4) Danger coefficient of materials of interest.

5) Doppler effect on reactivity of fissile and fertile material.

6) Rossi-α, or the period associated with prompt neutron multiplication.

I. DESCRIPTION OF THE EXPERIMENT

A. Reactor

Pictures of the reactor are shown in Figures 3 and 3a. The assembly machine is basically a platform on which two tables or carriages are mounted, one of which is movable. Half of the reactor is built up on each carriage by inserting drawers containing the reactor materials into a matrix structure consisting of square (2 in. x 2 in.) cross section stainless steel and/or aluminum tubing stacked in a square array (67 in. x 67 in.) and constrained in position by means of clamps which are fastened to the carriage.

Each half of the assembly contains five safety-control rods. These rods are fuel-removal type rods consisting of stainless steel fuel drawers fastened to the drive mechanism. Four of the rods in each half will function as safeties, and the fifth will be used as a control rod. By changing wiring connections any one of the rods may be used as the control rod. Phone jacks are provided on the control panel to accomplish the wiring change to convert a safety to a control rod. On a scram, all the rods will act as safeties, being driven out of the reactor by compressed air.

Each half of the assembly contains a 15-curie polonium-beryllium source which may be driven into or out of the assembly by means of a motor drive.

A personnel shield has been arranged and will be available if tests made in the first stages of operation prove it necessary. Two movable sections are planned, one coming into position in front of each half of the assembly automatically when the halves are separated to provide protection against the "fat man effect" and to personnel moving between the halves of the assembly during loading and unloading operations.

A hinged platform is provided that may be swung into place between the separated halves to stand on for loading and unloading operations. An interlock insures that the platform is out before the carriage can move.

Electrical connections to the control console are by conduit through or under the shield wall.

1. Carriage Assembly

The assembly machine consists of two wide flange beams mounted parallel to each other with welded cross members forming a bed on which two carriages are mounted. One of the carriages is a stationary unit mounted at one end of the bed. The other carriage is movable, sliding on machined ways which insure accurate alignment of the movable carriage as the halves are brought together. Devices indicating position are provided to check the position and alignment of the carriages as they approach each other. The carriage assembly bed is twelve feet long to provide sufficient travel of the movable carriage to separate the halves of the assembly by a distance of five feet in the open position. The carriages form a platform 67 in. x 100 in. on which to mount the assembly and controls. Figure 4 is a photograph of the carriage assembly prior to loading the matrix and associated equipment.

The movable carriage is driven by a lead screw, which is connected through a slip clutch and speed reducer to three gear head motors mounted at the end of the bed. Each motor is provided with a magnetic clutch wired so that only one motor may be connected to the main speed reducer at one time. The motors provide three speeds for the carriage as the reactor halves are brought together.

The slip clutch is provided between the lead screw and speed reducer for two purposes. If any obstruction should be left between the carriages, the clutch will slip before any damage is done to the assembly. Also, when the carriages are driven together, the clutch allows them to be driven to an exactly reproducible position not dependent upon a limit switch. This is accomplished by setting the torque of the clutch somewhat higher than required to drive the carriage and driving the carriage until the mating surfaces are in contact, causing the clutch to slip. This slipping is indicated on the control panel by a light connected by means of a commutator so that slipping of the clutch causes this light to go on and off.

Limit switches at two positions along the travel determine the speed at which the halves may be assembled as follows:

a. With a separation of 3 inches or less - low speed only, $\frac{1}{2}$ inch per minute ($\frac{3}{4}$- HP drive motor)

b. With a separation of 18 inches to 3 inches - intermediate speed only, 6 inches per minute ($\frac{3}{4}$-HP drive motor)

c. With a separation of 60 inches to 18 inches - high speed only, 30 inches per minute (3-HP drive motor).

There are additional limit switches in series serving as back-up which prevent the high speed motor from being energized in the intermediate and low speed range, and which prevent the intermediate speed motor from being energized in the low speed range.

On a scram, the carriage is driven out at a rate of 30 inches per minute for the entire travel by the 3-HP drive motor.

The movable carriage has the following position-indicating devices on the control panel:

a. A linear dial showing position of the carriage for the full travel. This is graduated to 0.1 inch.

b. A linear dial indicating carriage position for the last 10 inches of travel graduated to 0.050 inch.

c. A linear dial indicating carriage position for the last $2\frac{1}{2}$ inches of the travel graduated to 0.005 inch.

d. A circular dial indicating any misalignment of the carriages for the last 0.05 inch of travel graduated to 0.001 inch. This is driven by a differential selsyn operating between two selsyns, one located on each side of the carriage.

All these indicators are Selsyn-driven devices utilizing appropriate gearing.

2. Matrix Assembly

The matrix assembly is constructed of stacked tubes as described earlier. Each tube is 2 inches square and 33 inches long, with a 0.040-inch wall thickness. The aluminum tubes are 3003 F alloy, and stainless steel tubes are Type 304. It is now planned that the first assembly will be made entirely with the stainless steel tubes.

The core section of the matrix will contain aluminum or stainless steel drawers with 0.032-inch wall thickness into which the reactor materials will be placed for convenience of loading (see Figure 5). The drawers will be loaded in a separate work room, then brought into the assembly room and placed in position in the reactor.

The drawers are provided with lugs which engage in notches in the matrix tubes so that they are accurately positioned and provide a flat interface between the assembly halves.

In the blanket section of the assembly, the slugs will be loaded directly into the matrix tubes.

The slugs provided for loading the assembly are of various sizes to provide the desired flexibility of reactor arrangement in all sections of the reactor. They can best be described by breaking the reactor down into sections. There will be a cylindrical core section at the center of the reactor, large enough in diameter and long enough to accommodate all anticipated cores to be built. A cylindrical end blanket section, the same diameter as the core section, may extend to the ends of the matrix tubes from the core section. An annular intermediate blanket section will surround the core and end blanket sections the length of the reactor to allow a fine structure at core blanket interface. An annular outer blanket section will surround the intermediate blanket section the length of the reactor.

In the core section, where the greatest flexibility of arrangement is desired, 15-in. long (or other length) drawers will be loaded with 2 in. x $\frac{1}{8}$ in. slugs $\frac{1}{2}$ in., 1 in., 2 in. and 3 in. long. These slug sizes will be provided in U^{235}, depleted uranium, stainless steel, and aluminum perforated to give densities of 45% and 63%. Enough slugs are provided of each material to allow a large variety of core loadings to be assembled. The drawers will be loaded by stacking the slugs on edge in the drawer to permit easy visual inspection of the drawer loading. The aluminum slugs are color anodized to distinguish each density for this visual inspection. The U^{235} slugs are also coated with a $\frac{1}{2}$ -mil Teflon coating colored to distinguish them from the depleted slugs. Thus each constituent of a drawer is easily distinguished on visual inspection of the loaded drawer.

Seventeen-inch long drawers in the end blanket section will be loaded with 1 in. x 1 in. slugs 2 in., 3 in. and 5 in. long, since the required flexibility of arrangement is not as great in this section. These slug sizes will be provided in depleted uranium, stainless steel, and special aluminum perforated to give an aluminum density of 56%.

Fifteen-inch and seventeen-inch drawers in the intermediate blanket section will be loaded with 1 in. x 1 in. slugs 2 in., 3 in., and 5 in. long and with 2 in. x $\frac{1}{8}$ in. slugs $\frac{1}{2}$ in., 1 in., 2 in. and 3 in. long. These slug sizes will be provided in depleted uranium, stainless steel, and aluminum perforated to give densities of 45%, 56% and 63%.

All the drawers in the core section will be provided with special leaf springs (see Figure 5) which will be inserted at the back of the drawer. The springs hold the slugs against the front of the drawer.

The outer blanket slugs will be loaded directly into the matrix tubes in the assembly. The depleted uranium slugs will all be 2 in. x 2 in. x 2 in., and the stainless steel and solid aluminum slugs will be 2 in. x 2 in. x $\frac{1}{4}$ in. The various density aluminum slugs are provided to allow the aluminum concentration to be changed in the reactor.

The size of pieces and the length of drawers may be varied from the above example.

Figure 6 is a sketch showing a typical loaded core drawer.

Thimbles are provided for experimental purposes at a number of points in the assembly, in both the vertical and horizontal directions. Thimble holes are located on both the vertical and horizontal center lines. These are located approximately every three inches in each half of the assembly.

Counter drives are provided that may be operated from the control panel to accurately position a counter in these thimbles. Travel of the drive is sufficient to move a counter completely across the assembly.

3. Control-Safety Rods and Mechanisms

All the rods are dual purpose rods in that each can be operated as a control rod; yet all rods act as safeties in that they are driven from the reactor in the event of a scram.

A control-safety mechanism is shown in Figure 7. Each rod drive consists of a $\frac{1}{4}$-HP, reversible gear head motor, equipped with brake, driving a pinion through a magnetic clutch. The pinion drives a rack connected at one end to a 2-inch air cylinder and at the other to a stainless steel fuel drawer. The drives are mounted on a support plate located at the end of the carriage so that the fuel drawer will slide in a matrix tube. The fuel drawer is chrome-plated to minimize the danger of galling and sticking of the rod.

One hundred and twenty-five psi air pressure is applied to one end of the air cylinder at all times, exerting a 315-pound force tending to pull the fuel drawer out of the reactor. The other side of the air cylinder has 18 psi back pressure with a relief valve set at 25 psi. To scram the mechanism, the magnetic clutch is deenergized, releasing the pinion, and the air cylinder pulls the rod out of the reactor. Regardless of the position of any rod, it will be driven out of the reactor on a scram. The lower allowable limit on air pressure is 100 psi.

The torque on the magnetic clutch is adjusted sufficiently high to just overcome the load from the air cylinder and fuel drawer. Thus, the clutch would slip, if a drawer should bind, before any damage could be done to the drawer or matrix tube.

Setting the torque on the clutch to a minimum also shortens the time required to release the clutch in the event of a scram. Figure 16 gives the performance of the rod drive.

Full travel of the safety-control rods is 10 inches; appropriate limit switches control travel and operate indicator lights on the control panel. Control drive speed is 4 inches per minute. This speed may be changed, depending on the worth of a control drawer, to remain within the allowable rate of reactivity change. The safety-control rods have circular dials on the control panel which indicate rod position to 0.005 in. These dials are Selsyn driven. Since the Selsyn generator on the rod cannot follow the scram speed of the rod, it is driven by a rack which disengages from the rod on scram, a counterweight returning the rack slowly to the zero position. A lug on the end of the Selsyn rack engages with a matching lug on the rod, as the rod moves forward, providing a positive drive for forward movement of the rod. A gravity-actuated return on the Selsyn rack keeps the lugs engaged for outward movement of the rod at control speed.

4. Source Assembly

Two 15-curie polonium-beryllium sources are used for each half of the assembly. The source is mounted on the end of a flexible shaft and is driven from its coffin, at the side of the assembly, through a thimble to a point adjacent to the core on one side of the assembly. Appropriate switches limit the travel and indicate source position on the control panel. Since the source is either completely in or out of the reactor, indicator lights are sufficient for position indication. For working around the reactor, they are removed from the reactor and placed in the coffins. The sources are so interlocked that after the halves have been drawn apart, they must be replaced in the reactor before the reactor can be reassembled.

5. Instrumentation

The reactor is equipped with the following instruments for start up and operation:

a. two linear electrometers with recorders;

b. three trip level safety circuits with recorders;

c. two logarithmic amplifiers and period meters with recorders;

d. one gamma-ray monitor - logarithmic amplifier and recorder;

e. two proportional counter channels; and

f. one source neutron counter.

A block diagram of this instrumentation is given in Figure 8.

The linear electrometers are to be used for both start up and operation at all anticipated power levels. These will be used to measure the current from uncompensated boron-coated chambers. They cover a range of 8 decades by the use of appropriate resistor and shunt changes. These instruments have been found to be very reliable in operation, being free of instabilities and drift in the electronic circuits.

The trip level safety circuits are DC amplifiers used to shut down the reactor in case the reactor power goes above the preset level. They are connected to ion chambers located adjacent to the assembly. These will be of the type commonly used on other reactors for this purpose. Of the three supplied, two will be in use at all times during operation.

The period meter system consists of an ion chamber, logarithmic amplifier, and differentiating circuit of the type presently in use with other reactors. The output of the log amplifier as well as the output of the differentiating circuit is brought out to a recorder. This provides a single scale record of power level over the entire operating range without changing of scale factors.

The gamma-ray monitor will provide a check on the general gamma-ray level in the assembly room.

One proportional counter channel is audible from the operator's position and will be used for startup.

The source neutron counter is a BF_3-filled proportional counter biased to cut off gammas and used to sense source neutrons.

B. Building

The floor plan for the ZPR building is shown in Figure 10. The building consists of a high bay assembly room section of reinforced concrete, and a one-story section containing the control room, work room, vault, laboratory rooms, offices, service rooms, etc. This latter section is of concrete block exterior construction with the exception of the vault, which has reinforced concrete walls and ceiling. The whole building has a concrete slab floor. Interior partitions are stud and dry wall with the exception of the vault, mentioned above, and the boiler room with concrete block walls.

This building is designed in accordance with the standards for earthquake Zone II in which the Testing Station is located.

The dimensions of the assembly room itself are $45\frac{1}{2}$ feet long by 42 feet wide by $29\frac{1}{2}$ feet high. The total enclosed volume associated with the assembly room, including the passageway and ventilating equipment mezzanine, but excluding the airlock, is 75,000 cubic feet.

The shielding walls of the assembly room are made of reinforced concrete. The shielding wall between the assembly room and the control room is 5 feet thick up to 12 feet above the floor and 3 feet thick the remainder of the distance to the roof. The north wall is 2 feet thick; the west and south walls are one foot thick. The partial wall between the assembly room and the passageway and ventilation equipment mezzanine is 4 feet thick up to 12 feet high and 2 feet thick the remainder of the distance to the roof. The roof is supported by long span trusses and has 6 inches of concrete poured on top of a corrugated steel deck.

The shielding wall between the assembly room and the control room is penetrated by twenty-four 2-inch "S"-shaped conduits for wiring. In addition, there are twenty stepped holes with steel plugs through this wall for experimental purposes.

In order to contain radioactivity within the assembly room, the room and its openings have been built for minimum leakage.

Access to the assembly room is normally through the airlock. As shown in Figure 11, the airlock consists of a concrete cell with two gasketed, motor-operated sliding doors. These doors are interlocked so that they may operate in sequence only and may not be opened simultaneously. In case of power failure counterweights will close both doors. The leading edge of each door will operate a safety switch to cause the door to stop in case anyone is caught between the door and the jamb. The airlock doors are interlocked with the reactor scram circuit so that the reactor will not start up until the doors are closed, and a scram will occur if the doors are opened during operation. The door-opening mechanism is operated by a key switch. The Reactor Supervisors have keys for this switch, and in an emergency it may be opened without a key by breaking a seal.

There is also a motor-operated, gasketed freight door in the south wall which closes on power failure, and a manually operated, gasketed escape door in the east wall. The escape door has a lever and cam arrangement to assist in opening the door against the positive outside pressure of 2 inches of water.

The conduits through the shield wall will be sealed after the wires are run. The stepped holes through the shield are sealed with expansible rubber plugs and shielding plugs.

The ventilation system is designed to maintain a negative pressure of 2 inches of water in the assembly room under normal conditions. The supply system takes outside air through an emergency, compressed-air operated intake damper, a 2-inch thick fiber glass filter, two finned steam heating coils in series and a 12,000-cfm blower with two-speed motor. The exhaust system takes air from the ceiling of the assembly room and passes it through a 2-inch thick fiber glass prefilter and a $11\frac{1}{2}$-inch thick Chemical Warfare Service absolute filter. The exhaust fan is rated at 13,000 cfm at 5 inches of water. Flow of air through the exhaust fan is controlled by an inlet vane damper. The air passes through a compressed-air-operated emergency exhaust damper and is exhausted up a stack 25 feet above the roof of the assembly room.

The negative pressure in the assembly room is controlled by a differential pressure indicator controller located in the control room. Under normal conditions the controller will maintain a negative pressure of 2 inches of water on the assembly room by proportioning the air flow through the inlet vane damper to the exhaust fan. The range of the controller is from zero to -4 inches of water. The controller is interlocked with the reactor scram circuits so that when the assembly room pressure rises above a certain point, the reactor will not start up or will scram. The controller itself is interlocked with a thermocouple to shut off fans and close louvres should steam pressure be lost and intake air be cold enough to cause freezing of the heater tubes.

Upon loss of power, or by manually cutting the power, the emergency intake and exhaust dampers will close and seal off the ventilating system.

The assembly room is furnished with both 110 volts AC and 440 volts AC outlets. It is lighted by both mercury vapor and incandescent lamps.

There is no water supply line or outlet in the assembly room.

Steam is supplied only to the heating coils in the mechanical equipment room on the mezzanine over the passageway. Steam leakage actuates an audible and visible moisture detection alarm.

There are no floor drains in the assembly room. One roof drain runs along the east wall from the roof through the floor.

Crane service in the assembly room itself is furnished by a 5-ton capacity bridge crane having a vertical lift of 24 feet. The crane is controlled by pendant push buttons and has five operating speeds.

A 5-ton capacity monorail hoist with motor driven trolley operates between the loading platform through the freight door across the passageway and into the assembly room. This hoist has a 13-foot lift and a variable speed control operated by pendant push buttons.

The assembly room is protected by a mercantile premises alarm system manufactured by the American District Telegraph Company. In order to have access to the assembly room the person wishing to enter must identify himself as an authorized entrant by telephone to the Central Facilities Security Office and be recognized by the officer in charge in accordance with a prearranged signal.

All reactor control equipment is located in the control room, and the reactor will be operated from this point. In addition, some special experimental equipment will be mounted in this room. Motor starting relays, DC power supply, switch gear, fuse boxes, transformers, etc. are located on the walls of this room. Figure 12 is a photograph of the control console. From left to right on the photograph: The first cabinet is the terminal cabinet; the second contains the gamma-monitor chassis and recorder, and also the source neutron counter; the third contains the safety circuit chassis. The left wing of the main console contains the jacks for changing control rods to safety rods, three safety circuit recorders, a linear electrometer and recorder, and four safety rod position indicators for the moving half of the critical assembly. The upper panel contains the interlock jumper jacks, the three linear carriage position indicators, position indicator dials for the two control rods, differential carriage alignment indicator dial, a period timer, and a recorder which may be switched to either linear circuit. The lower slanting center panel contains all of the reactor operating controls consisting of the two key switches, the control power reset switch, the safety drive clutch switches, the control drive motor switches, the source drive switches, the carriage drive switches, a reactor "off" switch, (which releases all control-safety rod magnetic clutches), and a scram switch. The right hand panel contains the four-position indicator dials for the safety rods on the fixed half, a linear electrometer chassis, and a two-pen recorder for period and log power, and a temperature recorder. The two right-hand cabinets contain two period chassis, two period timers, and two proportional counter scaler-counters.

The two additional cabinets can be modified to contain experimental equipment as needed.

The vault is a room 29 feet long by 26 feet wide by $11\frac{1}{2}$ feet high, with walls and roof of reinforced concrete 9 inches thick. This is equipped with the requisite vault and day doors.

The sole use of the vault is for storing fissionable material. The fuel slugs will be stored on racks in special "birdcage" type containers which limit the storage density to two kilograms of U^{235} per cubic foot.

Ventilation to the vault consists of air supplied through a grill from a supply blower, filter, convector unit located in the boiler room, and an exhaust system consisting of prefilter of fiber glass, a C.W.S. absolute filter and a 300 cfm fan and 25-foot stack mounted on the roof.

There are no water lines or outlets in the vault, and no drains.

The vault alarm system is a Class A central station burglar alarm system built by the American District Telegraph Company. Procedure for a person wishing access to the vault is to identify himself to the Central Facilities Alarm Room as an authorized person and be recognized in accordance with a prearranged code.

Immediately outside the vault is the work room. This room will be used for loading, checking, and unloading drawers, and for accounting for S.F. material. Storage bins, drawers, and shelves are provided in this room for the aluminum, steel, and depleted slugs and for drawers, springs, etc.

Large red warning lights which blink when the reactor is operating are located in the control room over the airlock door and on the east wall of the assembly room where it can be seen both from the assembly room and the passageway. Exterior warning lights are mounted on the northeast and southeast corners of the building and on periphery fence light poles to the north of the building and southeast of the building. These exterior lights are to warn the patrolling guards and others to avoid the vicinity of the assembly room during reactor operation.

There are two horns which emit a ten-second warning blast when the carriage starts moving. One of these is located in the assembly room and the other on the exterior of the building on the southeast corner.

There are two manual scram buttons in the building, one on the control console and one on the partial wall in the assembly room next to the exit.

The ZPR-III Building siren evacuation alarm system is connected with EBR Building evacuation alarm system. An evacuation alarm switch is located in the ZPR-III Building.

C. Site

This experiment is located adjacent to the Experimental Breeder Reactor at the National Reactor Testing Station in Idaho. Figures 13 and 14 are site plans showing this location and the adjacent areas. The nearest populated off-site areas are Arco, approximately eighteen miles to the northwest, and Atomic City, about twelve miles to the southeast. Except for EBR-I, AFSR, and the BORAX Experiment the nearest populated location is Central Facilities, about three and one half miles to the east. Highway 20 passes the site about one and three-fourths miles to the east. These are the only inhabited areas on the site within a radius of about twelve miles.

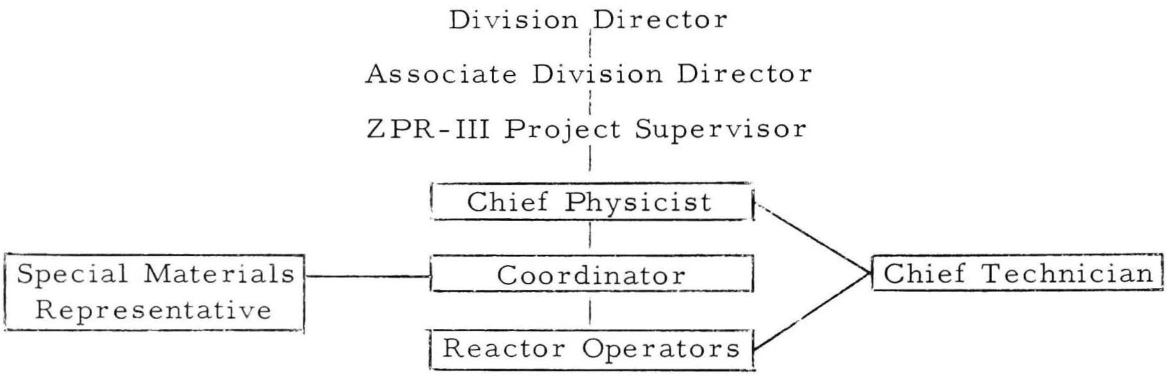
This is a desert area of plains of volcanic origin, uniformly covered with sagebrush and without surface drainage. Total precipitation is about ten inches per year, with the major amount of this falling as snow. Surface waters evaporate or sink into the ground to join the sub-surface waters which cross the plain from northeast to southwest at a slow rate. Here any surface water is diluted with the drainage from the mountains to the north and east.

The prevailing wind direction is southwest with a fair percentage of northeast winds typically in the early morning hours. An annual wind rose is shown in Figure 15 for the twenty-foot level as taken at Central Facilities during the year from June, 1950, through May, 1951. Many factors combine to give a large diurnal range of temperature near the ground resulting in strong vertical temperature gradients in the lower atmosphere. Negative vertical temperature gradients (lapse or unstable conditions) normally exist at night, though this is somewhat disturbed by local cloudiness or strong winds. Inversion conditions exist in the lower atmosphere roughly half the time. This subject is covered more fully by Humphrey and Wilkins in Report No. IDO-10020, "The Climatology of Stack Gas Diffusion at the National Reactor Testing Station." The area has fairly severe continental climate with large diurnal and seasonal temperature variations. Winter temperatures go down to -30°F with summer temperatures up to 100°F.

Earthquakes are not infrequent. The site has been established as a Zone II location, which specifies the relative intensities.

D. Management of the Facility

Management of the ZPR-III facility will be primarily in the hands of the ZPR-III Project Supervisor, whose position in relation to the other staff is shown in the following organization chart:



The Division Director has the first responsibility for the programs carried on by the Idaho Division.

The Associate Division Director has responsibility for directing the general program of ZPR-III.

The function of the ZPR-III Project Supervisor is to guide and direct the details of ZPR-III program and personnel. He shall insure that operation is in compliance with approved procedures. He must propose such rules as are necessary for safety and see that these rules are properly transmitted to the actual operating personnel.

The Chief Physicist is a staff member who is also an experienced reactor operator with at least a year of direct participation on ZPR-III. He has the experience and background to take charge of the reactor for an extended period and insure safe operation. He must approve the plans for each loading change and be physically present within sight of the console during reactor operation. He is in direct charge of operations at all times. He sees that proper procedures are followed and that equipment is functioning correctly. Alternates for the Chief Physicist may be authorized to perform these duties.

The Coordinator is an experienced reactor engineer or physicist, at the staff level, who has had previous experience of coordinating, under supervision, at least one ZPR-III assembly and is familiar with all the experiments normally performed. His function is to make the detailed plans for loading the core and blanket, and for each experimental loading thereafter. He must obtain the approval of these plans by the Chief Physicist, transmit these plans to the operators and see that they are properly executed. During operations it is his job to see that adequate records and data are kept. He must be familiar with the operation of the console and be present at the reactor when his experiments are in progress. Normally, for continuity, a single person will serve as Coordinator throughout the course of an assembly or series of experiments.

The Chief Technician is one of the Reactor Operators with several years of experience and particular aptitude for taking care of the mechanical problems of the machine. He provides continuity in the maintenance programs and keeps a log of maintenance. He supervises the checks of the interlocks and trains new technicians in the operation and maintenance of the equipment. He may check or approve loadings to see that they are performed as planned.

The Reactor Operators are the technicians who actually operate the reactor under the supervision of the Coordinator. They also perform routine maintenance.

Special Materials Representative is custodian of the vault containing fissionable material. He issues fuel to the loading crew in accordance with loading plans that have previously been approved by the Chief Physicist. He keeps account of the location of all fuel pieces.

For qualification to each of the above positions, an individual must undergo a period of training under the guidance of previously qualified personnel and indicate a satisfactory attitude toward the potential hazards and responsibilities of his particular job. All of the above positions except that of Special Materials Representative require a thorough knowledge of the operation of the reactor. Technicians achieve the grade of operator at the recommendation of the Project Supervisor only after suitable training and at least six months of operating experience. Positions on the organization chart are filled with personnel who have been declared qualified by the Division Director for specific positions for this reactor.

1. Fissionable Material

The management of fissionable material can best be described by following the procedure for loading of the assembly. At least two responsible persons will collaborate in the establishment of any loading. One of these will be the Project Supervisor or the Chief Physicist. The other will be the Coordinator for the experiment. After a loading has been established (enrichment, arrangement, volume percentages of a structure, coolant, etc.) an assembly master loading chart, showing the complete loading in each half of the assembly, will be made out, establishing the loading arrangement to be used for each drawer of the assembly. From the assembly master loading chart, master loading charts for each type of drawer loading will be made. The Chief Physicist will check the loading plans and sign his approval of the loading on the charts. These charts will then be used in the workroom adjacent to the vault to load the drawers before they are taken to the assembly room.

The custodian of the S.F. material will check the required S.F. material out of the vault for loading the drawers and keep an accurate record of the S.F. material loaded in each drawer. Before each drawer is filled by a loader, a drawer loading chart will be made out as a permanent record of the loading. Figure 9 is a sample of this chart. Each drawer will be checked for correct loading by a checker before it is removed from the workroom. It will then be placed on a special cart (designed to carry no more than two fuel drawers at one time) and taken to the assembly room to be loaded under the direction of the Chief Physicist.

Each drawer will be numbered to correspond with the number of a matrix tube to aid in the correct loading of the assembly. The assembly master loading charts will indicate the proper loading for each tube.

A master assembly loading chart, showing a cross section of each half of the assembly, will be kept in the control room. It will show the complete loading of the assembly at all times. The Chief Physicist will be responsible for indicating all changes in assembly loading on these sheets immediately after such changes are made.

The blanket will be loaded in the assembly room, the spare blanket material being stored there. The blanket slugs will be loaded directly into the matrix tubes, the drawers being omitted in this section, since only infrequent changes are anticipated. The loading of the blanket will be done under the direction of the Chief Physicist.

For experiments where radial measurements through the blanket are desired, a radial swath through the blanket will be provided with drawers. This will permit the advance loading of foils or counters in drawers and installation in the assembly when ready for the experiment.

Unloading operations will be the reverse of loading operations, the custodian of the S.F. material checking all S.F. material back into the vault as it is unloaded.

2. Operation

After the assembly has been loaded and checked, the reactor is ready to operate. Checking consists of visual inspection by a staff member or the Chief Technician to insure that the assembly is properly loaded, and that the assembly room is vacated. The control panel has two key-operated switches on the control power, both keys being necessary for reactor operation. The Coordinator and the Chief Physicist will each have one of these keys. In addition, the Division Director will have duplicate keys. This will automatically require the presence of two responsible persons whenever the assembly is to operate. These keys are to be kept in the possession of the responsible persons at all times except when they are in the control panel.

The Project Supervisor is responsible for the control of the console keys. Since several alternate individuals are authorized to fulfill the functions of Chief Physicist and Coordinator, it is the Project Supervisor's responsibility to issue keys to the proper individuals who are to perform a particular experiment. The Division Director's set of keys is ordinarily issued to an authorized individual in the event the other keys are unavailable. The Division Director's keys are issued on a day to day basis and must be returned to him or his representative by the end of the working day on which issued.

A daily check-off list to insure that all controls and safety mechanisms are operating properly, assembly is inspected, etc., must be filled out. In addition, there will be a weekly interlock check to insure proper operation of interlock circuits. Jack-type interlock jumpers and warning lights are provided on the front of the control panel, in full view of the operator, so that interlocks may be jumpered out for the weekly check or for experimental purposes.

The full list of interlocks on the reactor is as follows:

a. Scram Interlocks - the following occurrences cause scram:

1. Source leaves assembly.
2. Carriage retracts from closed position after having reached that position.
3. Airlock door opens or personnel counter indicates other than zero.
4. High power level (three circuits)

5. Short period (two circuits).
6. Low safety rod drive air pressure.
7. Air pressure becomes positive (gage) in assembly room.
8. Loss of high-voltage supply to period and power-level circuits (loss of line voltage also scrams these circuits).

b. Start Up Interlocks - The reactor control console cannot be reset for startup under any of the following conditions:

1. Carriage is not fully retracted.
2. Personnel counter is not at zero or the airlock doors not closed.
3. Low safety rod drive air pressure.
4. Air pressure in assembly room is not negative (gage).
5. All period and power level trip circuits not reset.

c. Carriage Drive Interlocks - Before the carriage can be started, the following conditions must be met:

1. The loading platform must be out.
2. The control console must be reset.
3. Both neutron sources must be in the reactor.
4. The neutron detection instrument must indicate that neutrons are present.

If all the above requirements are met, the movable carriage may be started in at its highest speed (30 in. per minute) until the halves are separated by 18 in. At this point a limit switch drops out the high speed drive. In order for the carriage to proceed further, the safety-control rods in use as safeties must be in the farthest in position: those used as controls must be in the farthest out position. When these conditions are fulfilled, the intermediate drive motor (6 in. per minute) starts automatically which drives the carriage until the halves are 3 in. apart. A limit switch then drops the intermediate speed drive out. The assembly is brought to this point automatically when the operator throws the proper switches. Beyond this point he must hold a switch in the closed position in order to bring the halves together. An interlock with the period meter will cause the carriage to stop at any time during the last 3 in. of travel if the period is less than 30 sec.

After the halves are brought together, the two control rods may be driven in to bring the reactor to criticality.

3. Maintenance

Maintenance of the equipment is the responsibility of the Project Supervisor. He may delegate the actual supervision of the repairs to the Chief Technician or other competent person, and he may call on such extra help as is necessary to insure adequate maintenance for electrical and mechanical equipment. He must anticipate what criticality and other hazards may develop and instruct the maintenance people in procedures necessary to avoid these.

The Chief Technician will keep a record of repairs and alterations to equipment in a Maintenance Log. All entries in this log will be acknowledged by the signature of the Chief Physicist. Periodic reports detailing all maintenance on the reactor shall be prepared by the Chief Technician and distributed to all ZPR-III staff personnel.

The Chief Physicist must verify that the reactor is in operating condition before each start-up, and if maintenance has been done he must check with the Project Supervisor to make sure that the reactor can be operated.

E. Limitation on Power Level and Activation of the Core

Calculations indicate that power levels of 250 watts do not create excessive radiation levels in the guardhouse, EBR building, or ZPR-III control room and office space. These calculations were made for bare assemblies with no correction made for self-shielding of the core itself. Direct radiation effects were calculated on the basis of attenuation due to distance from the core and the attenuation of intervening concrete shielding. "Sky shine" was calculated on the basis of reflection from an effective source located at the "center of gravity" of the radiation escaping through the roof of the building. Fast neutrons are the major constituent.

Activation of the fuel pieces in the core will more severely restrict power levels. Typical calculated as well as some observed gamma-radiation levels following operation at 1 watt are given in the accompanying table. It will be noted that the reactor on which the measurements were made was considerably larger and more dilute than the calculated reactor. It is not surprising therefore that the observed radiation levels are somewhat lower than those calculated.

RADIATION INTENSITY, MR/HR, AT VARIOUS TIMES AFTER SHUTDOWN FROM 1-WATT OPERATION

Between Halves of Assembly

	Calculated*			Measured**
Operating Time →	5 min	20 min	1 hr	1 hr
Time After Shutdown ↓				
1 sec	12,000	14,000	14,000	-
1 min	2,500	3,600	4,500	-
20 min	-	-	850	200
1 hr	57	200	480	100
1 day	1.3	5.1	16	-
1 week	0.13	0.51	1.6	-

At Surface of Fuel Box

	Calculated*			Measured**
Operating Time →	5 min	20 min	1 hr	1 hr
Time After Shutdown ↓				
1 sec	5,100	6,000	6,900	-
1 min	1,100	1,600	2,000	-
1 hr	24.9	87	200	19
1 day	0.60	2.3	6.9	1
1 week	0.05	0.23	0.69	-

At Surface of Fuel Plate (U^{235})

	Calculated*			Measured**
Operating Time →	5 min	20 min	1 hr	1 hr
Time After Shutdown ↓				
1 sec	2,300	2,600	2,700	-
1 min	480	690	840	-
1 hr	11	39	84	20
1 day	0.24	1.0	2.9	1
1 week	0.024	0.10	0.29	-

*The core size and composition in the above calculations is: 8.4-in. radius, 16.7-in. length core with 14% U^{235}, 21% U^{238}, 15% Fe and 50% Na. The critical mass was 160 kg of U^{235}.

**For the measured values the core used was Assembly 30 having 16.3-in. radius, 26.06-in. length, with 6% U^{235}, 9% U^{238}, 24.6% stainless steel, 23.3% aluminum, and 7.2% oxygen. The values between the halves were determined with a Juno meter against the interface. Midway between the halves at waist level the values were smaller by a factor of five. The critical mass was 395 kg of U^{235}.

The shutdown time required to reduce the gamma intensity between halves of the assembly to 100 mr/hr is plotted for various operating times as a function of power level on Figure 17. It is evident that there will be a continuing desire to operate with as low a resulting activation as possible consistent with the measurement requirements.

Desired Maximum Operating Power Level

Some measurements well out in the blanket on materials with low activation cross sections may require operation to a level of 1 kilowatt. For this, special precautions will be taken to ensure against overexposure. Since this would occur only in a heavily blanketed assembly it is unlikely that levels outside the assembly room would be above tolerance.

Long Term Activation of Fissionable Material

A conservative estimate of activation of fissionable material would be one based on a continuous operation leading to 50 kwh in two years (or 3 watts). The total number of fissions would be 5×10^{18}. Thus, less than 1 milligram of plutonium would accrue. Six months after 2 years continuous operation at 3 watts the fuel plates will have decayed to a gamma activity of 90 mr/hr at the surface. Since such continuous operation is unrealistic, it is unlikely that with intermittent operation the plates will have a surface gamma activity of more than 15 mr/hr.

II. HAZARDS AND ACCIDENTS

It was recognized at the outset that the proposed experiment is potentially hazardous. For this reason a site at NRTS was chosen instead of at Lemont. An attempt has been made to arrange the design and management in such a way that if there is no malfunction of safety mechanisms no damaging excursion can occur. However, there are assemblies which, if accidentally constructed through gross breakdown in management, coupled with failure of safety devices, could violently disassemble and destroy the building integrity. In addition, if one postulates failure of safety mechanisms and the existence of a rather large positive prompt temperature coefficient or a central void, even the planned assemblies can be in trouble. One must, in addition to accidents, admit that the possibility of sabotage to a facility of this sort always exists.

An experiment of this kind has several aspects which make it unique with respect to potential hazards. Most of these would not exist in a practical reactor, so that the predictions regarding accidents with this experiment do not apply elsewhere.

This experiment is basically a potentially hazardous one in several respects:

1. Because of the short lifetime ($\sim 10^{-7}$ second), an increase in reactivity above \$1 by even a few cents results in very short periods (e.g., 5¢ above prompt critical results in an asymptotic period of 267 microseconds).

2. There are no physical restrictions on the concentration of U^{235}, other than the total amount available (575 kg), so that a serious error in management of the fissionable materials or deliberate sabotage could result in assembling a critical mass in one-half of the machine.

3. The assemblies have no inherent means of reducing reactivity other than by thermal expansion coupled with small reactivity coefficients.

4. There may be as yet unknown autocatalytic effects. For example, the Doppler reactivity coefficient could be initially larger than the expansion reactivity coefficient. The positive U^{235} Doppler contribution is not countered by a negative U^{238} Doppler contribution because of lack of thermal contact between U^{235} and U^{238}.

A study of the hazard of accidents, notes on the hazard of sabotage, and consequences of accidents is presented on the pages to follow. To facilitate a more comprehensive look at the hazard situation, a summary of safety mechanisms, reactivity coefficients, and kinetic characteristics have been provided here.

A. Summary of Pertinent Information

1. Safety Mechanisms

There exist two systems which may be classed as safety mechanisms. The first system (I) is comprised of inherent and designed features which reduce reactivity by increasing leakage and by motion of fissionable material from a region of higher to a region of lower statistical weight and which restrict increase in reactivity to a safe rate. The second system (II) is comprised of interlocks and monitors designed to prevent operation in an unsafe manner. These, together with operational rules and procedures, constitute the defense against development of a hazardous situation.

System I

The mechanisms of this system are four.

1) The two-section type assembly, in which each section is only about one-half a critical mass, is used to promote safety in loading and to reduce reactivity by removing fissionable material from the central region and increasing leakage. The two sections are allowed to approach at 30 inches/min to a gap of 18 inches, then at 6 inches/minute to a gap of 3 inches, and are finally limited to a rate of $\frac{1}{2}$ inch/minute for which a maximum $dk/dt = +0.0004$/sec has been estimated. It is estimated that the last 3 inches are worth 12% dk/k for most assemblies, so that an error of 12% plus the worth of two control rods must be made before the assembly could become critical in the intermediate speed region. On scram, the halves move apart all the way at 30 inches/minute, reducing reactivity at the rate of $2\frac{1}{2}$ %/second.

2) Ten control-safety rods of fissionable material have been provided, five for each half. These reduce reactivity rapidly at any point in their travel by leaving the assembly. A typical time-travel curve (Figure 16) shows that after a 30-ms lag a rod moves out the first inch in 40 ms and can be completely withdrawn in 210 ms. The maximum reactivity estimated for one rod is 1% dk/k. The rod insertion speed is limited to 2 inches/minute and a maximum $dk/dt = +0.0001$/second has been estimated.

3) Sources have been provided for each half during assembly. At beginning of operation a Po-Be source of 15 curies, designed to ensure detection of multiplication, is inserted in each half. On scram, each source goes to its coffin.

4) Voids maintained by springs have been provided at the back of each central drawer which provide a space 0.5 cm long into which the fissionable material can expand if heated. These are adequate to reduce

reactivity by $\frac{1}{2}$ % to 1 $\frac{1}{2}$ % (depending on the core configuration) without requiring motion of most of the blanket mass.

The speeds of approach of halves and insertion of rods given here are those chosen for initial operation and may be altered if necessary by installation of new gear motors. The rate changing position for half motion can be altered only by moving switches to new positions.

System II

Monitors are provided to give the operator information on neutron density and its rate of change and to initiate scram if these quantities exceed prescribed values. These chamber monitors are positioned to see essentially neutrons multiplied by the assembly. Their signal strength is adequate to ensure actuation of the scram circuits in a few milliseconds after preset trip levels are exceeded. Counter monitors provide audible and visible recognition of increased multiplication.

A system of interlocks has been worked into the operating circuitry to reduce the probability of accidents occurring. Since these must be overruled for maintenance and periodic checks, a scheme of locking them out with jacks has been arranged so that the operator can have no doubt as to which are in operation. These interlocks are summarized in the following list:

1) The neutron level is below a prescribed range on the monitor (source out)

2) The required number of monitor circuits (3 level, 2 period) are not energized.

3) The air pressure to the control-safety rods is below the prescribed limit

4) The air lock door open

5) The personnel counter not at zero

6) The gap between halves is less than maximum

7) Two control-safety rods are not out

8) Eight control-safety rods are not in

9) The atmospheric pressure in the assembly room is not sufficiently below ambient

10) Both key locks are not open

11) The loading platform is not removed

12) Both sources are not fully inserted in their tubes

13) The carriage backs off its "in" limit switch after having been fully closed.

14) The period becomes less than 30 seconds with the carriage in its final 3 inches of travel (slow speed).

The interlocked operation-scram circuits have been built so that if any of the above conditions occur the halves may not be moved together and operation is prevented. Interlocks 6, 7, 8, and 10 cannot be bypassed with plug jacks. Although the 15 second trip point on the period scram circuits can be bypassed, a further trip point set at 5 seconds cannot be bypassed with plug jacks.

Interlocks 1 and 11 merely prevent the carriage from closing but do not cause a scram. Interlocks 7 and 8 prevent closure past 18 inches, but do not cause a scram. Interlock 14 prevents closure of the carriage past 3 inches if the period is less than 30 seconds. Interlock 6 requires that after a scram the halves move all the way apart before starting back together again. If any of these except 1, 6, 7, 8, 11, or 14 occur, a scram is initiated. In connection with 2, there are level trips and period trips which can cause a scram.

The period trips can be bypassed by holding down the push button switch which starts the sources driving in. This is necessary during insertion of the sources at start up, but is not permitted at any other time.

The console is wired so that if the keys are switched off the power to run the carriage out is still on, and the carriage will run apart automatically.

2. Reactivity Coefficients

Calculations using UNIVAC have provided means of estimating the magnitude of the more important reactivity changes in cores which are typical of those planned and of some which are not.

Control Rod Worth. A control rod has the composition of the surrounding core. Calculations and estimates indicate that a rod comprising a section of core the size of a drawer and length of the half assembly cannot be worth more than 1% dk/k. Approximate weighting indicates that the probable maximum worth of motion of the end of a rod near the center of the assembly is dk/k = 0.0015/inch.

Half Separation. Several types of core exhibit closely a linear dependence on gap of $(dk/k)/gap = 5\%/inch$ for gaps greater than 1 inch. For smaller gaps dk/k is less than this, having a value as low as $(dk/k)/gap = 2\frac{1}{2}\%/inch$ (see Figure 18).

Change in Core Length. Lengthening of the fissionable material of the core on heating results in varying values of $(dk/k)/(dL/L)$. For assemblies in which the core occupies all of the length of an inner drawer and expands toward the blanket to fill the spring void space, $(dk/k)/(dL/L) = -0.50$. After this space is filled and the blanket moves out with core, $(dk/k)/(dL/L)$ increases to -1.0. For assemblies wherein the core occupies only about half the inner drawer, so that core and blanket move together, $(dk/k)/(dL/L)$ varies from -0.22 to -0.50.

Enriched Drawer. A drawer filled with U^{235} pieces and inserted into a blanketed annular core containing only U^{235} pieces has been found to be worth 23% dk/k. With such an arrangement it is believed possible to attain a rate, by hand insertion, of $dk/dt \equiv \$30/second$.

Volumetric Expansion. Estimates of $(dk/k)/(dV/V)$ have been made for several homogenized cores on the basis of calculations for axial and/or radial expansion of slabs, cylinders, and spheres. Values between $(dk/k)/(dV/V) = -0.26$ and $(dk/k)/(dV/V) = -0.40$ were found.

Doppler Effect. The U^{235} is essentially thermally separated from the U^{238} in all the critical assemblies. This undesirable feature makes it impossible to count on the negative contribution of the U^{238} and a positive Doppler effect must be assumed. The magnitude of the positive contribution from U^{235} is influenced by the effect of dilution with U^{238} and other materials (including voids) on degrading the spectrum. The room temperature value of $(dk/dt)_D$ to assign to the various possible cores might, on the basis of unlikely considerations, be as great as $+50 \times 10^6/°K$. The Doppler coefficient for a core typical of EBR-II has been calculated at NDA by methods developed by H. Feshback, G. Goertzel, and H. Yamuchi. A reactivity effect of $(\delta k/dt) = +4 \times 10^{-6}/°C$ at room temperature was found. Goertzel's method implies a dependence of the coefficient on temperature of

$$(dk/dT)_D = (dk/dT)_{D_{R.T.}} \left(\frac{T_{R.T.}}{T}\right)^{3/2}$$

from which the change in reactivity with temperature due to Doppler effect is

$$\Delta k_D = (dk/dT)_{D_{R.T.}} T_{R.T.} \left(1 - \sqrt{T_{R.T.}/T}\right) .$$

Annular Core. The reactivity changes associated with inward expansion of an annular core have been estimated. For an annular core with inner blanket the reactivity change for a compression of the blanket of $dr/r = -0.026$ was found to be $\Delta k_{eff} = +0.00004$. However, expansion of the annular core into an empty central matrix element produces a very large positive change. For the postulated small enriched annular core expanding into a central void the size of a drawer, a change of $\Delta k_{eff} = +0.080$ is estimated. The large volume change accompanying this expansion (~25%) can only be accomplished after the core is vaporized. A similar but smaller effect is realized in the case of a larger core of the type planned with the center control rod drawer withdrawn. Here on vaporization the void would fill introducing about the same positive change as would be realized by inserting a control rod (2% maximum).

3. Kinetic Characteristics

The rates of rise for neutron population during changes in reactivity are not predicted by the "stable" or "asymptotic" periods obtained from the inhour formula. The rise rate is characterized by $n/\dot{n}$ (which becomes the asymptotic period after k_{ex} has remained constant for some time). For faster rates, the effect of delayed neutrons is not felt strongly, and $n/\dot{n}$ is like ℓ/k_{ex}. As the rate becomes slower, $n/\dot{n}$ is more like

$$\frac{\ell}{k_{ex} - (\beta - \frac{\ell}{n} \Sigma \lambda_i C_i)}$$

In addition to the rate, as k_{ex} approaches β (i.e., prompt critical),

$$\frac{n}{\dot{n}} \rightarrow \frac{\ell}{\frac{\ell}{n} \Sigma \lambda_i C_i} = \frac{n}{\Sigma \lambda_i C_i}$$

always. Above prompt critical, the term $n/\Sigma \lambda_i C_i$ becomes unimportant and

$$\frac{n}{\dot{n}} \rightarrow \frac{\ell}{k_{ex} - \beta} \quad ,$$

which is the stable period. Hence above prompt critical the rise rates be become just the stable period.

Since ℓ in these fast reactors is very small compared with thermal reactors, during changes in reactivity the rate of rise of neutron population is much more rapid in the region below prompt critical. Also, the period is much shorter above prompt critical, in the ratio of the lifetimes. The result is that reactivity addition through use of control rods should be much slower from an operating standpoint.

The values of asymptotic periods as a function of k_{ex} for a lifetime of 10^{-7} are shown in Figure 19.

The critical assemblies are characterized by prompt neutron lifetime, delayed neutron fractions, and precursor decay constants. The various assemblies studied do not differ in lifetime by a factor of four, so that $\ell = 10^{-7}$ second is chosen as representative. The total delayed neutron fraction is $\beta = 0.00755$. The precursor characteristics are taken from Hughes' data for U^{235}. Variation of the neutron population (n) and its time integral $\int(ndt)$ with a number of rates of increase of reactivity and rates of reduction of reactivity has been established. Of principal interest are the following, assuming an initial neutron population of 1/cc:

Values attained when sensible heating begins ($\Delta\theta = 30$)

Rate, $ per second	k_{ex}	n	$\int ndt$	t, sec.	Apparent Period, $n/\dot{n}$
100	0.00923	1.4×10^8	10^5	0.0122	47 μs
10	0.00806	4.5×10^7	10^5	0.1068	147 μs
1	0.00772	6.3×10^5	10^5	1.022	500 μs
0.1	0.00720	9.2×10^4	10^5	9.	70 ms
0.01	0.00600	7.6×10^4	10^5	80.	700 ms

Values attained when $k_{ex} = 0.00369$ (asymptotic period of ~five seconds).

Rate, $ per second	t, sec.	n	$\int ndt$	$n/\dot{n}$
100	0.00489	2.0	0.0068	4600 μs
10	0.0489	2.1	0.069	44 ms
1	0.489	2.3	0.77	400 ms
0.1	4.89	4.6	14	2 sec.
0.01	48.9	80	400	4 sec.

Values attained when $k_{ex} = 0.00573$ (asymptotic period of 1 second).

Rate, $ per second	t, sec.	n	$\int ndt$	$n/\dot{n}$
100	0.00758	4.	0.013	2300 μs
10	0.0758	4.3	0.14	22 ms
1	0.758	5.6	1.6	170 ms
0.1	7.58	50	40	500 ms
0.01	75.8	5000	1500	800 ms

In the case where no Doppler effect is experienced and thermal expansion is the only shutdown mechanism, there has been obtained a value for $(dk/dt)/n$ of -10^{-9} due to expansion. Correction to other values of $(dk/dt)/n$ is given. R is initial rate of insertion, (dk/dt).

$$\text{For first peak, } \int n\,dt = 4 \times 10^{6} R^{0.55} = 20\sqrt{2n_{max}}.$$

Maximum excess reactivity reached,

$$(k_{ex} - \beta)_{max} = 1.86 \times 10^{-3} R^{0.53}$$

Maximum value of n, first peak,

$$n_{max} = 2 \times 10^{10} R^{1.1}$$

The minimum period attained,

$$(n/\dot{n})_{min} = 60 \times 10^{-6}/R^{0.54} \text{ seconds}$$

n_{max} is inversely proportional to

$$-(dk/dt)/n$$

where

$$-(dk/dt)/n = -B$$

in the equation for excess reactivity:

$$k_{ex} = A + Bn \quad ;$$

hence,

$$n_{max} = \frac{20\ R^{1.1}}{-B} .$$

B. <u>Hazard of Accidents</u>

Accidents in experiments like this could occur as a result of: action by personnel in the assembly room; action by personnel in the control room; natural catastrophes such as fire, flood, or earthquake, malfunction of equipment; loss of control of fissionable material; possible autocatalytic characteristics. Coupling or cascading of these must occur before a damaging accident is experienced. Considered in the above order, there follows herewith an enumeration of these actions and their counteractions.

<u>Action by personnel in the assembly room</u>. The assembly must be constructed and altered, and measurements must be made. In the course of

building the assembly a loading error might be made which would result in a supercritical assembly, either in one-half or while a sizeable gap still exists and gap closure speeds are large. This may be protected against by

1) having the assembly in two halves, thus requiring that an enormous error be made to have trouble;

2) having several control-safety rods cocked which on scram-signal will reduce reactivity at a rate greater than can be attained by hand insertion of a drawer. This implies working scram-circuits.

3) Checks on drawer compositions and an accounting procedure for removal of fissionable material from vault.

Measurements require insertion of foils, chambers, or oscillators by hand before operation. These could make large changes in reactivity. The possibility is guarded against by calculations or preliminary reactivity measurements. The effect of presence of personnel as so much hydrogenous reflector on reactivity will be checked experimentally.

Action by personnel in the control room. Personnel in the control room can push wrong buttons, or do things in the wrong order, or make poor estimates, or jumper interlocks incorrectly. Except for the latter, these types of actions are counteracted by having a system of interlocks which require that the reactor be properly put in operation. The sources must be in, the personnel counter must register zero, the safety rods must be cocked, and so forth as listed in the summary of safety mechanisms, or the halves cannot be brought together. If the reactor becomes supercritical before expected due to a bad loading guess, monitors activate scram circuits if operators are unaware of excessive rates or power level. The safety rods can make the reactor subcritical for all rates of insertion of reactivity which are possible from the control room before sensible heating occurs. Since it is necessary to be able to jumper interlocks, the philosophy described previously has been adopted. The jumpers are made so obvious that the operator can tell at a glance which interlocks are inoperative. Here reliance is placed on the operators. There is no physical block against operating with interlocks inoperative.

Natural catastrophes. The probability of accidents being initiated by flood and fire has been reduced by eliminating water-supply pipes and inflammable material from the assembly room. Natural floods do not occur at this location. Earthquakes occur in this area, and the building is constructed to resist damage by earthquakes of magnitude for which this area is classified. It is believed that an earthquake could not cause distortions of a serious nature in the assembly.

Malfunction of equipment. It is a basic philosophy that the equipment be designed to fail safe. Loss of electrical power will cause electromagnetic clutches to de-energize and drives to stop. Jamming of moving parts causes clutches to slip, prohibiting further motion. Rod drives are so housed as to protect against small articles being placed or dropped into critical regions. Monitoring circuits are duplicated so that several may malfunction without loss of protection. Failure of all circuits is likely only in the event of power failure. Of all the components, only the cams of the switches which change carriage speed can fail without failing safe. This means that if the cam arms become bent and contact with carriage tabs is no longer possible, the carriage could drive all the way together at 30 inches/minute. If under these conditions the assembly should become critical, the safety rods can stop the excursion before sensible heating occurs. The apparent period which the period meter measures is always shorter than the asymptotic period given by the inhour equation. For large dk/dt, the period trip level would be exceeded at once. Even if dk/dt were \$30/second, over 90 ms is available for safety rod withdrawal, in which time the eight rods would have moved about $1\frac{1}{2}$ inches out. If the source is not in, there are more than enough spontaneous fission neutrons to sustain initial chains and prevent insertion of reactivity much above prompt critical before the reaction goes.

Loss of control of fissionable materials. Two types of errors of significance are misloading of fissionable material into drawers, and loading drawers in wrong box. The drawer loading procedure is planned with a double check. The drawer is accompanied by a master loading plan which lists the number of fissionable material pieces and shows their drawer location. The number of U^{235} pieces called for on the plan are all the loader can acquire from the vault. The loading is then visually checked by the assembly loader who is someone other than the drawer loader. Checking is by means of color code. The assembly loading is checked by inspecting the sequence of drawer numbers on the front face of each drawer. A complete breakdown of procedure would be required to allow assembly of a critical mass in one-half of the machine. Smaller errors would be counteracted by the normal monitoring on assembly of halves.

Possible autocatalytic characteristics. It is not known whether the assemblies which are made will have such characteristics. Motion of material, except in two cases, results in either reduction of or no change in reactivity. The two exceptions are motion of an annular core towards its hollow center and motion of fuel in a drawer towards the center face of the reactor in case a spring is inadvertently put at the front of the drawer. These motions require heating and hence connote an accident already started. The exceptional cases noted, then, are ones which would increase the severity of the accident. Since these changes in reactivity are far more rapid than any which safety rods can make, the shutdown mechanism of an expanding system must provide counteraction. Eventually the system will expand by disassembly to the point where the nuclear reaction stops. One further "autocatalytic" feature would be that in which the vaporized core material would combine with the oxygen in the air, releasing additional energy as a consequence of the exothermic reaction. There is no counteraction for this except final consumption of the vaporized material.

There is another aspect which must be discussed here. Because the assembly is made of small pieces which must be easily put in and taken out, there are clearances and tolerances which introduce voids in the lateral directions. Until these clearances are taken up by lateral expansion of the U^{235} pieces (which are only a few to the drawer) no radial expansion can be counted on to reduce reactivity. Furthermore, to do this would require heating to above the melting point of uranium. Once the uranium has melted, all the voids in the aluminum pieces, and between drawers and tubes, must be filled before macroscopic radial expansion of the core begins to assist in the shutdown. This would require vaporization of the U^{235}.

C. Hazard of Sabotage

Access is controlled to reduce the probability of theft, nuisance, and sabotage. The building must be entered through a guardhouse, which also controls access to the EBR plant. Visitors must have clearance or escort. The assembly itself, and the vault, are protected during off hours by an alarm system. This eliminates alteration of the assembly and access to fissionable materials during off hours. Those having the knowledge and opportunity to bring about a damaging excursion are subject to a special security check, minimizing the probability of instabilities, or lack of loyalty.

During off hours, the conditions for establishing a really severe excursion are not present, since the core must be altered and the safety system deactivated. During working hours a scheme whereby the core could be altered to a dangerous configuration in an unobtrusive manner is not easily conceived. Both keys to the reactor would be needed, along with the vault combination and absence of the SF representative. It would appear then, that only with the collusion of two or more people could a really disastrous incident be brought about. Sabotage by an individual could result in a mess and in putting the facility out of use for sometime if the safety interlocks are jacked out and the reactor made supercritical. This would require the acquisition of both reactor keys, and that the individual be one of the operating group.

D. Consequences of Accidents

1. Assembly and Building

It has already been said, and may be re-emphasized here, that the safety-rods and scram circuit, if operating, can take care of any inadvertent change in reactivity without damage to the reactor. If the safety rods do not operate, and there is no positive contribution to the reactivity on heating, but only the negative one due to linear axial expansion of the U^{235} pieces, the reactor may shut itself down without vaporizing.

However, in the possible event that a large positive temperature coefficient exists (or an annular core is made supercritical) and the safety rods do not operate, a very energetic excursion can occur. The mechanism might be as follows:

1. A rather high rate of insertion of reactivity puts the reactor above prompt critical at the time sensible heating begins.

2. The Doppler coefficient is assumed to be greater than the expansion coefficient initially and varies inversely as the 3/2-power of the absolute temperature. The reactivity then rises rapidly until a temperature is reached at which the Doppler coefficient is reduced in value to the negative expansion coefficient.

3. Unfortunately, this temperature could be at or above the melting point, and reactivity then would continue to reduce only by continuing the motion of the core and blanket due to momentum. The Doppler effect will cause the reactivity to rise again as if the negative expansion coefficient were nearly zero.

4. This rise must continue until all the core voids are filled. The U^{235} must vaporize to do this. If a central hole exists the reactivity will also now increase.

5. Now, however, the pressure builds up and the core expands, moving the blanket pieces outward as if the blanket had no cohesion, only inertia. The inertia of the blanket pieces inhibit the expansion still further, so that it takes longer to realize that configuration which is not critical.

6. By the time the nuclear reaction is ended the pressure stops building up and the blanket pieces continue to move at a reducing acceleration until pressure is relieved, after which they coast at a rather high velocity and the core expands into the room. The uranium vapor ignites and the ensuing release of heat may double the energy release. The blanket pieces have enough kinetic energy to penetrate the building walls, and the room air is heated to many times the bursting pressure.

An accident based on this mechanism has been calculated in detail in Appendix A. It was estimated that about 1.5×10^{20} fissions would occur, and an energy release from the nuclear reaction of 1.2×10^{9} calories would be realized. In addition, burning of the U^{235} would yield about 3×10^{8} calories, so that an energy release of 1.5×10^{9} calories was estimated.

The accident calculated in detail in the appendix could not occur in this manner if the Doppler coefficient be smaller. If the Doppler coefficient be less than $+10 \times 10^{-6}/^{\circ}C$ (as is believed to be the case), the excess reactivity cannot get greater than it is when sensible heating begins. By the time melting of the U^{235} occurs the axial expansion will have reduced the excess reactivity to well below prompt critical. The reactor will then be on a long period (several seconds). Heat can now be transferred to the other core materials, particularly to aluminum which will vaporize at a much lower temperature (1800°C). The expanding aluminum will disassemble things before a greater temperature is reached. The total fissions would be those which supply enough heat to bring the total core to 1800°C and vaporize the aluminum. It requires 2500 cal/g to vaporize aluminum from room temperature, 75 cal/g to raise uranium to 1800°C, and 2000 cal/g to raise steel to 1800°C. There are 6.0×10^5 g of uranium, 6.4×10^4 g of aluminum, and 9.8×10^4 g of steel in the core. Thus 3.6×10^8 cal are required. This corresponds to 4.5×10^{19} fissions, and the accident is less severe. The heated air from this plus metal-oxygen reactions would still rupture the building.

It is possible that shutdown to below prompt critical occurs well before any metal melts. The slow heating of the whole system which followed would result in a general expansion. For a volume expansion coefficient of 50×10^{-6}/°C, a 500-degree rise would afford a $dV/V = 0.025$ which would be ample to put the reactor below delayed critical.

In lieu of a large Doppler coefficient, another mechanism is available at times for rapid introduction of reactivity after the accident starts. If the central drawer is a control rod which may be out, leaving a void, then when core expansion occurs on vaporization after heating, even with a slow period, the space may be filled suddenly. This would be like putting in the control rod in a very short time. It could result in a reactivity addition of 2% at the most. Thus at beginning of blanket expansion under pressure from the vaporized core, the α would suddenly be increased. To be as severe as the calculated accident, the α would need to be as great, or a total k_{ex} of about 0.023 is required.

Still one more accident should be discussed. If a small enriched annular core were constructed in one half, and one started to fill the hole in the center by shoving in rapidly a drawer of U^{235} pieces, the assembly could become critical with the drawer just started in. The reactivity in by the time sensible heating begins is about 0.008, assuming a rate of \$30/second. The axial expansion would hold the reaction at prompt critical. Vaporization into this central cavity will boost the reactivity up to about 4% above prompt critical. (The mass ratios of core and blanket are 5 to 1. While the core is filling, the blanket will move out one-fifth as far as the mean mass radius of the core moves in, thus reducing the total change in reactivity.) This takes about 3.5 e-fold times after vaporization. The blanket must continue to move to reduce the reactivity to zero. The extra 0.2-cm expansion required takes an additional 2/3 of an e-fold time. However, in this small core there are only 53 kg of U^{235}, so that only 0.2 times as many fissions are required to produce the same state. On this basis it is estimated that a total of 2.5×10^{20} fissions are realized before shutdown. This is only twice as great as for the other, but could result only from sabotage, because no cores remotely resembling this are contemplated.

In making these analyses, the compression of the blanket is neglected. Since the pressures are very high, this material compression will be significant. In compressing the blanket material, the outer face of the piece being compressed does not move, relatively. The mass center of the piece moves only half as far as does the inner face for uniform compression. Comparing with the high pressure data of Bridgeman, in a given number of e-fold times the net outward motion of the inner face is at least twice that of the general motion of the piece, and shutdown occurs in at least half the calculated time.

This effect is even more important in the case of the small annular core, wherein the result of considering compressability is to reduce the maximum reactivity reached by a large amount, so that, with the reduced α, shutdown is realized in fewer e-fold times.

If the excess reactivity is added slowly, so that it does not exceed about 0.006 when heating begins, the reaction will shut down automatically by expansion of the U^{235} pieces in the axial direction without melting.

If the excess reactivity becomes greater than 0.006, but less than 0.01, the axial expansion will reduce the reactivity below prompt critical so that the reactor is on a long stable period of 75 seconds. Sufficient heat may be transferred to consider that the entire assembly is heating up, with heat being transferred from the U^{235} to the rest of the assembly. The reaction would be shut off below the melting point of the aluminum, and the temperatures probably would not exceed 500°C.

If the excess reactivity becomes greater than 0.01, but stays less than 0.014, the axial expansion will shut down to below prompt critical, and periods of about 0.1 second will ensue. The core aluminum and uranium will probably melt and may start toward a more reactive configuration. The materials are moving under gravity, so that in effect only enough reactivity can be added to get just above prompt critical. Now the reciprocal period will be large (>100). Heating will be rapid, but vaporization of the aluminum should take place before uranium vaporizes. The energy release at vaporization is about the maximum.

In accidents where excess reactivity is greater than 0.014 when sensible heating begins, or greater than 0.008 after expansion into the drawer voids, the reaction can terminate only after vaporization of the U^{235} takes place, and the blanket inertia is overcome. The energy release is then several times that required for core vaporization.

In view of the nature of the assumptions made in the calculations, it is not unreasonable to expect that the following numbers are upper limits on the most severe accident:

Total number of fissions	10^{20} fissions
Total nuclear energy release	8×10^{8} calories
Total chemical energy release	3×10^{8} calories
Maximum core pressure reached	200,000 atmospheres
Velocity of blanket sections	1500 ft/sec

The nuclear energy release is the equivalent of 1/2 ton of TNT, and the peak pressures are about 1/2 those of TNT. The peak overpressures at the building wall in the shock wave could be as high as 30 psi. Heating of the air results in a pressure rise of about 100 psi. For these numbers one expects the destruction of the assembly building and subsequent release of essentially all the fission products to the atmosphere.

2. Surrounding Area

Physical damage due to the explosion will be limited to the area immediately adjacent to the ZPR building. Some damage to the EBR building might ensue, but the force of the explosion is directed away by the massive shielding walls. The radius of possible damage will be determined by the range of missiles. This is unlikely to be more than a thousand feet.

Of principal concern is the radiological damage. Two analyses were made to estimate radiation hazard to the surrounding area. The first was for radiation exposure to the cloud while it travels. The second was for long-time exposure to the precipitated activity.

Radiation from the Cloud

The reactor is normally operated at low power, so that only the fission product activity from the burst is considered. This activity decays as $t^{-1.2}$. One can assume that 100% of the total fission products get into the cloud and 60% of the dosage is effective to a ground receptor. Adjusting the expression for radiation as suggested in "Summary Report of the Reactor Safeguard Committee," pp. 42-44, to allow for these differences, it is found that

$$\text{dose in roentgens} = R = \frac{1.9 \times 10^{-4}\, F\, V^{0.2}}{h\, d^{2.2}}$$

Here V = wind velocity, cm/sec; h = cloud height, cm; d = distance from origin, cm; F = total number of fissions in burst.

For 10^{20} fissions the radius at which R = 300 roentgen has been calculated for cloud heights of between 30 and 200 meters and wind speeds between 1/2 and 5 meters per second as shown below (radius in feet):

Radius in feet at which dose is 300 roentgens

h, meters V, cm/sec	200	100	60	30	10
1300	1330	1820	2290	3150	5190
500	1215	1670	2110	2900	4750
100	1050	1440	1820	2500	4100

For comparison, use of the approximation exclusion radius (miles) = 0.003 (total energy of burst, kws)$^{1/3}$ leads to a radius of 2360 ft.

Exposure to Precipitated Activity

In studying this exposure it is assumed that the fission products are carried with the cloud and are deposited over the projected ground area of the cloud at a time t_0 after cloud formation. That ground area is chosen within which a receptor would receive an LD_{50} dose. It is assumed that 80% of the activity is gamma and 20% beta and the effectiveness of the precipitated activity is taken as 1.5×10^{-5} r units per hour for fission activity of 1 mev per square cm per second.

The ground area which will give an effective dose of R roentgens after t hours exposure for 10^{20} fissions, all of which gets into a cloud, is

$$A = \frac{1.75 \times 10^9 \, (t_0^{-0.2} - t^{-0.2})}{R} \text{ square feet}$$

or

$$A = 3.9 \times 10^6 \, (t_0^{-0.2} - 0.33) \text{ square feet for 300 roentgens and 10 days exposure.}$$

By comparing distances it takes to allow the cloud to spread over this area, and the times to get to the position, the critical distance from the source to a point beyond which the dose is less than 300 roentgens has been calculated. The calculations are based on a diffusion formula due to O. G. Sutton for a point source on the ground.

For stable weather conditions and wind speed of 2 meters per second this distance is 10 miles, while for turbulent conditions and a wind speed of 5 meters per second the distance is 4300 feet. To this should be added the cloud radius. Hence, the distance at which it seems certain the dose will be less than 300 R from long exposure is estimated to be about 5500 feet for turbulent conditions and 10 miles for stable conditions.

It should be noted that it has been assumed that all the fission products get into the cloud, that no fallout is assumed before precipitation occurs, and that complete precipitation is assumed with the cloud standing still. In addition, it is assumed that the receptor is exposed for 10 days.

APPENDIX A

CALCULATIONS FOR A SEVERE ACCIDENT

In an attempt at describing in detail one of the most severe types of accidents, an analysis was made in which it was assumed that the safety mechanisms were inoperative and the nuclear reaction was terminated by expansion. Furthermore, it was assumed that a large positive Doppler coefficient (C_D) exists which varies inversely as the $\frac{3}{2}$ power of the absolute temperature (T).

The core used was characterized by its lifetime, delay fraction, volume fraction of fissionable material, heat capacity, expansion coefficients, reactivity coefficients and blanket mass loading. To be pessimistic, a composite core was chosen with

Lifetime = $\ell = 10^{-7}$ seconds

Volume fraction of voids = 0.32

Volume fraction of fissionable material = 0.15 = V_f

Volume of core = 10^5 cc = V_c

Length of core = 51 cm (20 inches) = L_c

Radius of core = 25 cm (10 inches) = r_c

Grams of U^{235} = 2.85×10^5 grams

Blanket:	Mass Loading, m_B, lb-sec^2/in./in.^{2}
Inner end blanket length = 12.5 cm	0.0088
Inner outer end blanket gap = 0.4 cm	
Outer blanket length = 18 cm	0.0214
Inner radius = 25 cm	$1.65 \times 10^{-4}(r^2-100)$
Outer radius = 55 cm	

Number of neutrons/fission = ν = 2.5

Density of U = ρ = 19 grams/cc

Delay fraction = β = 0.00755

Specific heat to melting point = 0.035 cal/g-°C = S_H

Energy release $= \left(\frac{0.2389}{3 \times 10^{10}}\right) \frac{V_c/V_f}{\ell \rho \nu} \int ndt = 1.12 \times 10^{-5} \int ndt = \Delta E$, cal/gram

The temperature rise is $\frac{\Delta E}{S_H} = \frac{1.12 \times 10^{-5}}{0.035} = 3.2 \times 10^{-4} \int ndt$ up to the melting point

$$\frac{\Delta k}{k}\Big/\frac{\Delta L}{L} = -0.40 \quad ,$$

$$\frac{\Delta k}{k}\Big/\frac{\Delta r}{r} = -0.60 \quad ,$$

$$\frac{\Delta k}{k}\Big/\frac{\Delta V}{V} = -0.30$$

Linear expansion coefficient = $14 \times 10^{-6}/°C = \delta\theta_L$

Volume expansion coefficient = $42 \times 10^{-6}/°C = \delta\theta_V$

$$\left(\frac{\Delta L}{L}\right)_\theta = \delta\theta_L\, \theta \quad ,$$

$$\left(\frac{\Delta V}{V}\right)_\theta = \delta\theta_V\, \theta \quad ,$$

$$\left(\frac{\Delta r}{r}\right)_\theta = \delta\theta_L\, \theta \quad ,$$

$$\left(\frac{\Delta V}{V}\right)_\theta = 3\,\delta\theta_L\, \theta = 2\left(\frac{\Delta r}{r}\right)_\theta + \left(\frac{\Delta L}{L}\right)_\theta$$

$$\left(\frac{dk}{dt}\right)_\theta = \frac{dk}{d\theta}\cdot\frac{d\theta}{dt} = \frac{\Delta k}{\theta}\cdot\frac{d\theta}{dt} = \left(\frac{\Delta k}{k}\Big/\frac{\Delta L}{L}\right)\delta\theta_L\, \dot{\theta} = -0.40 \times 14 \times 10^{-6} \times 3.2 \times 10^{-4}\, n \quad ;$$

hence,

$$\left(\frac{dk}{dt}\right)_\theta = -1.79 \times 10^{-9}\, n \quad ,$$

$$\Delta k_\theta = -1.79 \times 10^{-9} \int n dt \quad .$$

It is unlikely that a rate greater than dk/dt = \$2/sec can be attained. This would result from going supercritical by closing the gap at 30 inches/minute. At this rate the maximum excess reactivity which can be realized before sensible heating begins is

$$k_{ex} = 1.86 \times 10^{-3} R^{0.53} + \beta = 0.007751 \text{ for } R = 0.0151 \quad ,$$

This corresponds to a stable period of 577 μs or α = 1732. The value of $\int n dt$ when θ = 1°C is

$$\int n dt_{\theta=1} = \frac{1}{3.2 \times 10^{-4}} = 3120 \text{ neutron-sec/cc} \quad .$$

To get to θ = 1100°C, the melting point,

$$|\int ndt|_{M.P.} = 3120 \times 1100 = 3.43 \times 10^6 \quad .$$

As heating begins, the Doppler effect causes an increase in reactivity given by

$$\left(\frac{\partial k_{ex}}{\partial T}\right)_D = C_{Do}\left(\frac{T_0}{T}\right)^{3/2}$$

Therefore,

$$(\Delta k_{ex})_D = 2C_{Do}\, T_0\,[1 - \sqrt{T_0/T}\,] \quad .$$

Letting T_0 = 300°K and C_{Do} = $+50 \times 10^{-6}/°K$,

$$(\Delta k_{ex})_D = 0.03\,[1 - \sqrt{300/T}\,] = 0.03\,[1 - \sqrt{300/300 + 3.2 \times 10^{-4}\int ndt}\,] \quad .$$

Up to the melting point, the expansion of the core longitudinally effects a reduction in reactivity:

$$\left(\frac{\partial k_{ex}}{\partial \theta}\right)_E = \left(\frac{\Delta k}{k}\Big/\frac{\Delta L}{L}\right)\delta_{\theta_L} = 0.40 \times 14 \times 10^{-6} = -5.6 \times 10^{-6} \quad ;$$

$$(\Delta k_{ex})_E = -5.6 \times 10^{-6}\,\theta = -5.6 \times 10^{-6} \times 3.2 \times 10^{-4}\int ndt = -1.79 \times 10^{-9}\int ndt$$

The maximum expansion is $0.43/25.5 = 0.0168 = \Delta L/L$ when the spring-held void at the end of the drawer is filled. This would take a temperature rise of 1200°C, which would be above melting point. The blanket pieces in the aft end of the drawer would keep moving so that the core would expand this far. The change in reactivity would be

$$(\Delta k_{ex})_E = -5.6 \times 10^{-6} \times 1200 = 0.00672$$

The $\int$ ndt must rise by a factor of 1200 to give a θ = 1200. This required 7 e-folding times. The inertia of the blanket in the front drawer inhibits the expansion. However, the relation between expansion and time for the core-blanket interface, considering inertia and compression, is given to a good approximation for an exponential rise by

$$\frac{\Delta L}{L} = \frac{4E_c\,\delta\theta_L}{m_B L \alpha^2}\,(e^{\alpha t} - 1) = \frac{6360}{\alpha^2}\,(e^{\alpha t} - 1) \quad \text{for } E_c = 10^7 \text{ psi} = \text{compression modulus}$$

This indicates that for a mean α of 20,000 the change in length can be effected in 7 e-folding times. Since the initial α is only 1732, the inertia of the blanket piece will not significantly inhibit the core expansion.

Therefore, up to 1200°C the above values of $(\Delta k_{ex})_D$ and $(\Delta k_{ex})_E$ are good, and the net value of Δk_{ex} is

$$(\Delta k_{ex})_{1200} = 0.00775 + 0.01658 - 0.00672 = 0.01761 \quad .$$

The period now corresponds to

$$\alpha = \frac{0.01761 - 0.00755}{10^{-7}} = 100{,}000 \quad .$$

The core can no longer expand macroscopically since the U^{235} is melted and must fill the voids in the core first. These voids are clearance voids plus holes in the aluminum filler plates and drawers and amount to $V_V/V_C = 0.32$.

To do this means to expand the U^{235} which occupies 15% of the core into a volume which is 15 + 32 = 47% of the core. It is necessary for the core to vaporize to accomplish this. The temperature must rise to 3900°C and the heat of vaporization must be added. The heat which must be added to raise the U^{235} from ambient temperature to the boiling point is 150 cal/gram. An additional 400 cal/gram must be added for vaporization. Hence the total heat which must be added to vaporize U from room temperature is 550 cal/gram. Since $\Delta E = 1.12 \times 10^{-5} \int ndt$,

$$\left| \int ndt \right|_{vap} = \frac{550}{1.12 \times 10^{-5}} = 4.9 \times 10^{7} \quad .$$

During this heating up period the Doppler effect has not been further reduced by expansion so that the excess reactivity is

$$(\Delta k_{ex})_{vap} = 0.00775 + 0.03 \left[1 - \sqrt{300/4200}\right] - 0.00672 = 0.002293$$

and

$$\alpha_{vap} = (0.02293 - 0.00755)/10^{-7} = 153800 \quad .$$

It is not strictly true that there is no reduction in reactivity during this time because the central portion of the core U^{235} vaporizes first and there is a general motion of fissionable material from the region of greatest effectiveness. However, this ameliorating effect was ignored in these calculations, and, instead, a mean value of α of 125,000 was assumed over the range from the melting point to the vaporization point. The $\int ndt$ rises by a factor of $4.9 \times 10^7/3.43 \times 10^6 = 14.3$, which required 2.66 e-folding times, or about $2.66/125000 = 21\ \mu s$.

At this point the total energy release in the core and the total number of fissions are

$$E_R = 550 \times 2.85 \times 10^5 = 1.57 \times 10^8 \text{ cal}$$

and

$$F_T = E_R\,(3 \times 10^{10}/0.2389) = 1.57 \times 10^8 \times 1.256 \times 10^{11} = 1.97 \times 10^{19} \text{ fissions} \quad .$$

It is now considered that the pressure can build up in the core under constant volume conditions during the first stages of blanket expansion. It is assumed that the blanket has no cohesive strength and only inertial resistance. The pressure is then

$$P = \frac{P_0}{T_0}\,T \quad .$$

If we assume the reactor is rising on a steady period, then the $\int ndt$ is

$$\int ndt = \left|\int ndt\right|_{vap} (e^{\alpha t}) \quad .$$

The temperature rise above vaporization temperature is proportional to the change in $\int ndt$ which is

$$\Delta \int ndt = \int ndt - \left|\int ndt\right|_{vap}$$

$$= \left|\int ndt\right|_{vap} (e^{\alpha t}-1) = 4.9 \times 10^7\,(e^{\alpha t}-1) \quad .$$

During this change at constant volume, a value of $C_v = 0.013$ cal/gram-°C is chosen so that

$$\Delta\theta = 3.2 \times 10^{-4}\,\frac{0.035}{0.013}\,(\Delta \int ndt) = 8.6 \times 10^{-4} \times 4.9 \times 10^7 (e^{\alpha t}-1)$$

$$= 4.2 \times 10^4 (e^{\alpha t}-1)$$

and

$$T = 4200 + \Delta\theta = 4200\,[1 + 10\,(e^{\alpha t}-1)]$$

$$P = P_0\,[1 + 10\,(e^{\alpha t}-1)] \quad .$$

The equation prescribing the time-motion characteristics of the blanket is

$$P = m_B\,\frac{d^2(\Delta r)}{dt^2} \quad ,$$

where P is the pressure in psi, m_B is the mass loading of the blanket on one square inch of the core surface, and Δr is the change in radius of the core-blanket interface.

Now, because of the looseness of the blanket components, the mass loading comes on the core only as the plate and drawer clearances are used up. Thus, the total mass loading of the first blanket box adjacent to the core does not ensue until the radius has changed 0.06 inch on the average. After such a change the mass loading is 0.0030 lb/sec²/in./in.². As the clearance is diminished, m_B becomes larger. By the time the clearance in two boxes is used up, the k_{ex} is considerably reduced. Hence, it seems reasonable to use a value of m_B of 0.0030 lb-sec²/in./in.² as constant.

Then

$$P_0 \, [1 + 10 \, (e^{\alpha t} - 1)] = m_B \frac{d^2(\Delta r)}{dt^2} = 0.0030 \frac{dv}{dt} \quad ,$$

and

$$v = \frac{1}{m_B} \int P_0 \, [1 + 10 \, (e^{\alpha t} - 1)] = \frac{10 P_0}{m_B \alpha} \, [e^{\alpha t} - 0.9 \, \alpha t - 1]$$

$$\Delta r = \int v dt = \frac{10 P_0}{m_B \alpha^2} \, [e^{\alpha t} - 0.45(\alpha t)^2 - \alpha t - 1] \quad .$$

An initial value of P_0 = 120000 psi seems likely from the gas equation. Therefore,

$$\Delta r = \frac{4 \times 10^8}{\alpha^2} \, [e^{\alpha t} - 0.45(\alpha t)^2 - \alpha t - 1]$$

and

$$v = \frac{4 \times 10^8}{\alpha} \, [e^{\alpha t} - 0.45(\alpha t) - 1] \quad .$$

If the α is assumed constant, the value of $\Delta r/r$ after $\alpha t = 2.5$ would be 0.010 and $(\Delta k_{ex})_E = -0.006$, so that the excess reactivity would reduce to 0.0169. However, over the time interval $\alpha t = 2.5$, k_{ex} is being reduced and hence α becomes smaller. By approximate computation, it is estimated that $(\Delta k_{ex})_E$ would be >-0.015 before $\alpha t = 2.5$. This reduces reactivity below prompt critical, so that the nuclear reaction can be considered stopped. The above approximate calculation does not take into account compression of the blanket material which occurs at these high pressures and which would cause k_{ex} to be reduced more rapidly; nor was motion of the end blanket considered. However, it is safe to say that the reaction is stopped 2 e-folding times after vaporization.

At this point

$$P = 120{,}000 \, [1 + 10 \, (7.4 - 1)] = 7.8 \times 10^6 \text{ psi}$$

$$\int n dt = 4.9 \times 10^7 \times 7.4 = 3.6 \times 10^8 \quad ;$$

$$v = \frac{4 \times 10^8}{150{,}000} \, [7.4 - 0.9 - 1] \left(\frac{0.003}{0.065} \right) = 680 \text{ in./sec} \equiv 175 \text{ ft/sec}$$

(assuming the total radial blanket mass loading) .

The total energy release is now

$$E_R = 550 \times 2.85 \times 10^5 \, (\int n dt / |\int n dt|_{vap}) = 1.16 \times 10^9 \text{ calories} \quad .$$

The total number of fissions is

$$F = E_R \, (3 \times 10^{10}/0.2389) = 1.46 \times 10^{20} \text{ fissions} \quad .$$

After nuclear shutoff, the blanket pieces will continue to accelerate until the pressure is relieved. It will be assumed that the vapor expands adiabatically, neglecting the work on the blanket. Then

$$pV^k = \text{constant}$$

and

$$p = p_1 \left(\frac{V_1}{V} \right) = p_1 \left(\frac{r_1}{r} \right)^{3k} \quad .$$

The blanket acceleration is then

$$\frac{dv}{dt} = \frac{p}{m_B} = \frac{p_1}{m_B} \left(\frac{r_1}{r} \right)^{3k} \quad .$$

This can be integrated to give the velocity if the substitution $v = \frac{dr}{dt} = \dot{r}$ is made. Then

$$v dv = \frac{p_1 r_1^{3k}}{m_B} \, r^{-3k} \, dr$$

and

$$v = v_1 \sqrt{1 + \frac{2 p_1 r_1}{v_1^2 \, m(3k-1)} \left[1 - \left(\frac{r_1}{r} \right)^{3k-1} \right]} \quad .$$

At large radii ($r > 2r_1$), where it can be expected that the pressure is relieved, this has a maximum value of

$$v_{max} = v_1 \sqrt{1 + \frac{2 p_1 r_1}{v_1^2 \, m_B \, (3k-1)}}$$

If k is chosen to be $k = 5/3$, $m_B = 0.065$, $v_1 = 680$ in./sec, $p_1 = 7.8 \times 10^6$ psi, $r_1 = 10$ in., then

$$v_{max} = 680 \sqrt{1 + \frac{2 \times 7.8 \times 10^6 \times 10}{680^2 \times 0.065(4)}} = 24{,}500 \text{ in./sec}$$

or

$$v_{max} = 2000 \text{ ft/sec} \quad .$$

Such velocities would certainly result in penetration of the assembly room walls. It has been estimated that if all the heat energy went to heating the room air, the resulting pressure would be more than ample to blow the building apart.

APPENDIX B

REACTIVITY COEFFICIENTS

The nuclear properties of assemblies typical of those to be investigated in the critical facility have been calculated using the multigroup diffusion theory programs set up by Argonne for the UNIVAC at the AEC Computing Facility at New York University. Assemblies were chosen as either typical of those to be constructed, or those, possible to construct, which presented greater hazard in the event of nuclear accident.

Effects of Reactor Expansions and Drawer or Control Rod Worths

The effects of axial and radial expansions for cylindrical reactors, and the effects of control rods were determined by using the one-dimensional solutions, axial and radial, for cores of approximately the same compositions. This follows the usual mathematical approximation of the validity of "split" solution for a reflected cylinder, but eliminates the machine time necessary for iteration to a two-dimensional consistent solution. These calculations were performed using cross section set No. 17, a six-group set. The problem descriptions, with pertinent results, are listed in Tables B-I and B-II. It should be noted that the "split" solution approximation assumes an equivalent bare core except in the dimension under consideration. This does not significantly alter expansion effects or control rod worths in that dimension, but does require a determination of reflector savings in the other dimensions to arrive at a critical mass. The critical masses listed depend strongly on the reflector savings assumed (and also listed) and are intended only as an indication of the types of assembly considered.

Effects of Introduction of Hydrogenous Material

The effect of homogeneous addition of hydrogenous materials to typical reactors has been calculated for three reflected spherical cores, varying widely in enrichment. Reactivity effects were obtained for uniform addition of ten volume per cent addition of water to core and blanket as follows (calculated using a 19-group spectrum, H2, to emphasize low energy effects).

1. Sphere: 26-cm radius core

   Volume fractions: U^{235} - 0.130; U^{238} - 0.173;
   Fe - 0.125; Al - 0.236

   Addition of 10 volume per cent water: $\delta k/k = +0.073$

   Per mole of water in the core: $\delta k/k = +18 \times 10^{-6}$

Table B-1

	1	2	3	4	5	6*	7	8	9	10**	12
CORE											
Geometry	Rt. Cyl.	Rt. Cyl.	Rt. Cyl.	Rt. Cyl.	Sphere	Annular Rt. Cyl.	Sphere	Rt. Cyl.	Rt. Cyl.	Annular Rt. Cyl.	EBR-II Annular Cyl.
Radius, cm	17.2	21	31.3	17.5	21	3.1cm-7cm	7.8	21.1	24	8.2-24.2	8.2-24.2
Assumed Ref. Sav.	15	13	15	13.6				15			
Length cm	76.2	66.2	26	31.6		38.1		42	36.6	46.6	36.1
Assumed Ref. Sav.		15				6.9 one end			15	10	
Core Volume	71×10^3	91.7×10^3	80×10^3	30.4×10^3	38.7×10^3	4.56×10^3	1.99×10^3	58.7×10^3	66.2×10^3	76×10^3	
Volume Fraction											
Fissile & Fertile	0.318	0.318	0.318	0.300	0.300	0.846	0.846	0.318	0.318	0.318	Composition Listed in Table, p. 8
U^{235}	0.142	0.120	0.132	0.191	0.177	0.728	0.702	0.140	0.131	0.159	
U^{238}	0.176	0.198	0.186	0.109	0.122	0.118	0.144	0.178	0.187	0.159	
Fe	0.125	0.125	0.125	0.15	0.15	0.079	0.079	0.125	0.125	0.125	
Al	0.236	0.236	0.236	0.27	0.27	0.017	0.017	0.236	0.236	0.136	
BLANKET COMPOSITION											
Thickness 30 cm, axial and radial (see Table B-II)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	11 cm (2) 19 cm (1)	
Critical Mass, kg for assumed Ref. Sav.	192	208	200	110	130	65	26.5	156	165	230	210
$\delta k/k$ per per cent linear expansion	Axial into spring gap 0.50 Axial Moving Blanket 1.0	Radial 0.5	Axial Fast Heating 0.22 Axial Slow Heating 0.34	Radial 0.45 Axial Slow Heating 0.68	Radial 0.81	Radial 0.46	Radial 0.88	Axial 0.35	Radial 0.77	Radial 0.65	Axial Fast Heating 0.5
Worth of $\delta k/k$, % control rod (1 drawer)						94% enriched rod 23 Graphite rod 5.5			Normal Fuel At Center 2 At Outer Edge 0.8	Normal Fuel At 16.3 cm 1.28	At Center 1.6 At Outer Edge <8.7
Core expansion into central annulus $\delta k/k\%$						8					
Compression of central blanket $((\delta k/k)/(\delta r/r))$										1.1	

*Core annulus contains 0.25 volume fraction Fe

**Core annulus contains blanket composition (2)

2. Sphere: 21-cm radius core

   Volume fractions: U^{235} - 0.178; U^{238} - 0.121; Fe - 0.15; Al - 0.27

   Addition of 10 volume per cent water: $\delta k/k = +0.064$

   Per mole of water in the core: $\delta k/k = +30 \times 10^{-6}$

3. Sphere: 11.5-cm radius core

   Volume fractions: U^{235} - 0.455; U^{238} - 0.018; Fe - 0.153; Al - 0.15

   Addition of 10 volume per cent water: $\delta k/k = +0.032$

   Per mole of water in the core: $\delta k/k = +90 \times 10^{-6}$

4. For an annular core similar to core 10 of Table B-I

   Addition of 10 volume per cent water: $\delta k/k = +0.076$

The first three cores are blanketed with blanket composition (1), the fourth is blanketed similarly to core 10 of Table B-I.

Table B-II

BLANKET COMPOSITION

Material	(1) Volume Fraction	(2) Volume Fraction
Uranium, depleted	0.843	0.55
Iron	0.079	0.136
Aluminum	0.017	0.15

"Fat Man Effects"

Not much in the way of experimental data is available for determining the worth of hydrogenous material as a reflector for dilute fast assemblies. Indications are that, for very concentrated systems, 93% enriched sphere, a 9-inch uranium-238 reflector is worth more reactivity-wise than an infinite water reflector (Tables 1.5.6 and 1.5.9 of Reactor Handbook, Volume I). Preliminary analysis of experiments on the Fast Exponential Experiment at Argonne indicates that for assemblies as dilute as 5 uranium-238 to 1 uranium-235 the effects of uranium-238 reflectors and paraffin reflectors are comparable.*

*Private communication.

Calculations performed with the 19-group spectrum for assemblies in the range of 1:1 to 5:1 give reflector savings for paraffin which vary less than 3 per cent from those calculated for uranium, in this case the paraffin savings being higher. Both calculation and experiment indicate that a cadmium interface reduces the reflector savings for paraffin by about 50%.

Thus, for uranium-reflected assemblies the half core will not become critical with hydrogenous reflector on one end. However, one cannot feel completely safe unless preliminary experiments are performed to determine the effects of hydrogenous moderators on the assemblies. It should be pointed out that the construction of the facility permits close approach only at the separation face.

Effect of Gap Between Assembly Halves

Methods have been developed(1) for the calculation of the effect of transverse gaps on the reactivity of thermal systems. In particular the method of ORNL-1320 has been checked experimentally and agrees well for small gap widths.

This method has been adapted to the calculation of fast neutron systems and used to estimate the effects for three such systems, essentially the systems 1,3, and 8 of Table B-I.

The reactivity loss as a result of gap width is plotted in Figure 18. The maximum slope is about 2% per cm or 5% per inch. For the last six inches of carriage motion the speed is one-half inch per minute, corresponding to a reactivity change of 0.043% per second. The intermediate speed is 12 times faster or 0.52% per second. The reactor must contain at least 24% excess reactivity to become critical with a gap of 6 inches, however. The decision as to drive speeds and separation distances must be a compromise between slowness for safety and speed for operational convenience. It is felt that the speed selected for final assembly is slow enough to insure safety, and that a gap width of 6 inches with its associated reactivity control of 24% is sufficient margin to allow faster motions. The effect of gap width will be investigated experimentally. In no case will motions be allowed which change reactivity at a rate greater than 0.05% per second.

---

(1)Tamor, S., "The Effect of Gaps on Pile Reactivity," ORNL-1320, 1952. Goldberger, M. L. Wilkins, G. E., "The Effect of Gaps on Pile Reactivity," CP-3443, 1946.

APPENDIX C

ENVIRONMENTAL CONSIDERATIONS

A. Reactor Site

The ZPR-III facility is located in the same exclusion area as the EBR-I and the Argonne Fast Source Reactor at the National Reactor Testing Station in Idaho. The current Testing Station map is given in Figure 13. The nearest residential areas are Arco (population 1600) 18 miles west northwest and Atomic City (population 200) 12 miles southeast. A summary of other on-site and off-site population areas is given in Table C-I.

Table C-I

POPULATED AREAS NEAR ZPR-III (1961)

Area	Estimated Population	Direction from ZPR-III	Distance, Miles from ZPR-III
	On-Site Areas		
Central Facilities	1,000	East Northeast	3
MTR-ETR	700	North Northeast	$4\frac{1}{2}$
Chemical Processing Plant	400	Northeast	5
Naval Reactor Facility	1,400	North Northeast	10
OMRE-EOCR	300	East	$5\frac{1}{2}$
SPERT	140	East Northeast	$6\frac{1}{2}$
Army Reactors - AREA	100	East	$8\frac{1}{2}$
Aircraft Nuclear Propulsion	200	Northeast	27
BORAX-EBR-I	100	West Northwest	$\frac{1}{2}$
EBR-II, TREAT	200	East Northeast	18
	Off-Site Areas		
Atomic City	230	Southeast	12
Arco	1,600	West Northwest	17
Howe	75	North	18
Carey	100	West Southwest	55
Terreton-Monteview-Mudlake Area	200	Northeast	36
Roberts	750	East Northeast	47
Rigby	2,300	East	56
Idaho Falls	33,000	East	50
Shelley	2,700	East Southeast	45
Blackfoot	7,500	Southeast	38
Pocatello-Alameda-Chubbuck	40,000	South Southeast	50

B. Hydrology[1C]

The National Reactor Testing Station is located on a level plain at an average elevation 4865 ft ranging from an elevation of 4775 to 5400 ft above sea level.

The surface of much of the plain is covered by waterborne and windborne top soil under which there is considerable depth of gravel ranging in size from fine sand to 3 in. in diameter. At the several locations inspected to date, the gravel lies from approximately 1-50 ft under the top soil. Lava rock extends below the gravel layer downward to a considerable depth, ranging at least to the water table. The lava rock is honey-combed with openings of $\frac{1}{8}$ in. in diameter. Frequently large openings occur and these range upwards to the size of tunnels, tubes and caves. What little surface drainage there is, is towards the northeast opposite to the main body of water flow. Normally, surface drainage is small due to the high porosity of the gravel overburden. The testing station overlies a natural underground reservoir of water having an estimated lateral flow of not less than 500 cubic ft/sec (323,136,000 gal per day).

The main sources of water for this reservoir are the streams which start in the mountains to the north and disappear into the porous soils of the NRTS area. These streams include the Big Lost River, the Little Lost River and Birch Creek.

While the path of water-flow from the surface to the ground water level is unknown, it is expected that the drainage would be rapid. The flow will be very rapid through the gravel overburden while the drainage through the lava rock would be less rapid, but still very high compared with flow through sands or clays. It is expected that the flow would be around rather than through the clay beds.

The estimated rate of flow of the main body of water through the lava is approximately one-half mile per year. Based on this estimate contaminated water would reach the Snake River in Canyon Springs and enter the Snake River in about 120 to 140 years, depending on the exact location of the reactor plant within the testing station area.

REFERENCE

1C. Koch, L. J., et al., Hazards Summary Report, EBR-II, ANL-5719 (May 1957).

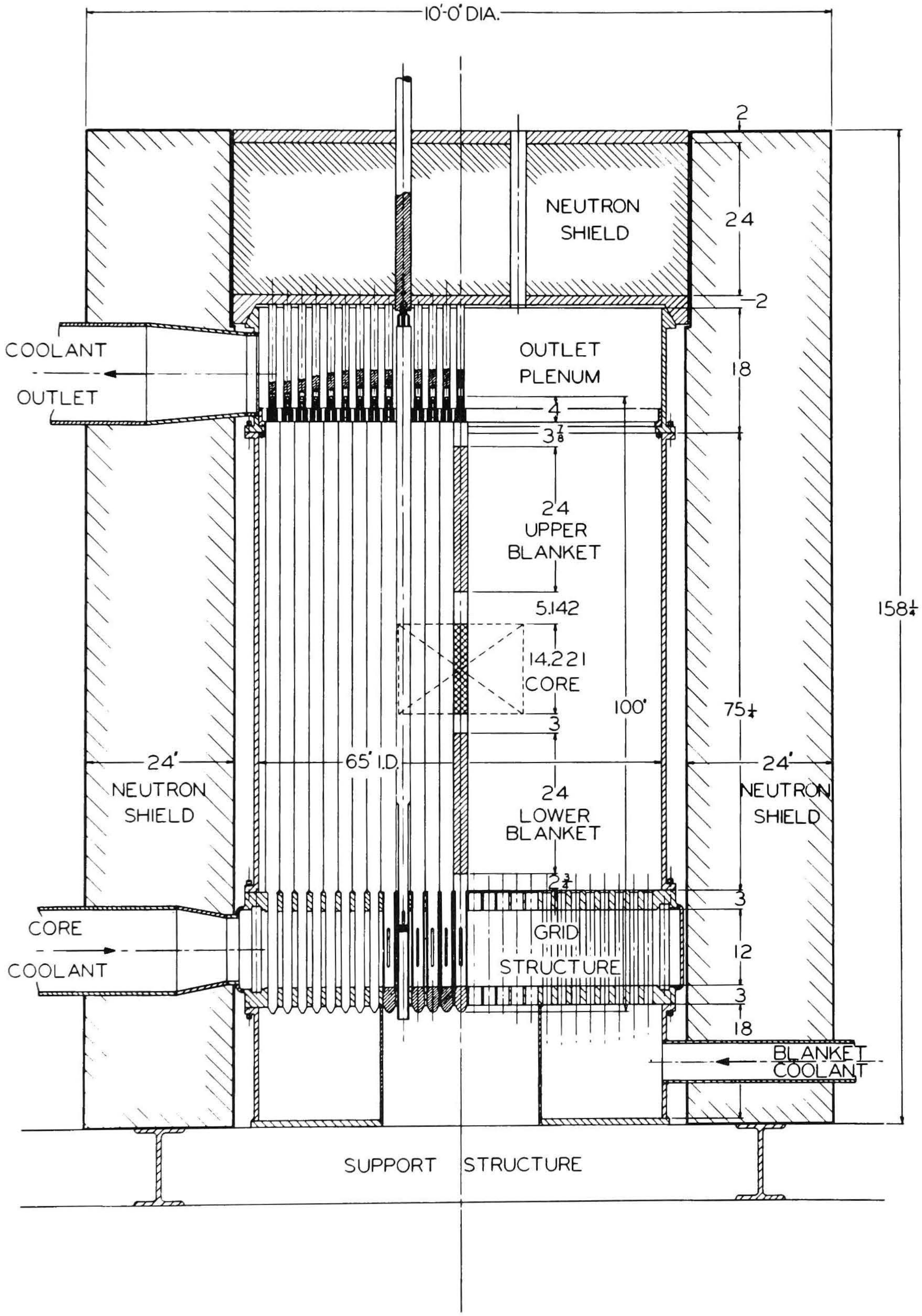


Figure 1

EBR-II Reference Design Core Elevation

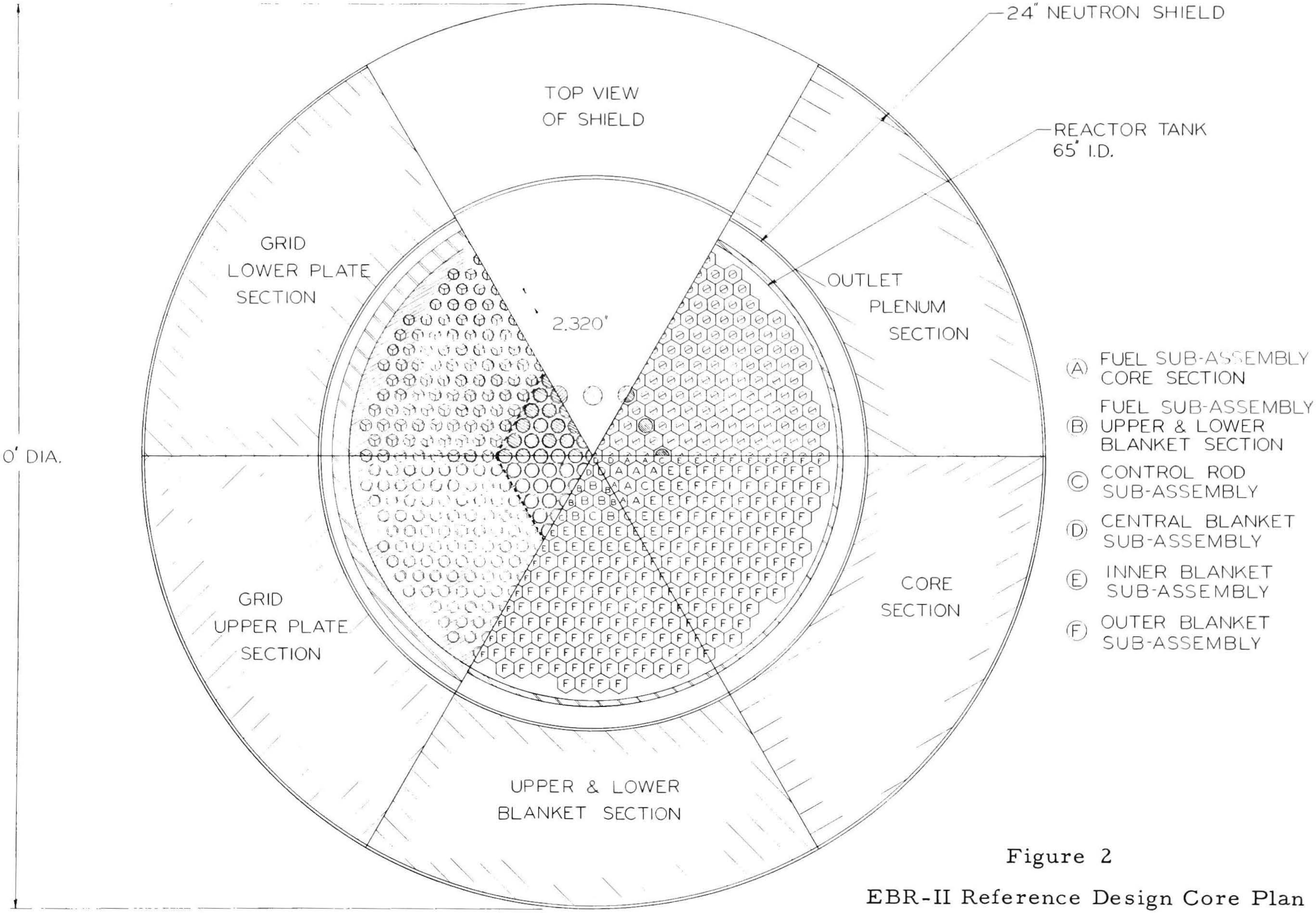


Figure 2

EBR-II Reference Design Core Plan

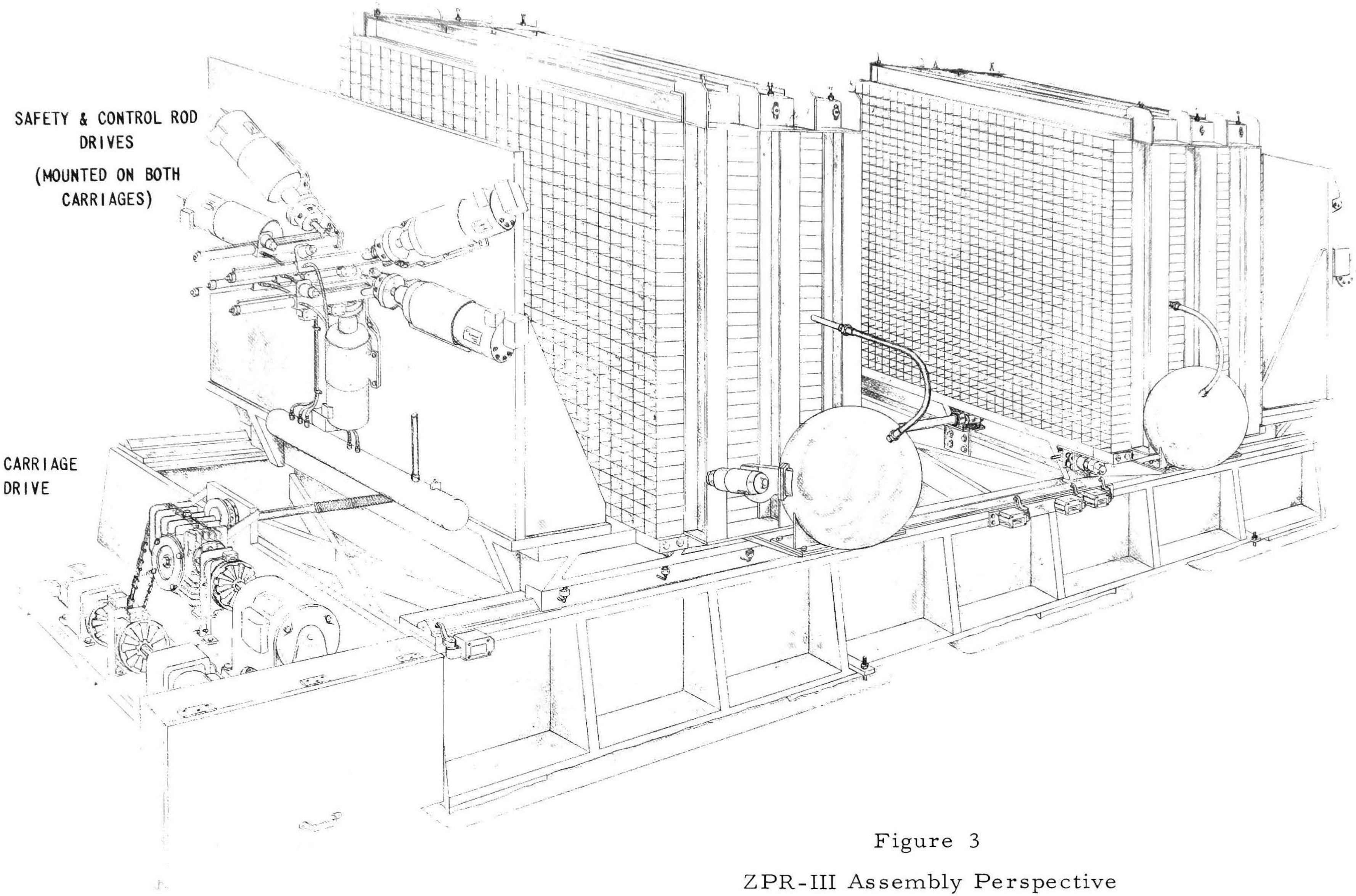


Figure 3
ZPR-III Assembly Perspective

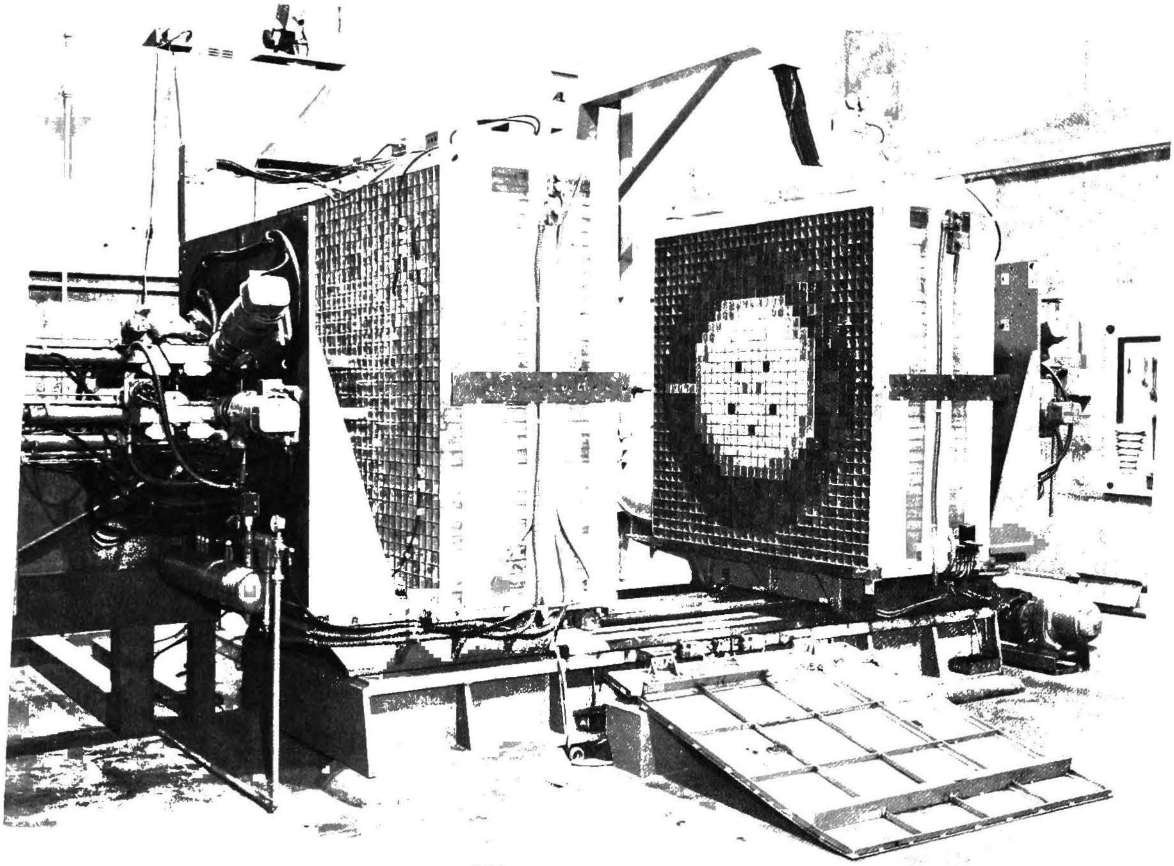


Figure 3a

Photograph of ZPR-III Assembly

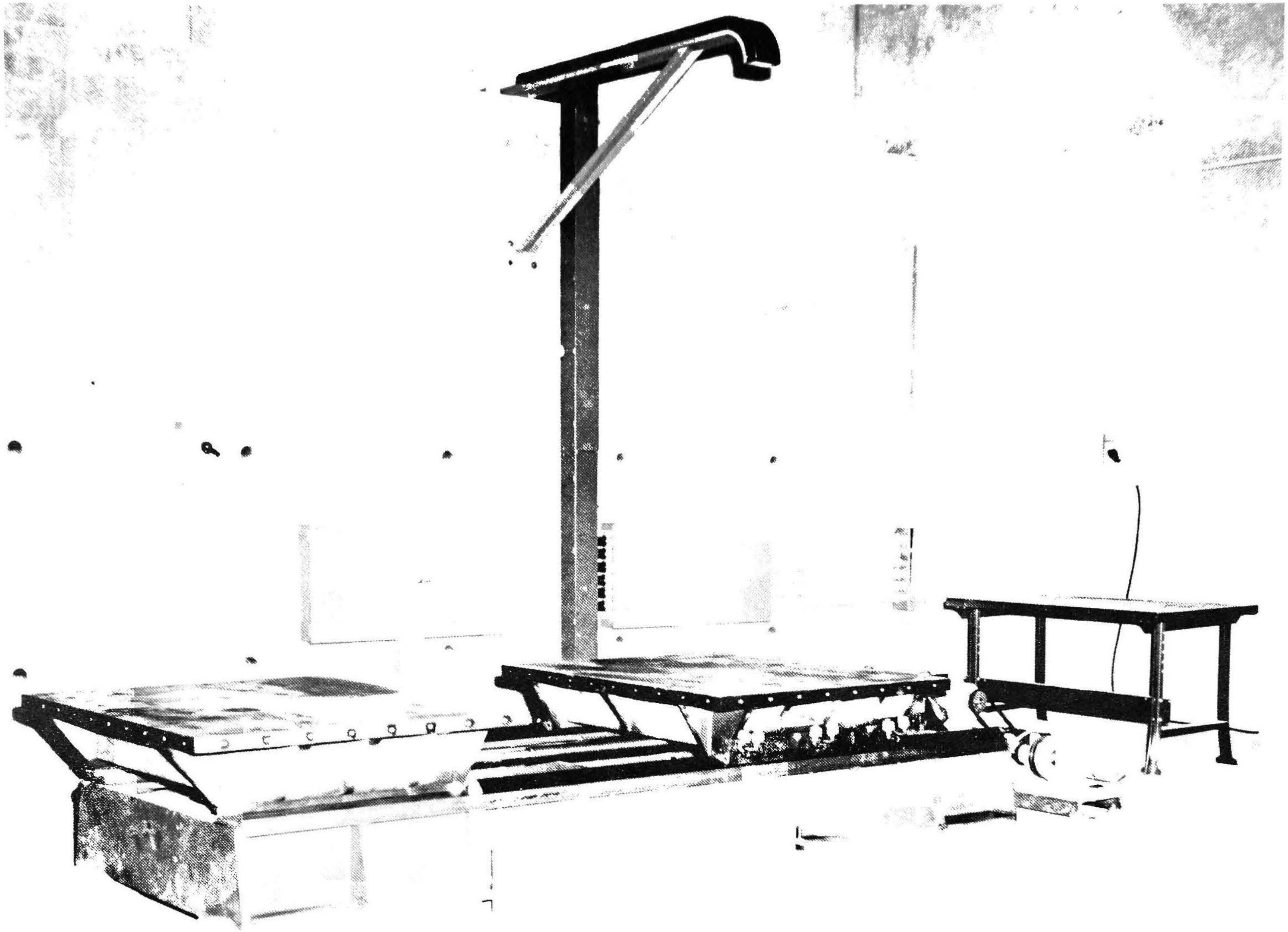


Figure 4

Carriage Assembly

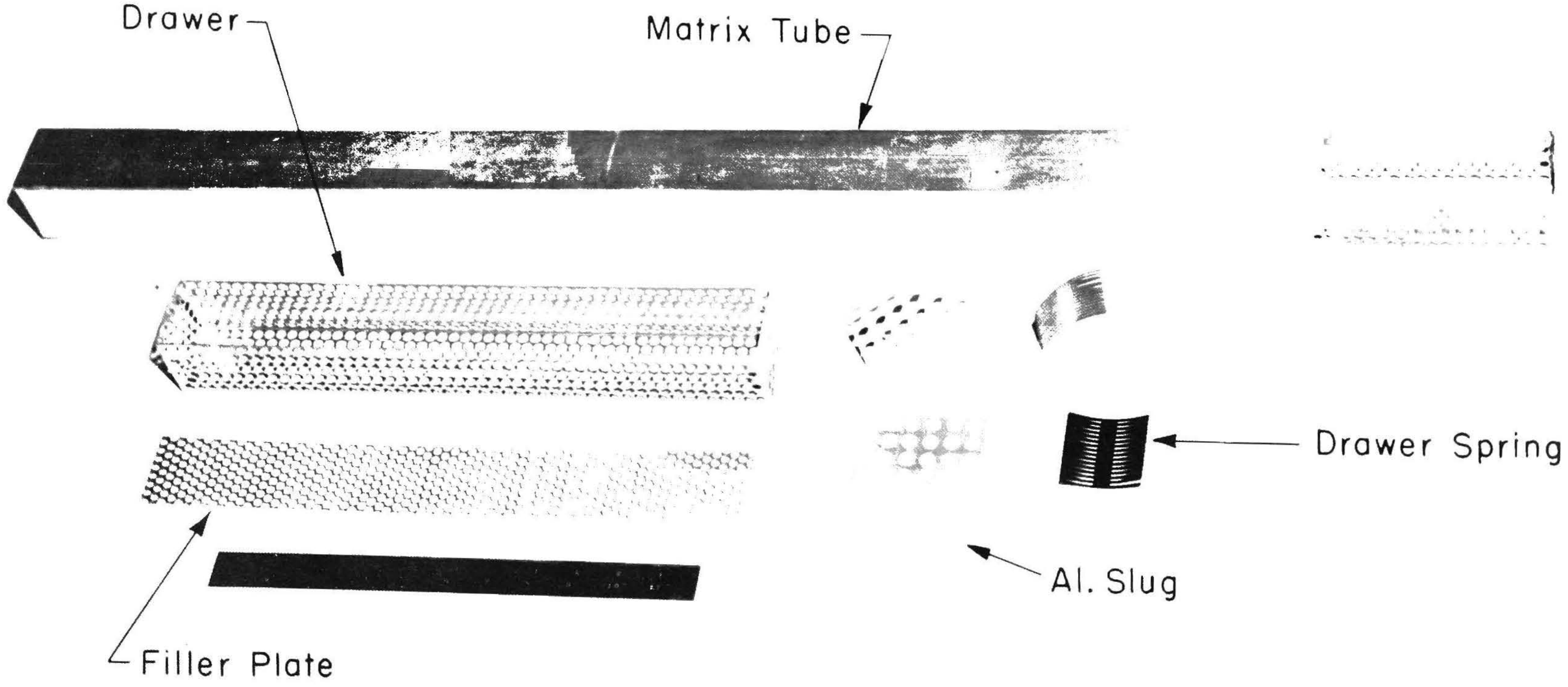


Figure 5

Matrix Tube and Drawer Components

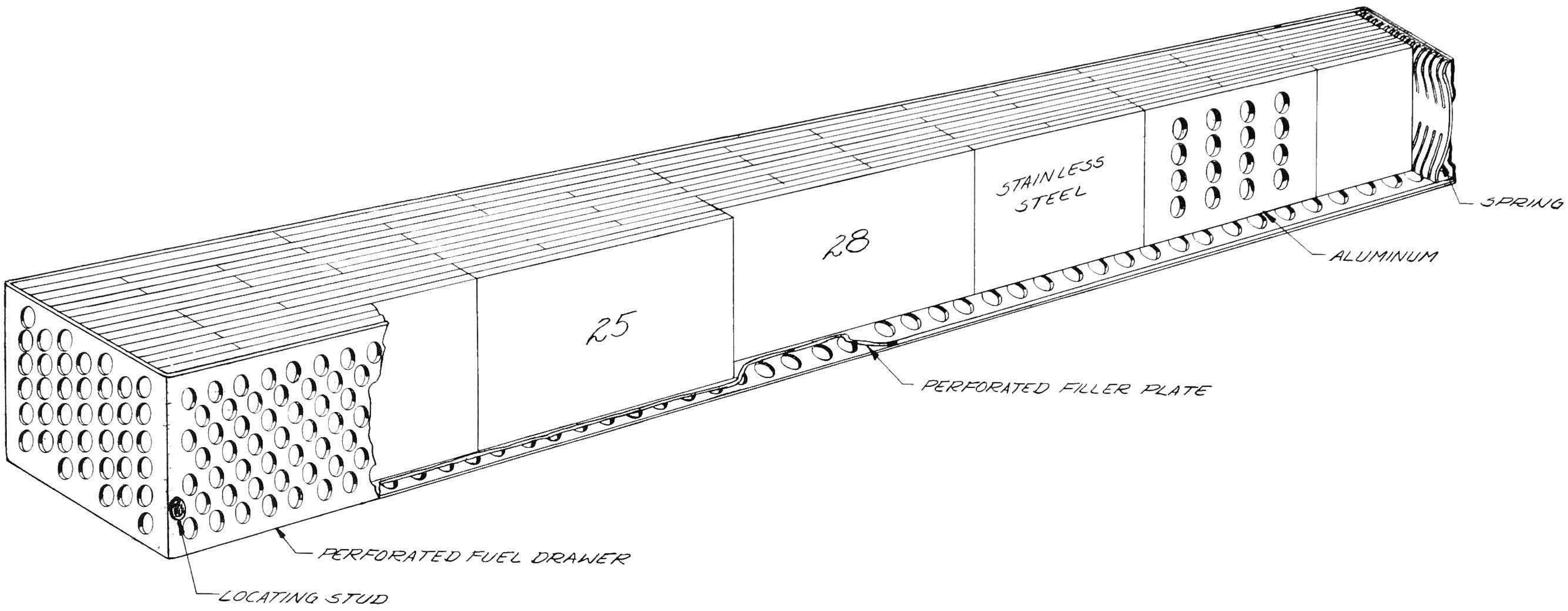


Figure 6

Typical Loaded Core Drawer

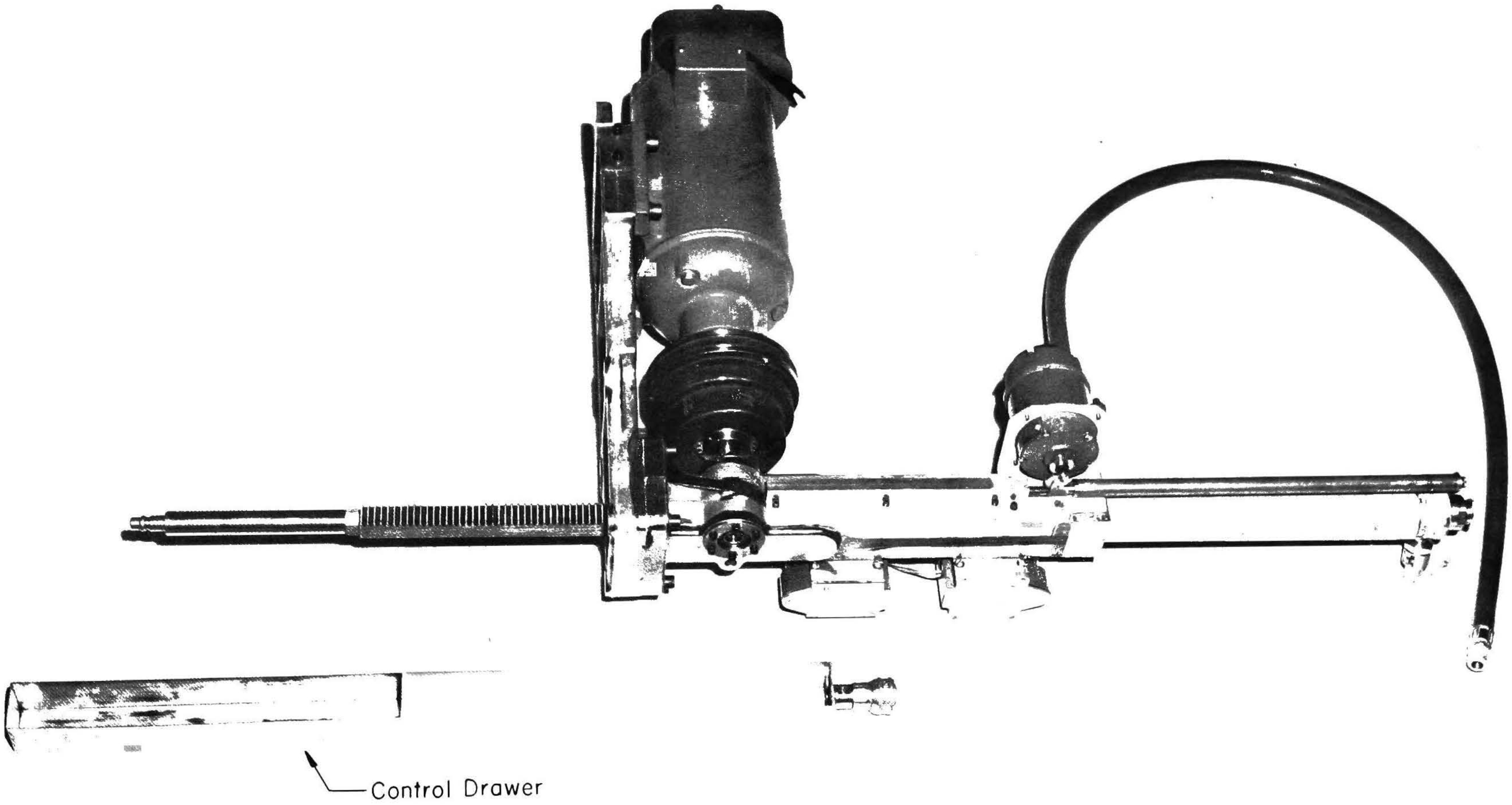


Figure 7

Control-Safety Mechanism and Control Drawer

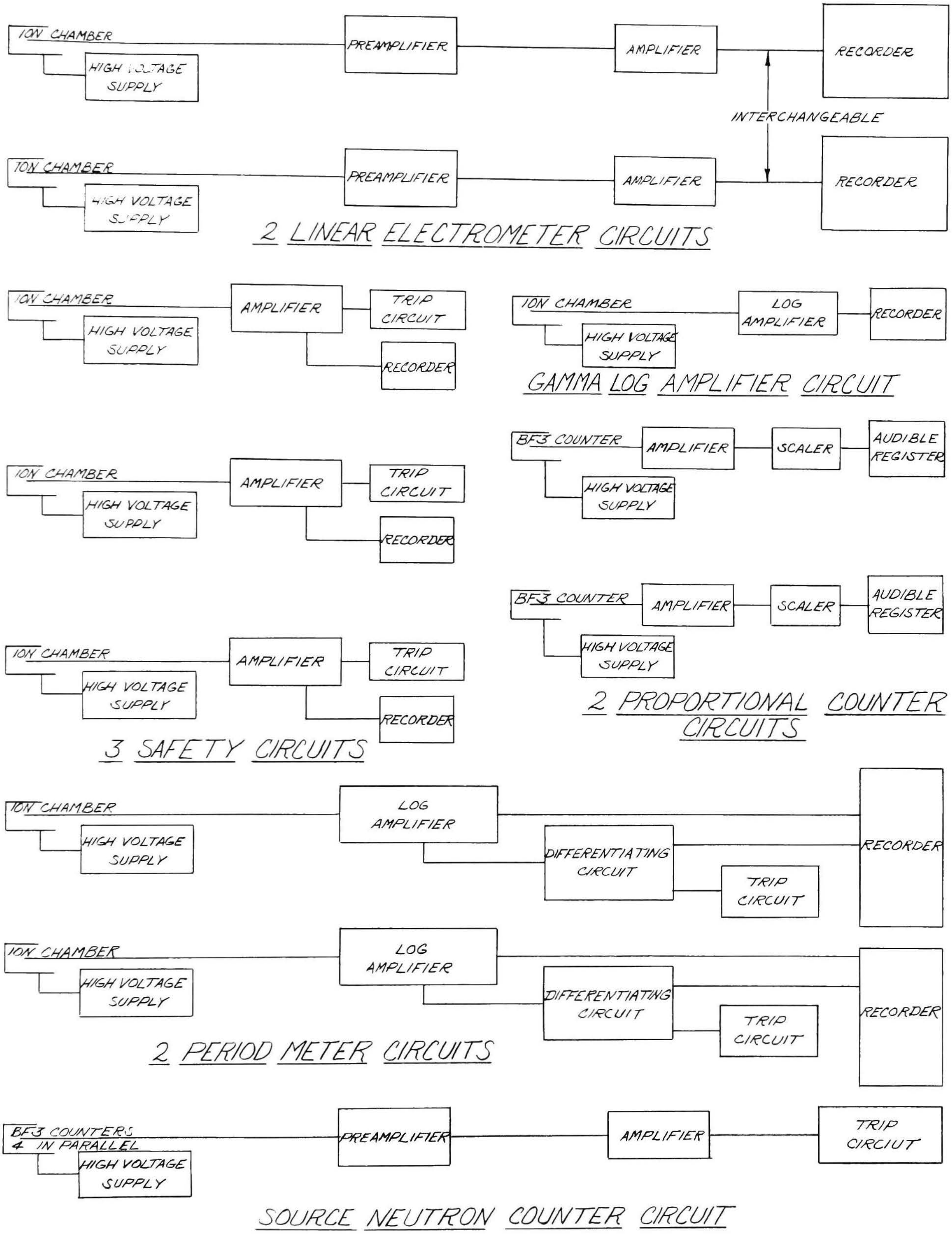
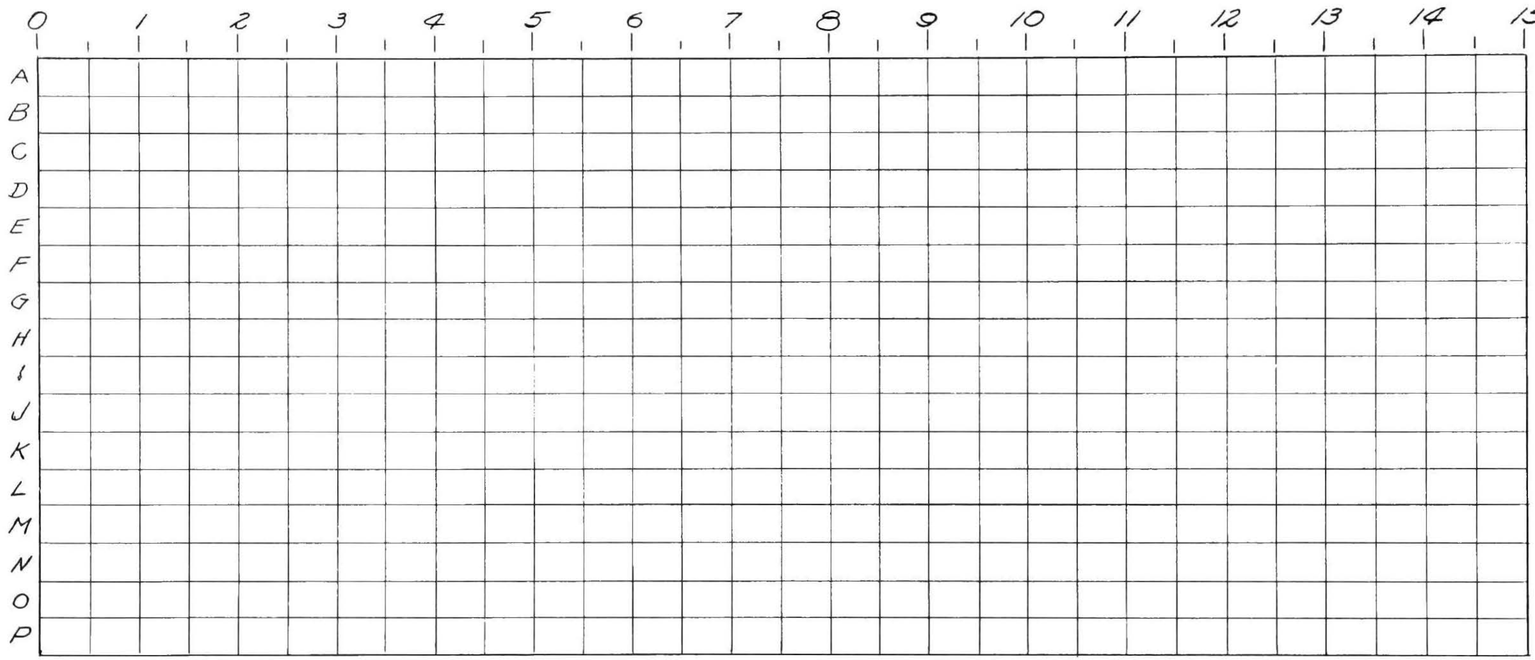


Figure 8

Block Diagram of Instrumentation

LOADING TYPE ________ DRAWER NUMBER ________ DATE ________



IS SPRING IN BACK OF DRAWER ☐

TOTAL WEIGHT IN DRAWER

☐ 25 ______________

☐ 28 ______________

☐ AL. 63 % DENSITY ______________

☐ AL. 56 % DENSITY ______________

☐ AL. 45 % DENSITY ______________

☐ STAINLESS STEEL ______________

LOADED BY ______________

CHECKED BY ______________

APPROVED BY ______________

Figure 9

Sample Drawer Loading Chart

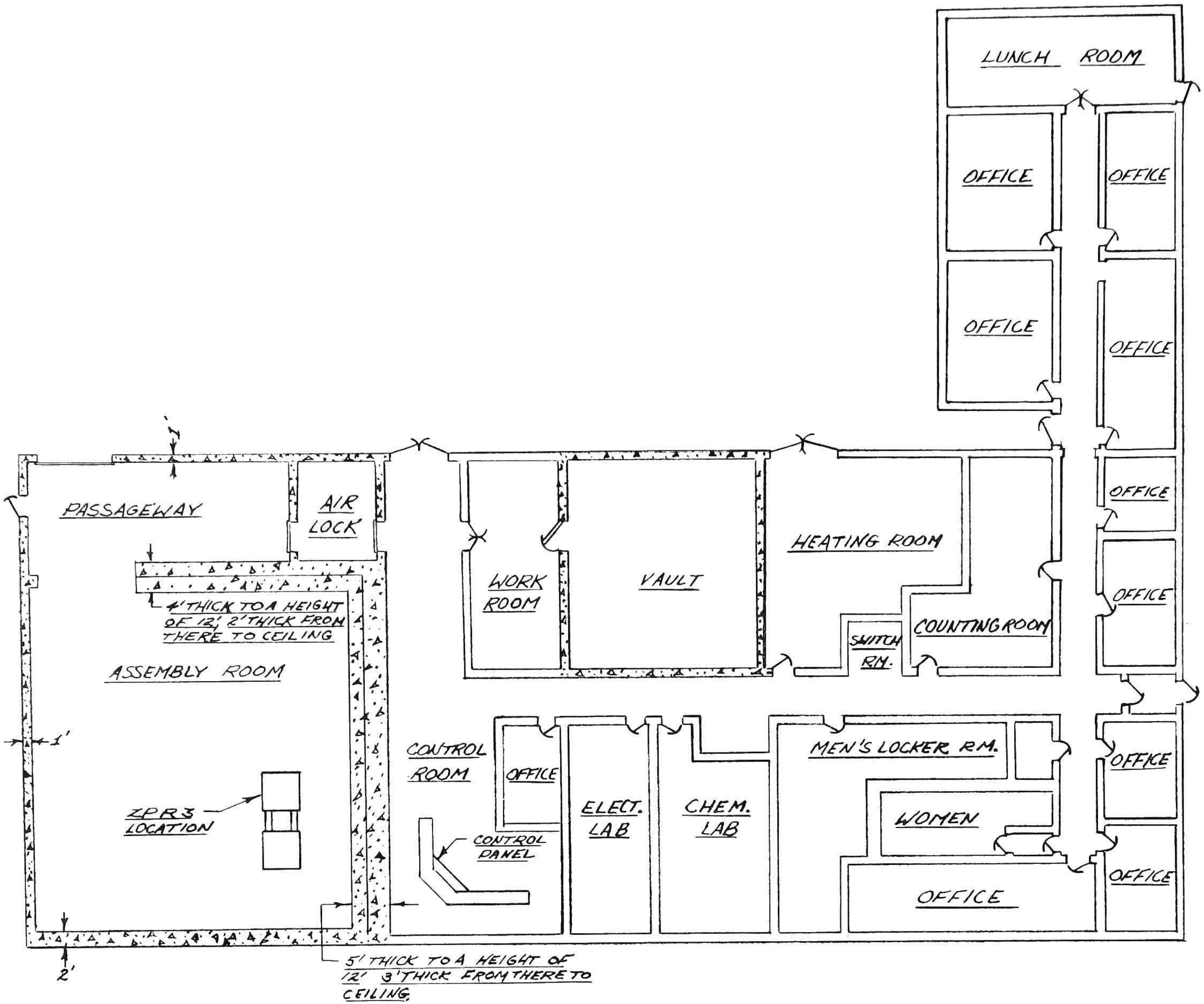


Figure 10

Floor Plan for ZPR Building

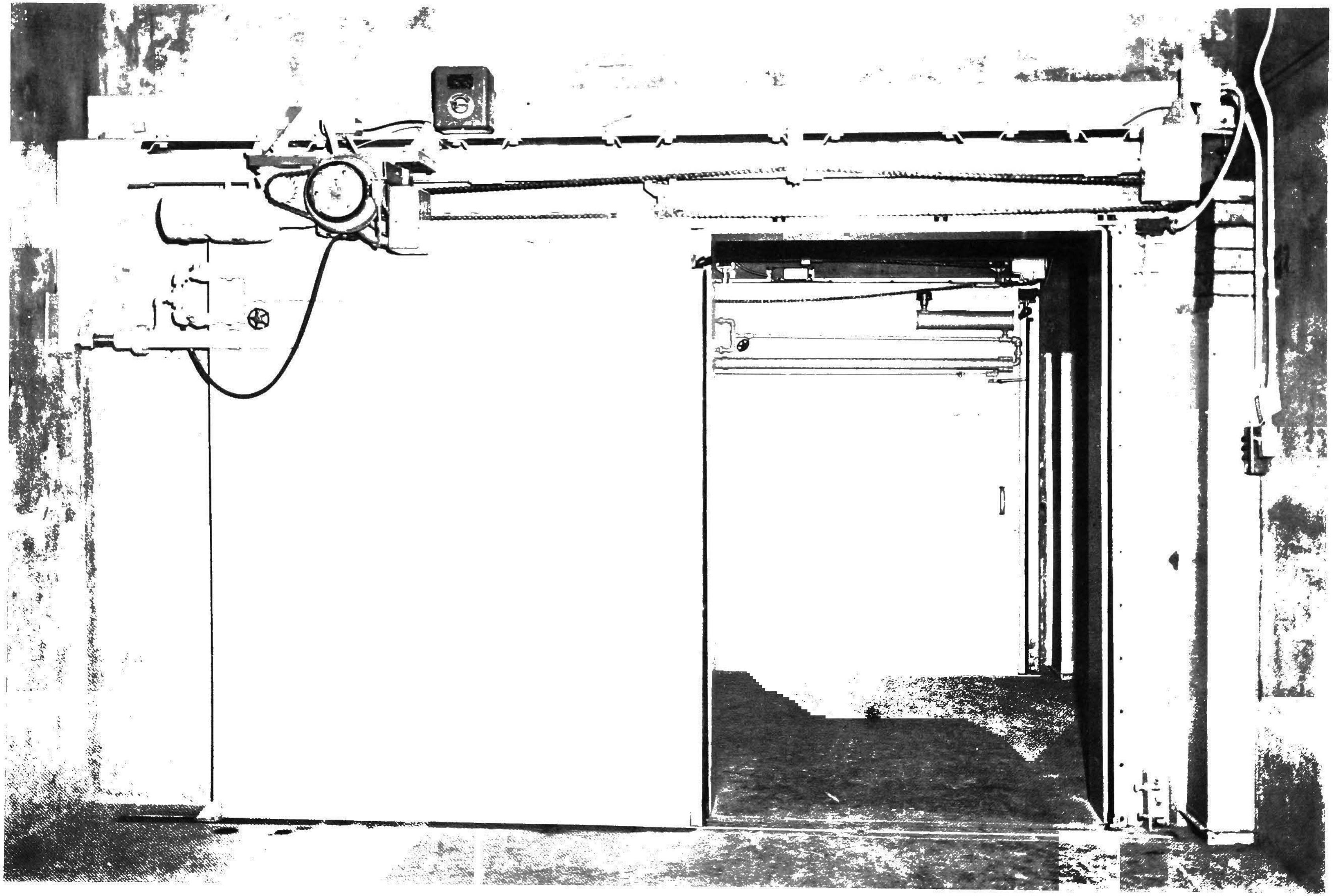


Figure 11

Airlock Entrance to Assembly Room

Figure 12
Control Console

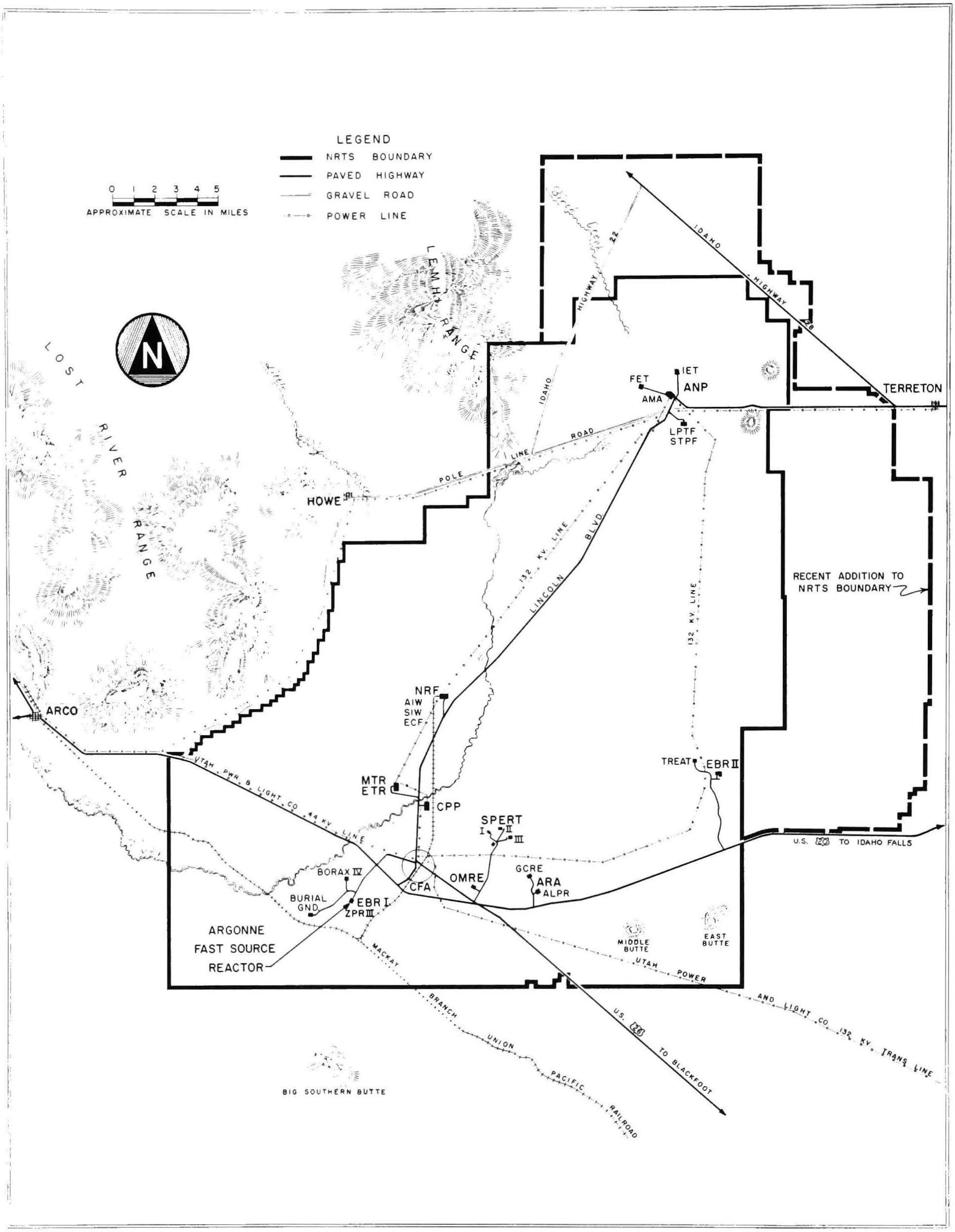


Figure 13

NRTS Site Plan

Fold
out

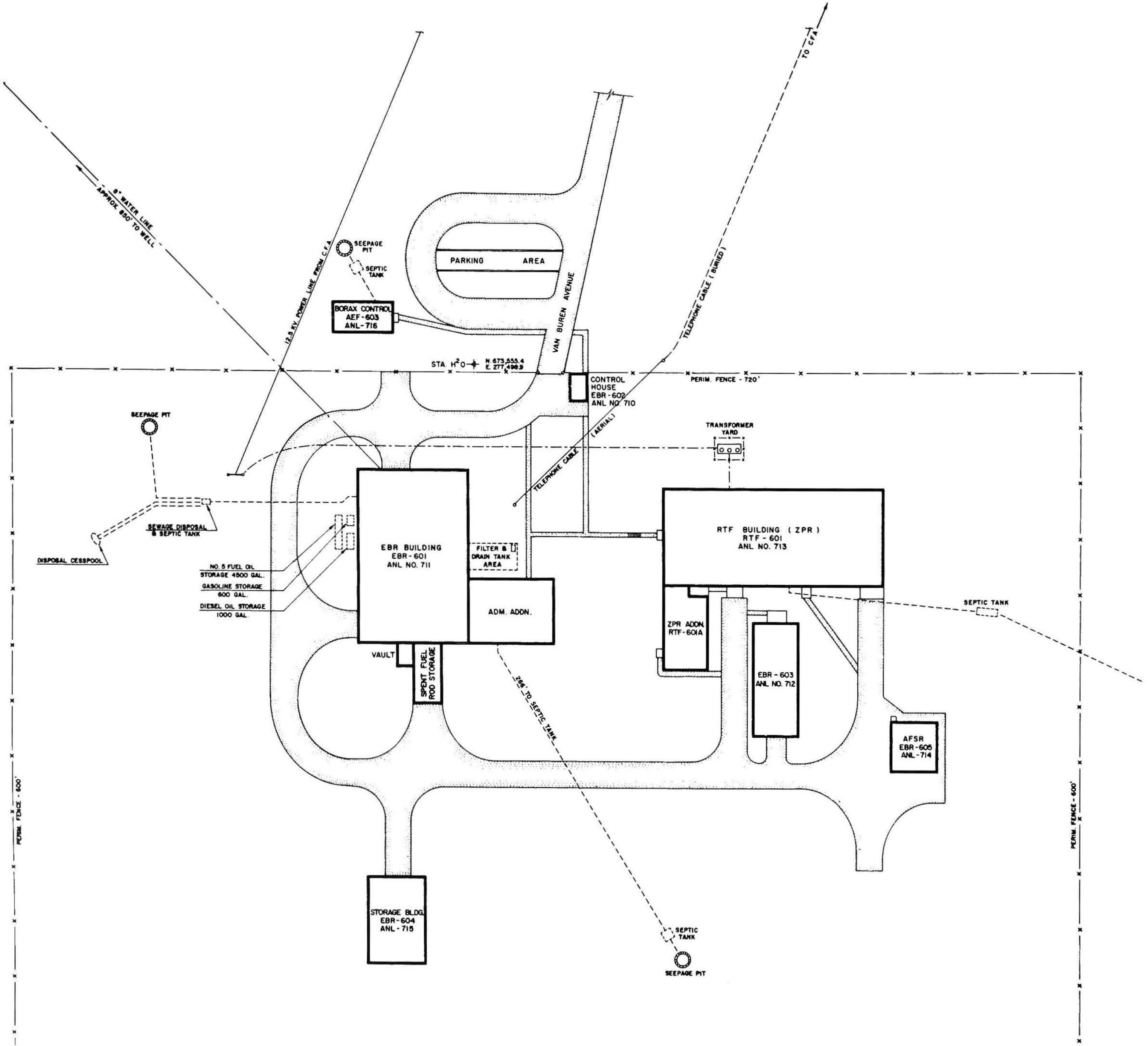


Figure 14

EBR Area P

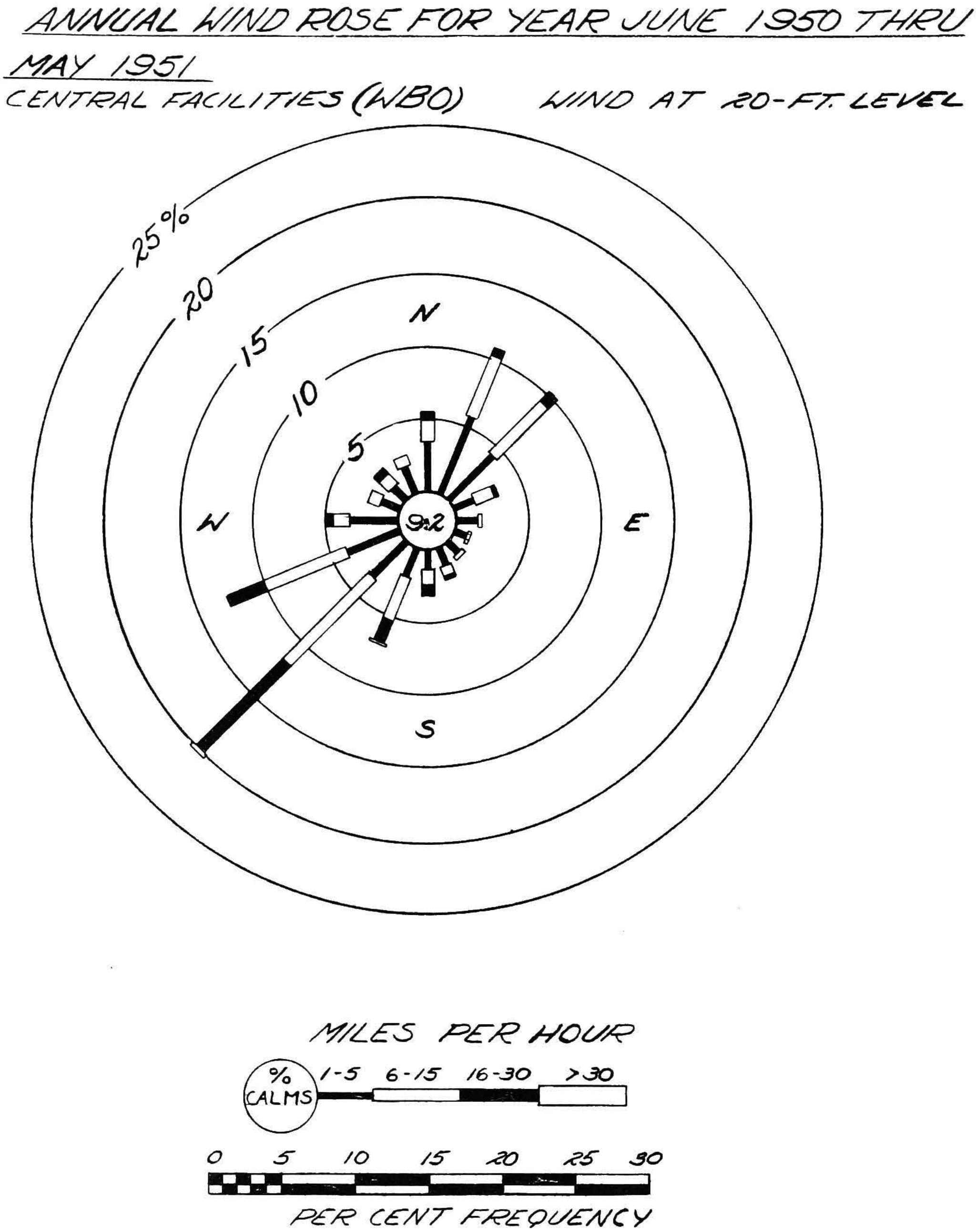


Figure 15

Wind Rose

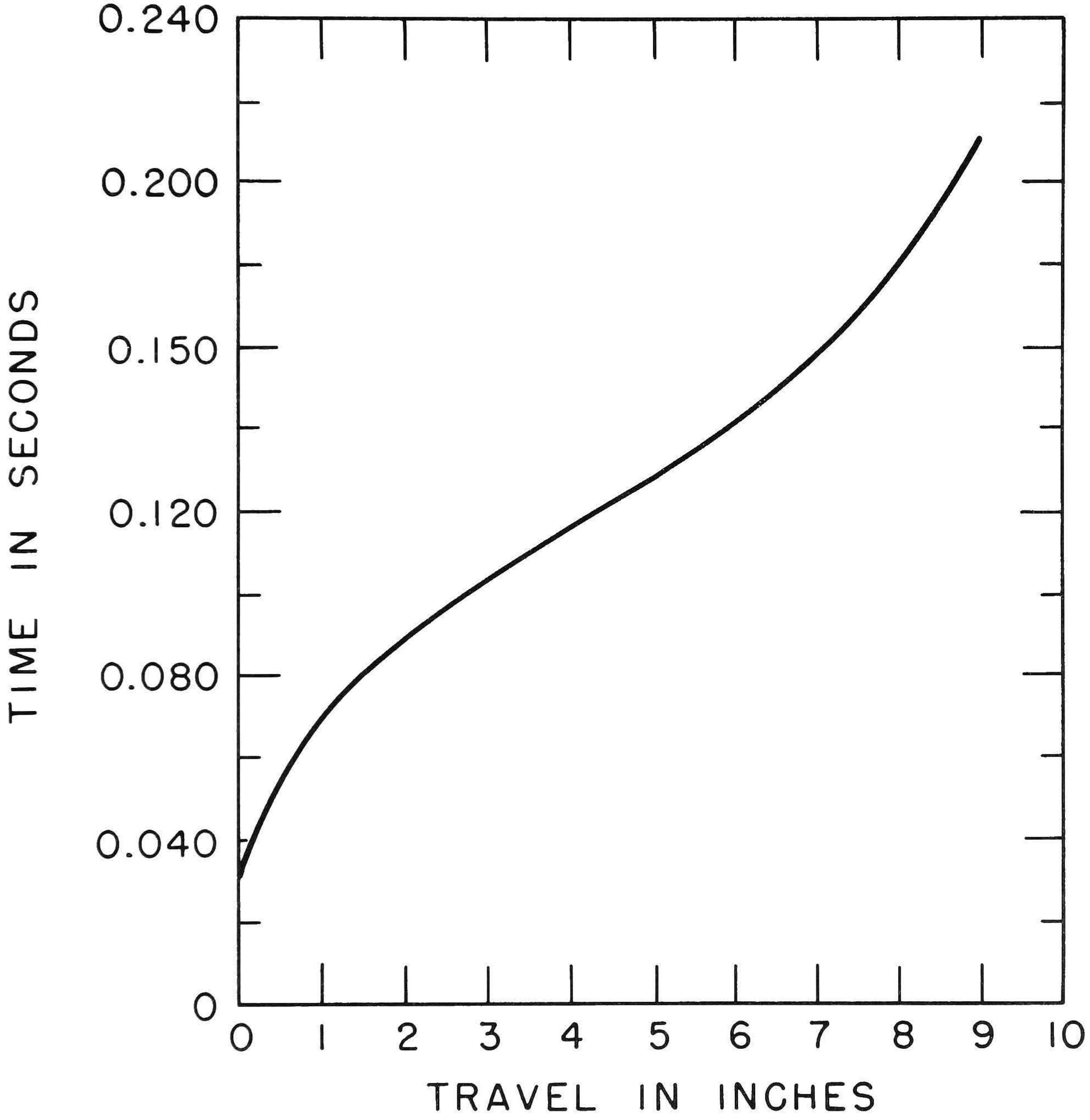


Figure 16

Time-Motion Performance of Safety Rod

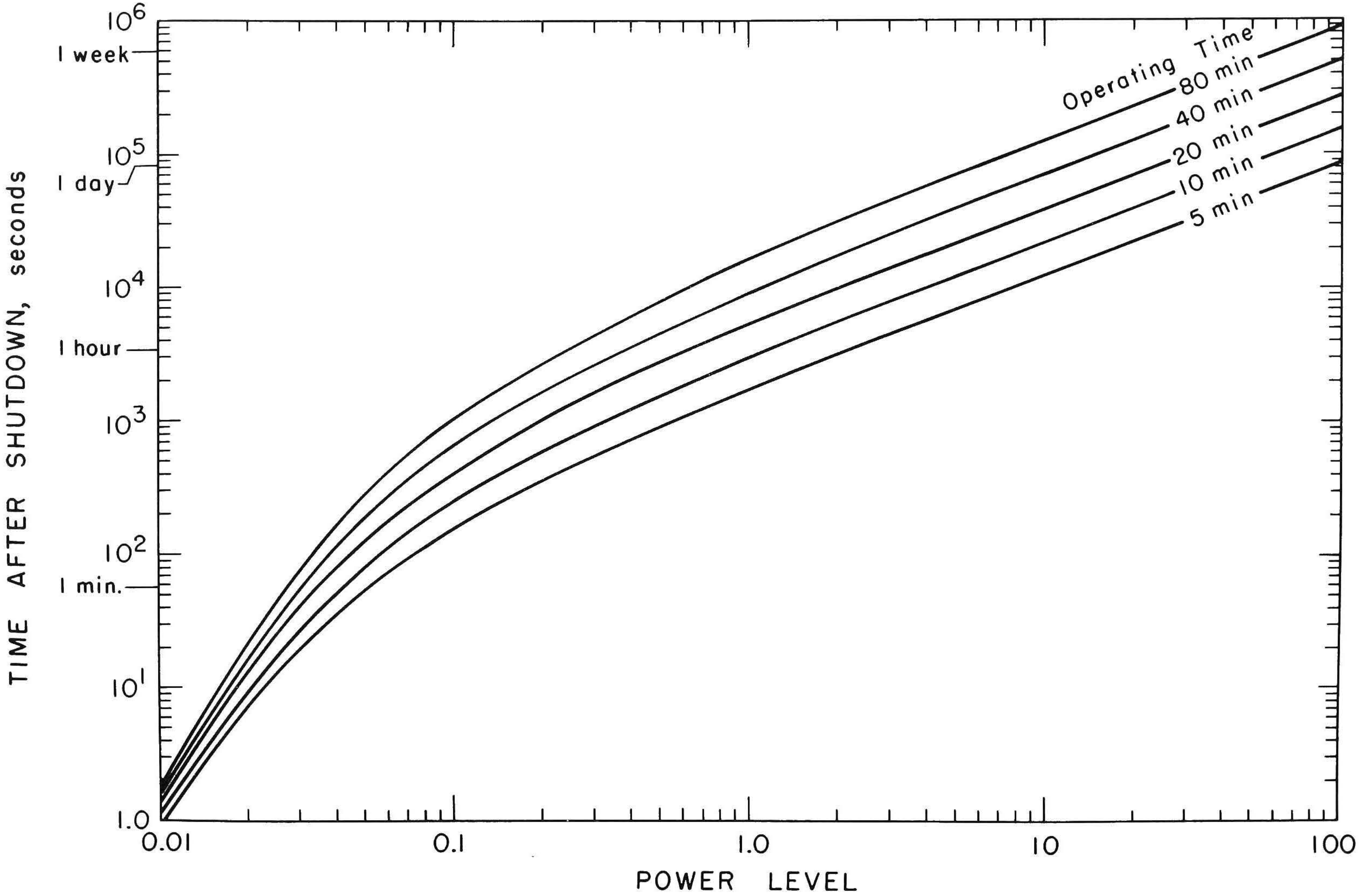


Figure 17

Waiting Time for 100 mr/hr Between Halves

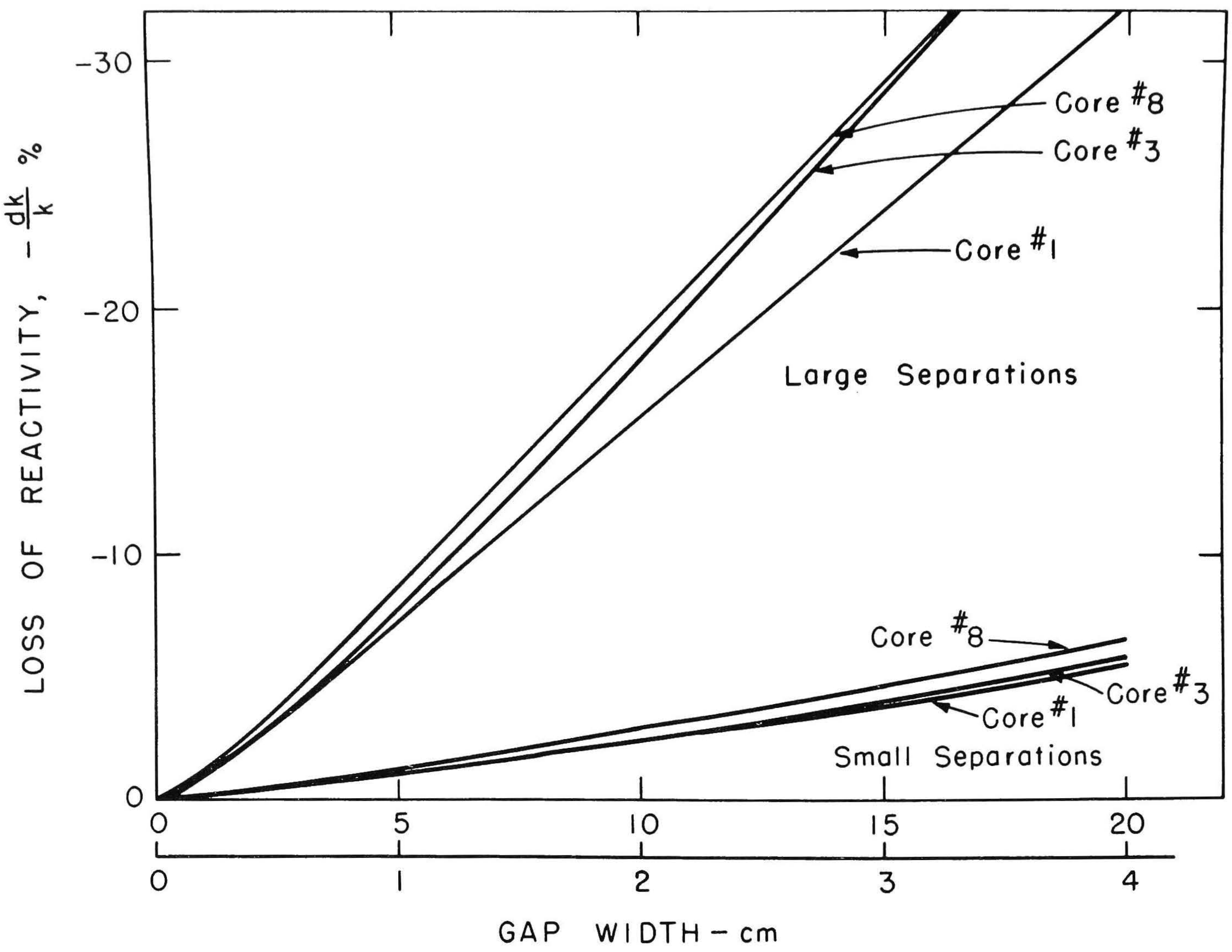


Figure 18

dk/k vs Gap Between Halves

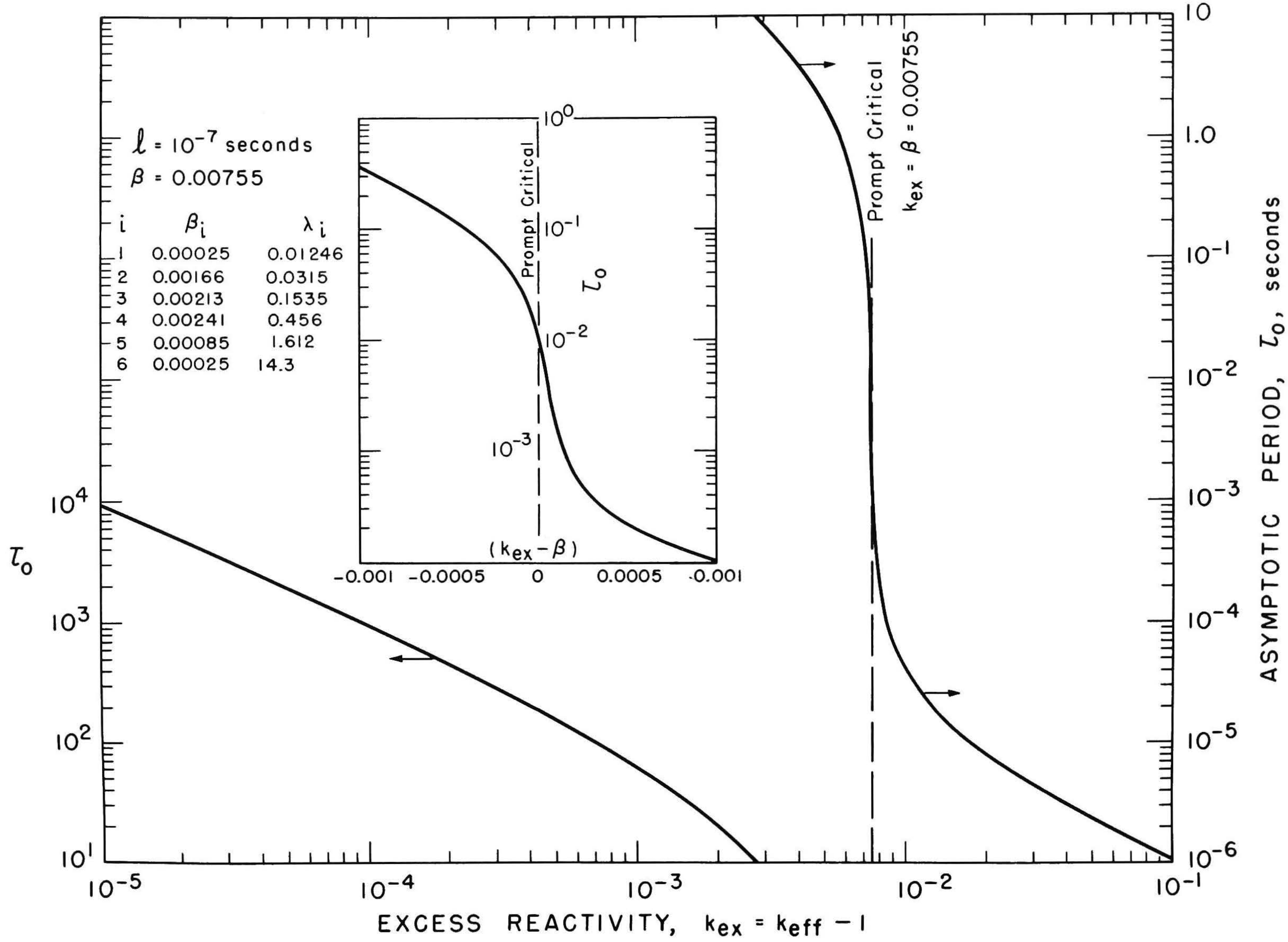


Figure 19

Asymptotic Period vs Excess Reactivity

X

B