THE DESIGN, CONSTRUCTION, AND CALIBRATION OF A FLEXIBLE CONTROL ROD FOR THE V. P. I. SUBCRITICAL REACTOR

by

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INTRODUCTION

The introduction of a graduate program in Nuclear Engineering Physics at Virginia Polytechnic Institute was made in September 1956. Since that time, one of the experimental facilities constructed was a graphite moderated, natural uranium, subcritical reactor. During the period of its operation, the reactor has been a source of considerable experimentation. However, in order to make the reactor a more realistic test facility and further instruction in the basic operating principles of reactors, the installation of a control rod was necessary.

The problem of installing a control rod in the subcritical assembly is complicated by the limiting two foot clearance between the top of the reactor and the ceiling. Within this space it is necessary to insert and operate an effective seven foot, solid, straight rod along the vertical axis of the reactor. In addition, it is desirable that a provision be made for changing the neutron absorbing material in the control rod in order to permit further investigation of materials having various neutron absorbing properties.

A flexible control rod satisfying the above requirements was designed and constructed. The initial tests, using cadmium as the neutron absorbing material, are to determine the effect of the control rod on the neutron flux in the vicinity of the rod and to determine if a control rod so constructed is effectively a solid, straight rod.

REVIEW OF LITERATURE

Seven years had elapsed after the discovery of the neutron by Chadwick in 1932 before Hahn and Strassman, using the neutron, produced the fission of uranium in 1939. The energy release suggested by Einstein's $E = mc^2$ and the possibility of a chain reaction were soon confirmed, and in 1942 Fermi and his associates developed the first nuclear reactor(54).

Since that time, the importance and unlimited potential of nuclear power has given rise to extensive research and development in all phases of nuclear reactor technology. The results of this effort, written at various laboratories, has been collected and published by the government in the form of United States Atomic Energy Commission Research and Development Reports. These unclassified documents--together with the theory and basic concepts carefully put forth by Glasstone(14), Glasstone and Edlund(24), Murray(45), Schultz(56), Stephenson(68), and others--have been the major sources of reference regarding the specific area of concern here; i.e., reactor control and, in particular, the various elements affecting the optimum design of reactor control rods.

To determine the feasibility of a proposed design, the factors influencing the individual behavior of control rods are carefully considered. These include the intended purpose and type of control rod required(23)(51)(60)(71); the size, shape, and location of the control rod(3)(73); the neutron absorbing material used and its degree of "blackness"(1)(72)(73); and finally the cost(39)(76). Supplementing these considerations and an important aid in minimizing the uncertainties of predicted performance is the evaluation of previously designed control rods through calibration techniques(4)(6)(7)(11)(33)(35)(36)(42)(43)(53)(64).

The design of a flexible control rod as presented in this thesis is the solution to a problem which is not common, and, as a result, the literature reviewed gives no indication that this or any similar design has previously been considered. In addition, the procedure used in calibrating the control rod differs from those cited in the literature. It is concluded that for this particular thesis problem the methods of approach are new for both the design and calibration of a control rod.

DESIGN

Control Rod

The control rod design for a subcritical reactor having no space limitation presents little or no problem, since the rod is not necessary for limiting the fission process. A rod containing the neutron absorbing material and a mechanism for inserting and withdrawing the rod in the reactor is a satisfactory method for demonstrating the effect of a control rod on the neutron flux in the reactor. For the Virginia Polytechnic Institute reactor, however, the requirement is hampered by the limiting two foot clearance between the top of the reactor and the ceiling. Within this space it is necessary to insert a seven foot rod together with a provision for operating the rod along the vertical axis of the reactor while still maintaining the effect of a solid, straight rod on the neutron flux.

To overcome this problem, a flexible control rod was designed. The size of the rod is governed by the dimensions of the hole provided for the control rod in the reactor. This 2-1/2 inch square hole along the vertical axis of the reactor extends from the top of the reactor to a depth of seven feet. The rod is made 2-1/4 inches in diameter which allows 1/8 inch clearance between the rod and the sides of the hole. This amount of clearance is necessary due to the irregularities along the walls of the control rod hole. The total length of the rod is nine feet. This allows for two additional feet of rod to be connected to the rod-drive mechanism when the control rod is fully inserted in the reactor.

In order to have the control rod flexible and still maintain the effect of being solid and straight, the rod is cut into eighteen six-inch sections at an angle of 45 degrees and is connected by internal pivoting arms. These pivoting arms are designed to operate internally in order that the surface of the rod will be uniform throughout its length. This will insure the neutron absorption properties of the control rod to be uniform. These properties will also be free of neutron flux disturbances which may be caused by dissimilar metals on the control rod surface.

The internal pivoting arms, together with the 45 degree angle-cut of the rod sections, allow each section to break 60 degrees with respect to each adjacent section. Figure 1 shows that this method makes it possible for the rod to be taken out of the reactor within the two foot clearance and still effectively present a solid, straight rod to the neutron flux when inserted into the reactor.

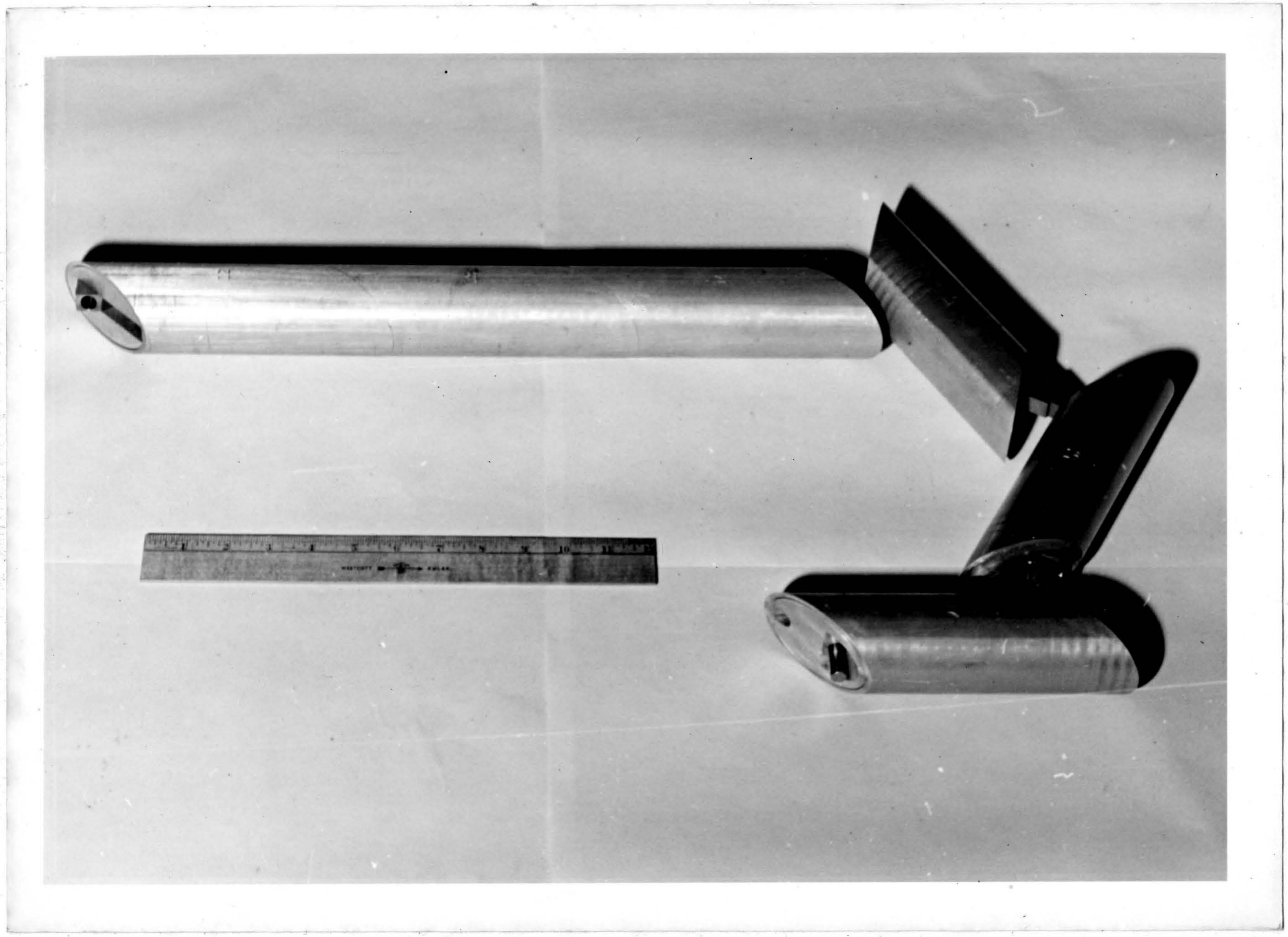


Figure 1. Six Control Rod Sections Assembled.

The pivoting arms are attached to the rod sections by means of a pivot pin through the diameter of the rod base. Each section is then assembled to its adjacent section by connecting the opposite end of the pivoting arm to the coupling pin of the adjacent rod section. The pivoting arm is secured to the coupling pin by means of a retaining clip which makes quick assembly and disassembly of each control rod section possible. Figures 2, 3, and 4 show this method of connecting the rod sections and the design of the rod base and associated components, respectively.

To make the rod a more versatile piece of equipment, it is desirable that a provision be made for changing the neutron absorbing material. Hence, materials with various neutron absorbing properties and their effect on the neutron flux can be investigated.

This is accomplished by placing the neutron absorbing material in protective tubular sleeves which are also six inches in length and are cut at a 45 degree angle. The sleeves are then slipped over each rod section together with a circular shim. This shim eliminates the slack between the lined sleeve and the rod section. (For neutron absorptive materials having different thicknesses, shims of appropriate size will be used.)

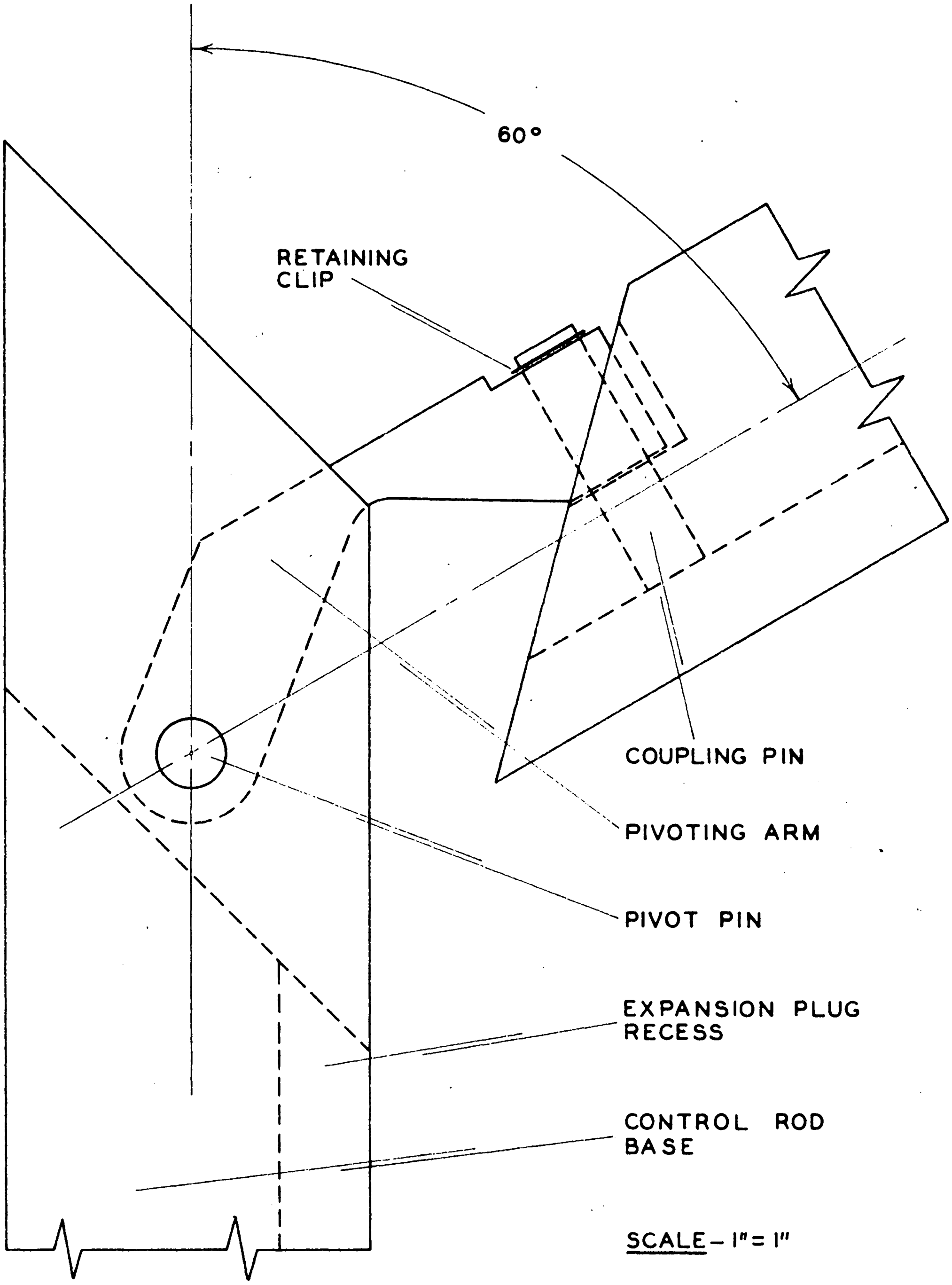
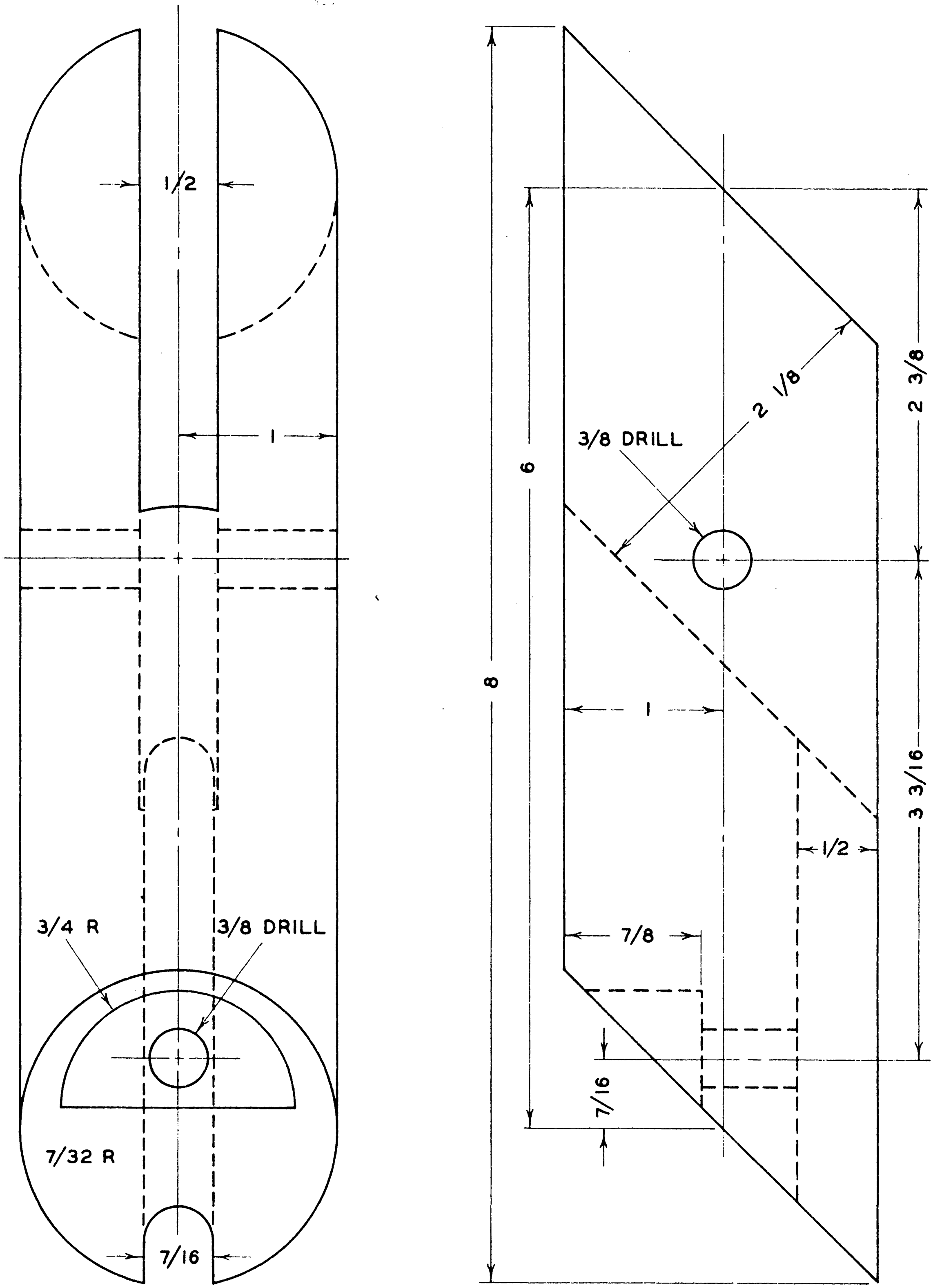
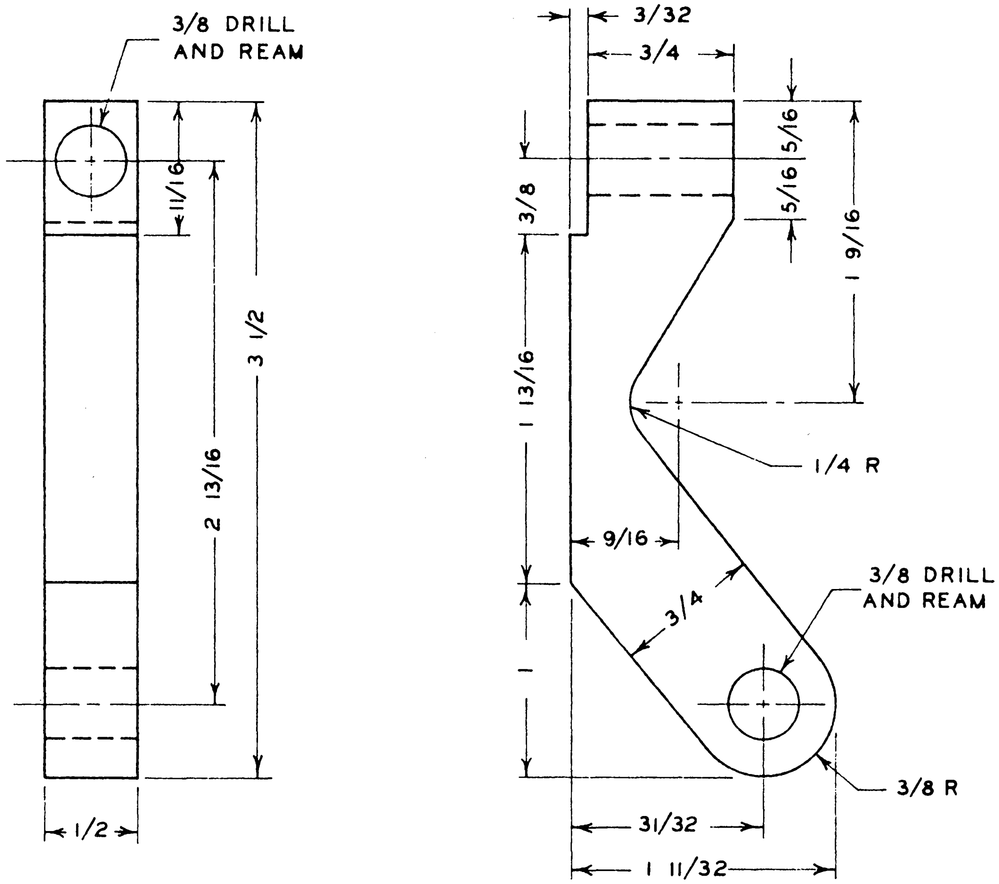


FIGURE 2. FLEXIBLE JOINT OF CONTROL ROD

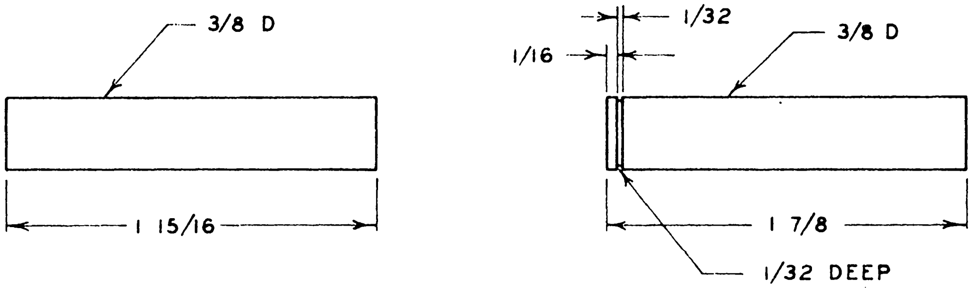


SCALE-1" = 1"

FIGURE 3. CONTROL ROD BASE SECTION



PIVOTING ARM



PIVOT PIN

COUPLING PIN

SCALE – 1" = 1"

FIGURE 4. PIVOTING ARM, PIVOT PIN, AND COUPLING PIN

Figure 5 is a drawing of the lined sleeve and shim assembled. The rod sleeve assembly is then held together by means of an expansion plug placed on the inside of the rod. When the plug is expanded, pressure is exerted between the rod and sleeve assembly, thus holding the rod-sleeve assembly in place. This method makes the interchangeability of the neutron absorbing material possible in a relatively short period of time. Figure 6 shows one complete section of the control rod disassembled.

Control Rod Drum and Threading Cam

A means of inserting the control rod into the reactor and storing those sections of the rod not in the reactor is necessary. It is also necessary that the control rod be able to traverse the vertical axis with no lateral movement since the clearance between the rod and rod hole is limited to 1/8 inch.

A hexagonal drum was designed which will accomodate the 60 degree break of each control rod section. It is then possible to store the complete control rod on the drum in three revolutions of one layer across. This will give the control rod the shape of a hexagonal helix when withdrawn from the reactor. In order for the

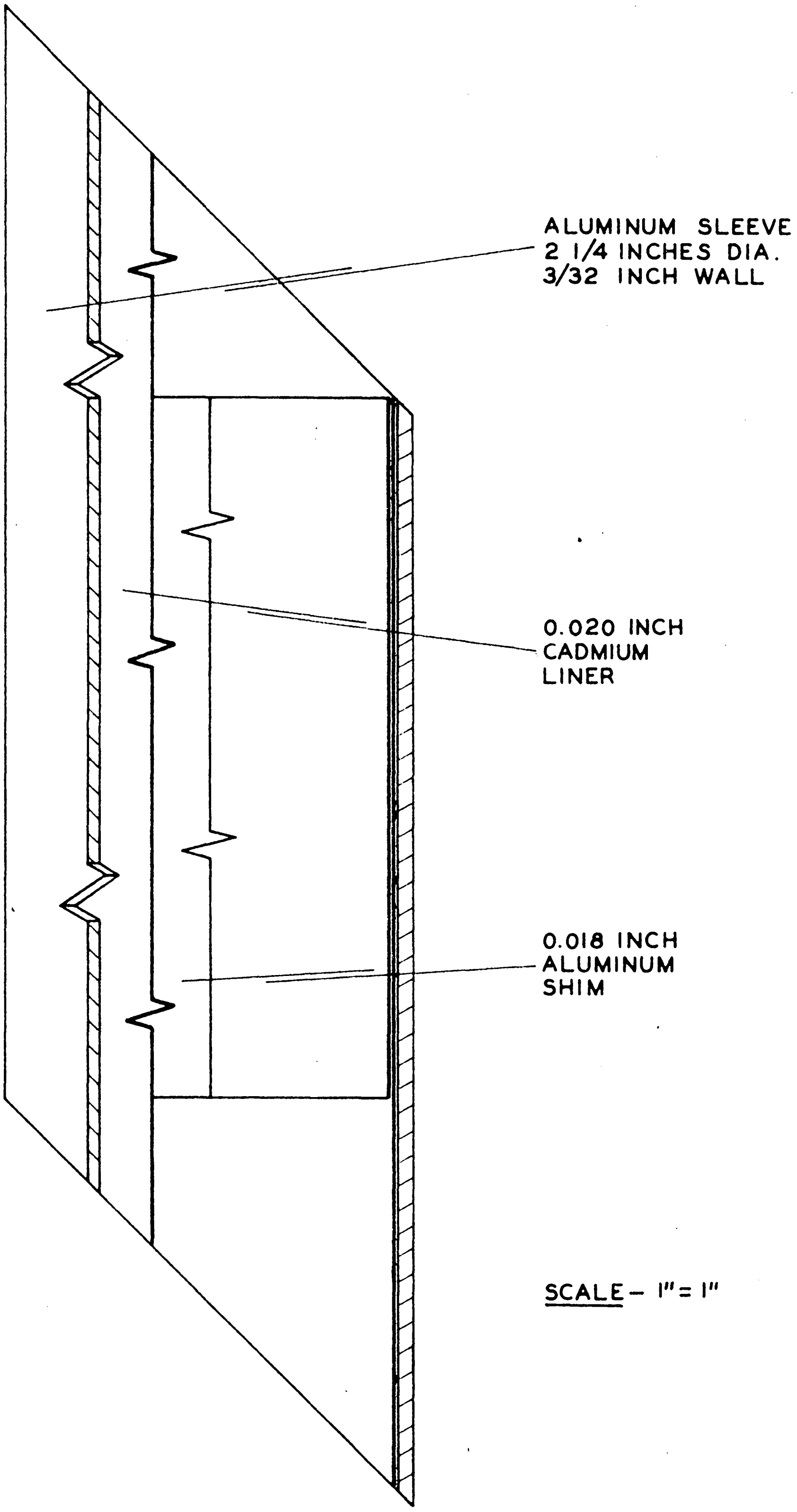


FIGURE 5. CADMIUM LINED SLEEVE AND SHIM

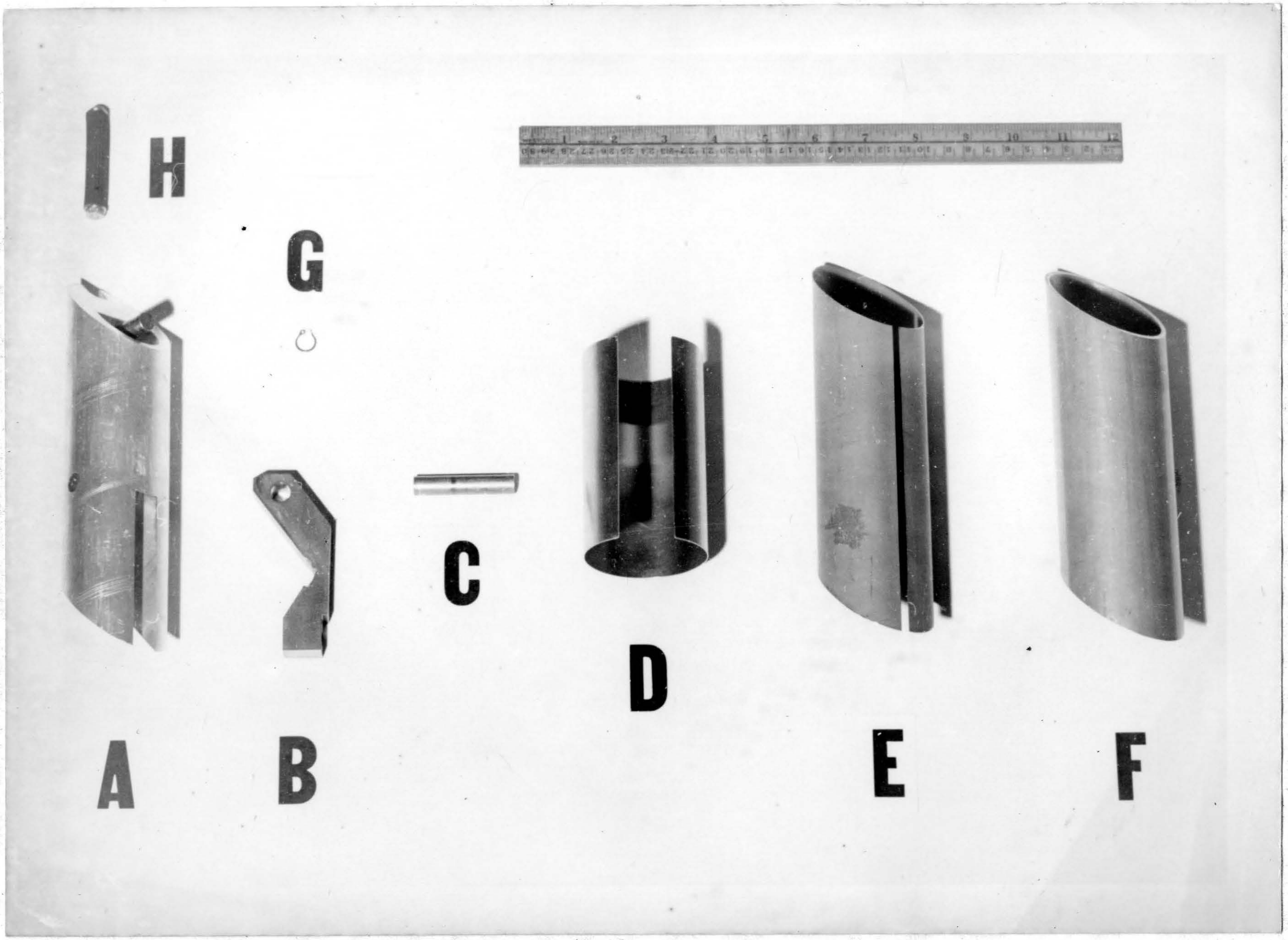


Figure 6. Components of Control Rod Sections.

Symbols for Figure 6

A	Control Rod Base Section
B	Pivoting Arm
C	Pivot Pin
D	Shim
E	Cadmium Liner
F	Control Rod Sleeve
G	Retaining Clip
H	Expansion Plug

control rod to have uniform, vertical, and non-lateral movement during the insertion into or withdrawal from the reactor by means of the drum, both the hexagonal and helical shapes of the rod have to be compensated for simultaneously.

To accomplish a drum movement that will enable the rod to operate smoothly in a vertical line, a threading cam was designed. The contour of this cam is shaped to eliminate the hexagonal effect of the control rod as the drum rotates about its axis. The drum will then oscillate causing the rod to operate in a vertical plane as the drum rotates against the cam surface. Figure 7 illustrates the effect of the cam surface on the drum.

To eliminate the helical effect and allow the rod to operate in a vertical line within the vertical plane, sides are put on the cam. The drum is then equipped with cam followers which will ride the cam surface between the cam sides. These followers are placed on each corner of the hexagonal drum. The angle formed by any two adjacent followers corresponds to the lead angle of the helix. (The helix is formed by the control rod when it is wrapped on the drum). Hence, the eighteen cam followers necessary for three revolutions of

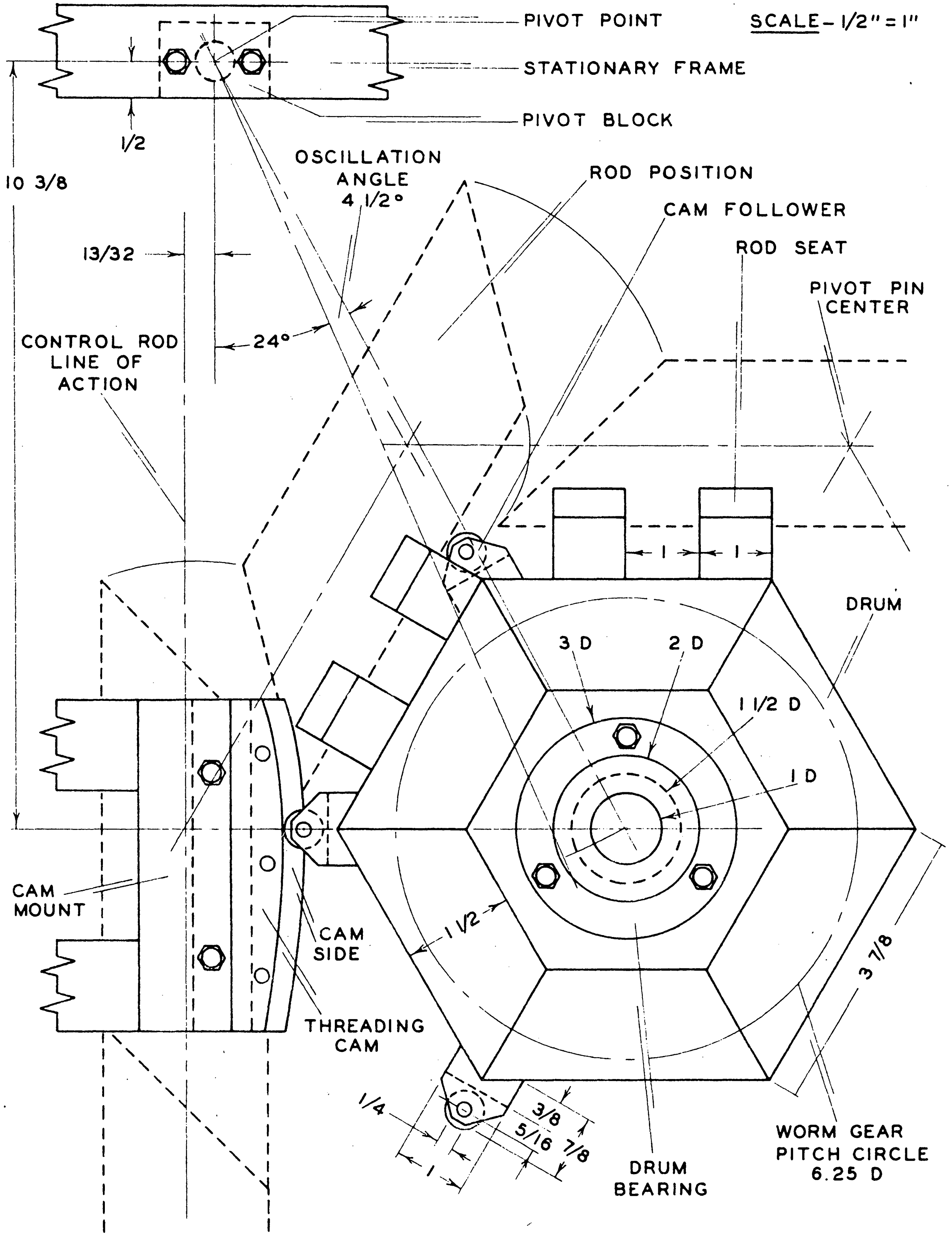


FIGURE 7. END VIEW OF CONTROL ROD DRUM AND THREADING CAM

the drum take the shape of a hexagonal helix similar to that of the control rod when on the drum. With the threading cam stationary, the drum is free to be moved by the cam followers as they pass over and through the threading cam. Thus, the drum will oscillate, compensating for the hexagonal shape of the rod, and simultaneously be threaded along its axis, compensating for the helical shape of the rod as the control rod is unwrapped from the drum.

In order that the rod leave the drum in a vertical position, the axis of the drum is inclined at an angle corresponding to the lead angle of the helix. The threading cam is then placed so that any two adjacent cam followers on the face of the drum where rod separation (from the drum) occurs, will lie in the same straight line as that formed by the center line of the cam. Figure 8 shows this threading effect of the cam sides on the drum.

Rather than making the drum long enough to accommodate the helix of the rod plus the helix of the cam followers, the followers are placed under each rod section. At the same time the helix of the cam followers is made to lead the helix of the control rod by one revolution. This shortens the drum by two revolutions

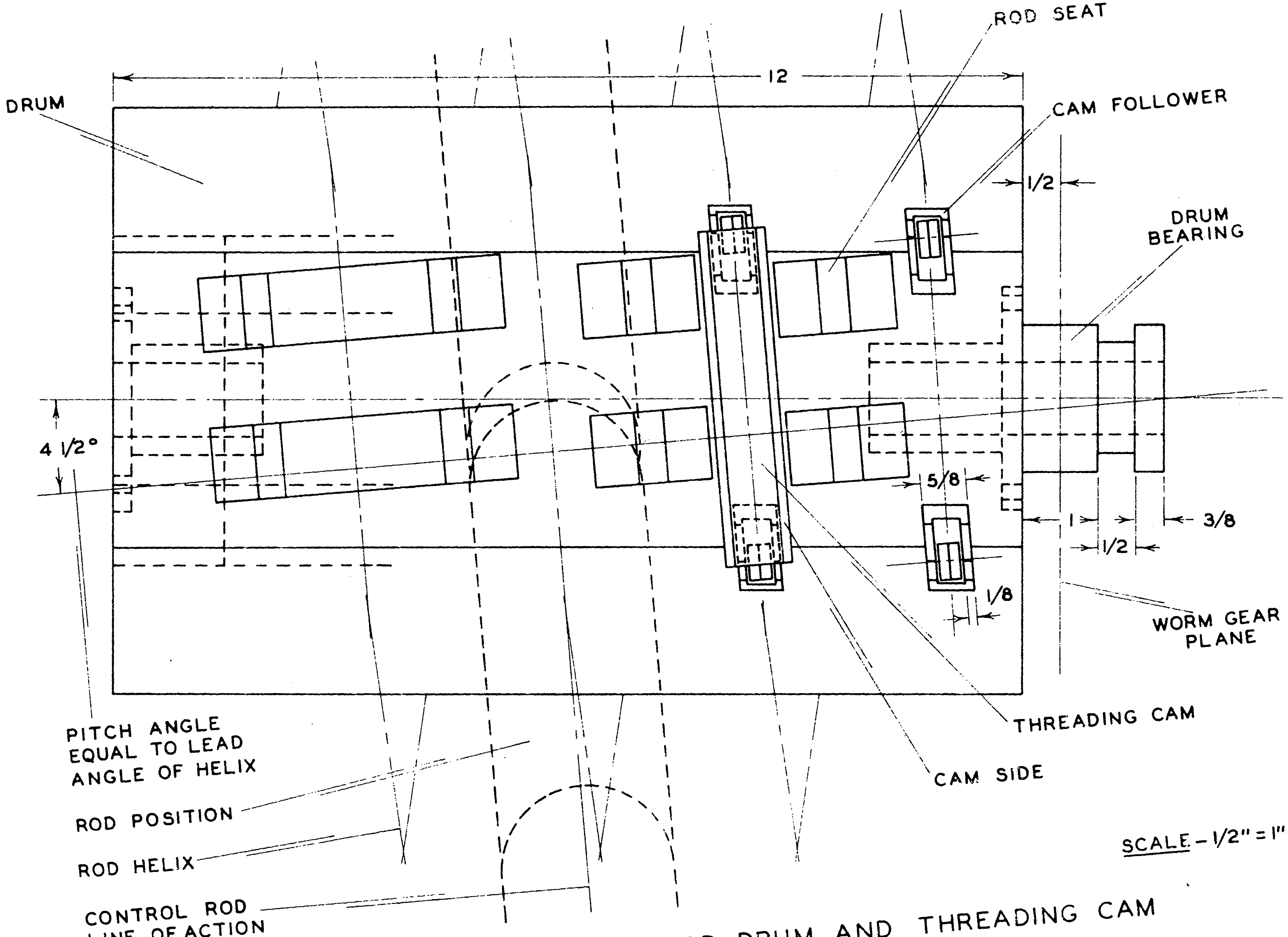


FIGURE 8. FRONT VIEW OF CONTROL ROD DRUM AND THREADING CAM

of the helix. The threading cam will now perform its function one revolution ahead of the rod. After unwrapping one revolution of the control rod, the second revolution of cam followers will be exposed and free to engage the cam for the unwrapping of the second revolution of the control rod. This operation continues until the desired amount of rod is removed from the drum. The operation is reversible and the control rod can be withdrawn from the reactor in the same manner. Figure 9 shows the rod drum and the disassembled threading cam.

Housing Frames

To house the control rod and drum assembly and to facilitate its operation, two frames are needed; a stationary frame and a pivoting frame. The stationary frame houses all of the components necessary for the proper operation of the completed apparatus. The pivoting frame contains the drum shaft on which the drum and control rod are mounted.

The pivoting frame is suspended in the stationary frame by two pivot pins. This permits the control rod and drum assembly to oscillate as the cam followers pass over the threading cam which is now attached to the

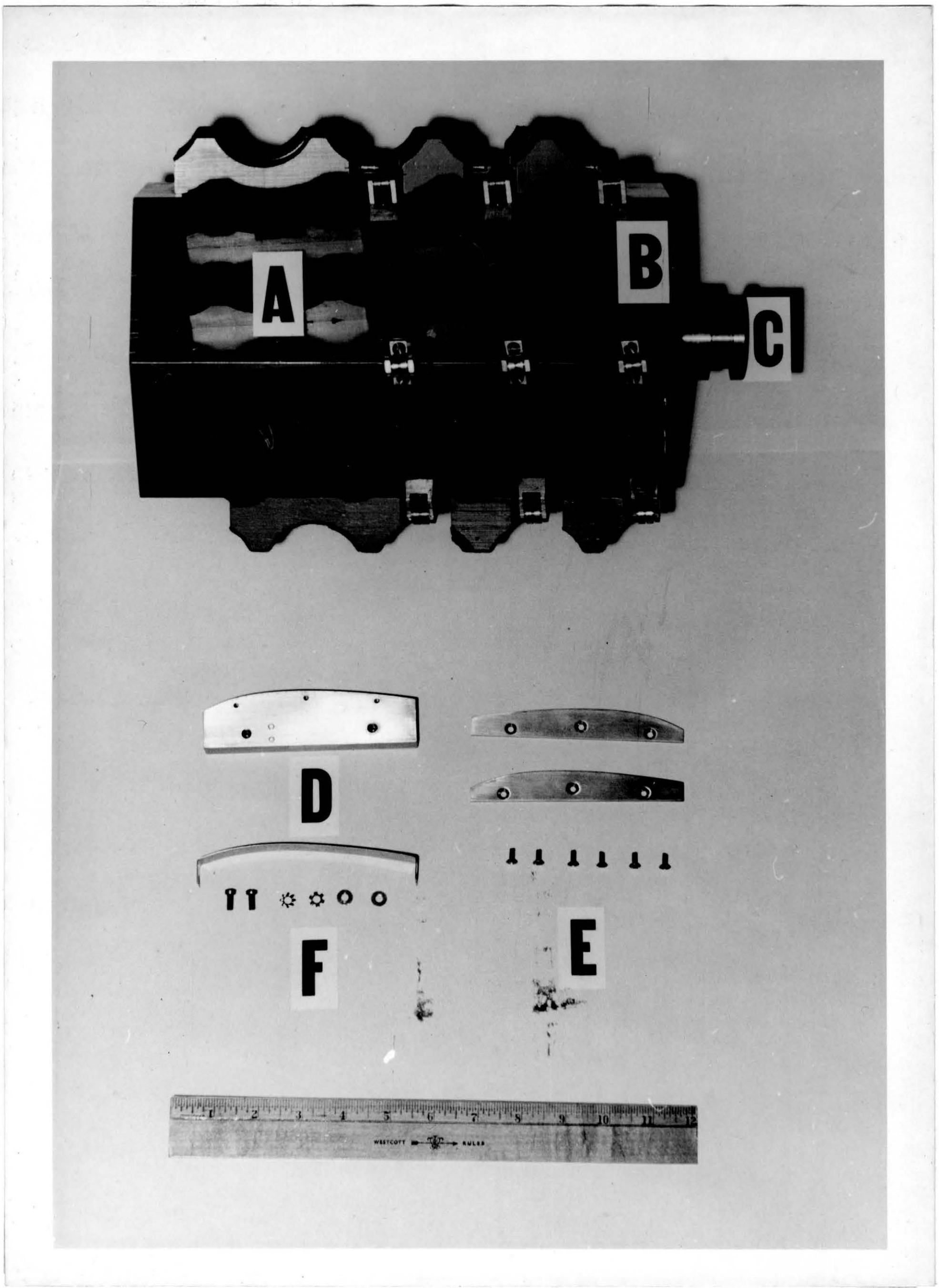


Figure 9. Control Rod Drum and Threading Cam Components.

Symbols for Figure 9

A	Control Rod Seats
B	Roller Bearing Cam Followers
C	Drum Bearing with Guide Arm Annular Groove
D	Threading Cam
E	Threading Cam Sides
F	Stainless Steel Cam Surface

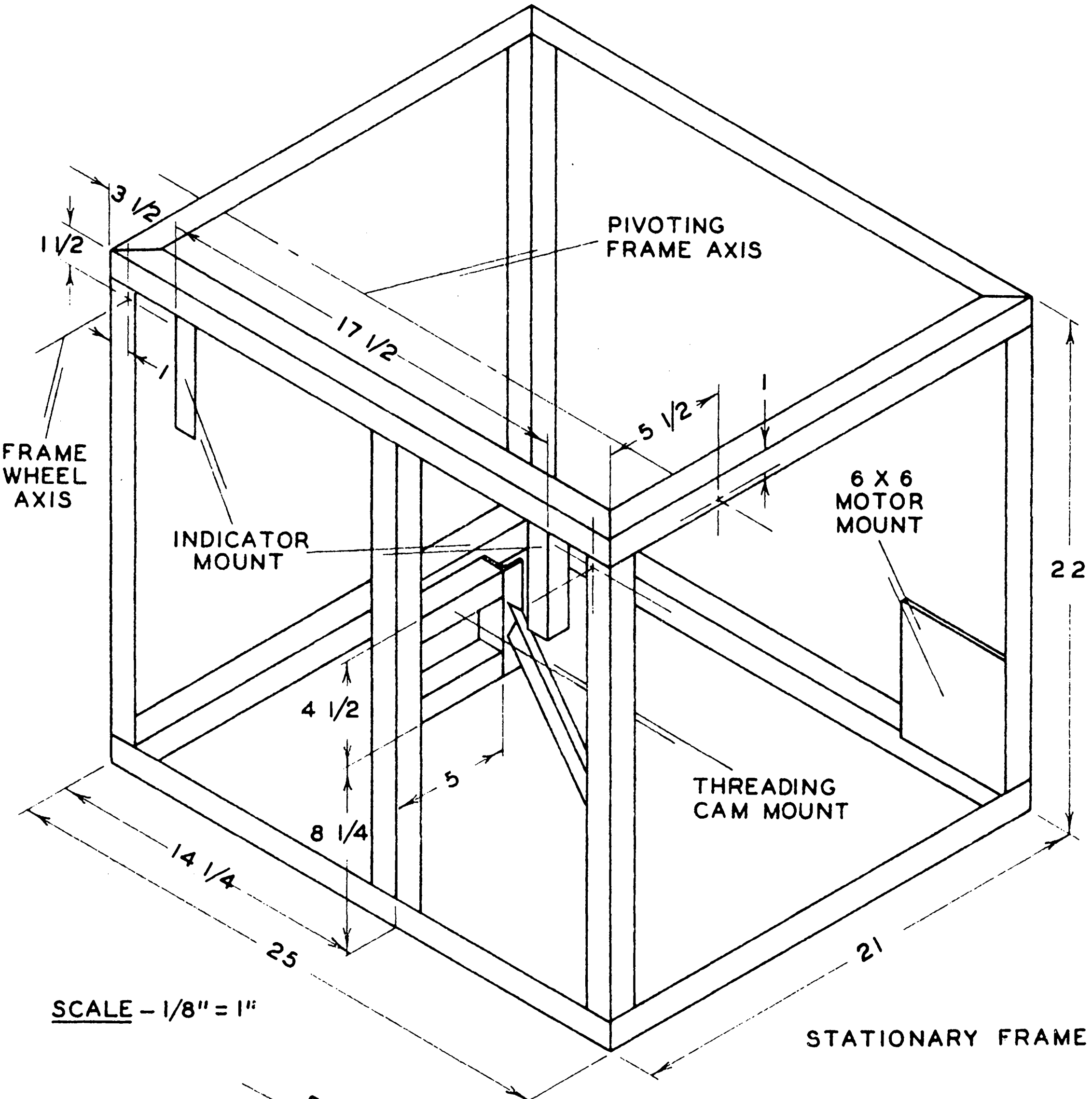
stationary frame. The free length of the drum shaft is equal to the length of the drum plus the length required for three revolutions of the control rod helix. Thus, the drum can move along its shaft as necessitated by the threading effect of the cam followers passing through the sides of the cam.

The pivoting frame and excess shaft length now permit the stationary threading cam to position the drum at any instant for uniform, vertical, and non-lateral movement of the control rod. Figure 10 is a drawing of the stationary frame and pivoting frame.

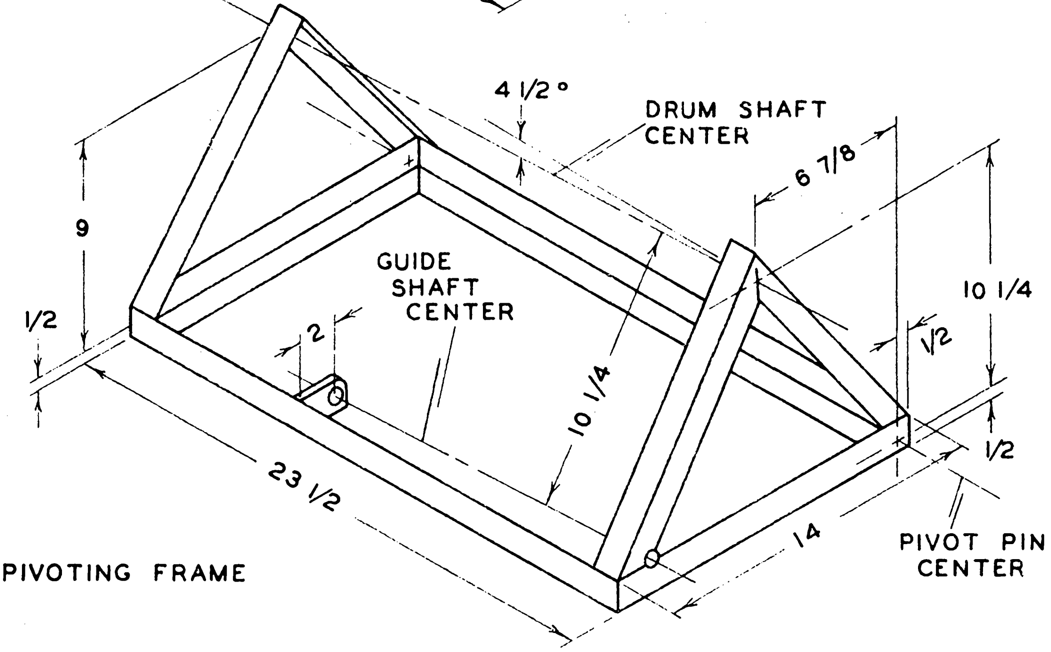
Control Rod Drive Mechanism

A means of driving the control rod drum and positioning the control rod at the desired depth in the reactor is necessary. An 1800 r.p.m. reversible motor is used with an overall gear reduction of 500 to 1 between the motor and the drum. The calculations used to determine the motor size are given in Appendix 1. This ratio produces a control rod movement of approximately one foot per six seconds.

The overall ratio used for the drum drive consists of (i) a 10 to 1 gear reduction built onto the motor housing and (ii) a 50 to 1 ratio between a worm and a



STATIONARY FRAME



PIVOTING FRAME

FIGURE 10. STATIONARY FRAME AND PIVOTING FRAME

worm gear. The calculations used to determine the worm gear size are given in Appendix 2. The worm gear is attached to the end of the drum and centered on the drum shaft. In order for the worm to be mounted in a way that it could engage the worm gear as the drum oscillates and moves along its shaft, a worm guide shaft and worm guide are added to the pivoting frame. The guide shaft is placed in the pivoting frame parallel to the drum shaft and at a distance from the drum shaft that will allow the drum (with the control rod) to rotate. The worm guide is fitted on to the guide shaft and allowed to slide along the shaft. A worm guide arm welded to the worm guide extends perpendicular from the guide shaft. The free end of the guide arm is made to engage a circular groove in an extension of the drum bearing at the worm gear end. With this end of the guide arm in the grooved bearing, the drum can rotate while holding the guide arm in place. The guide arm will also move with the drum as the drum moves along its shaft. This is possible because of the parallel guide shaft on which the worm guide and guide bar are mounted. The guide arm is now stationary with respect to the plane of the worm gear, and the worm can be mounted in a housing and attached to the guide bar at a position which will allow the worm to engage the worm gear at all times. Rotation of the worm will now drive the drum through both its oscillatory and threading motions as the cam followers engage the threading cam.

The torque necessary to drive the worm has to be transmitted from the motor through a recoupling device with transverse movement, since the motor is mounted on the stationary frame. Between the output shaft of the motor and the worm shaft, a slip-shaft having universal joints at each end is connected. The universal joints and the sliding motion of the slip-shaft enables the torque to be supplied from the stationary motor to the drum as it oscillates and moves along its shaft. Figure 11 shows a disassembled view of the parts required for the drive mechanism.

Indicator

A means of determining the position of the control rod in the reactor at any time is needed in order to aid in the interpretation of data taken during experiments. This will also make it possible to repeat the experiments with a satisfactory degree of accuracy. An indicator having a movement which is proportional to the travel of the control rod was designed.

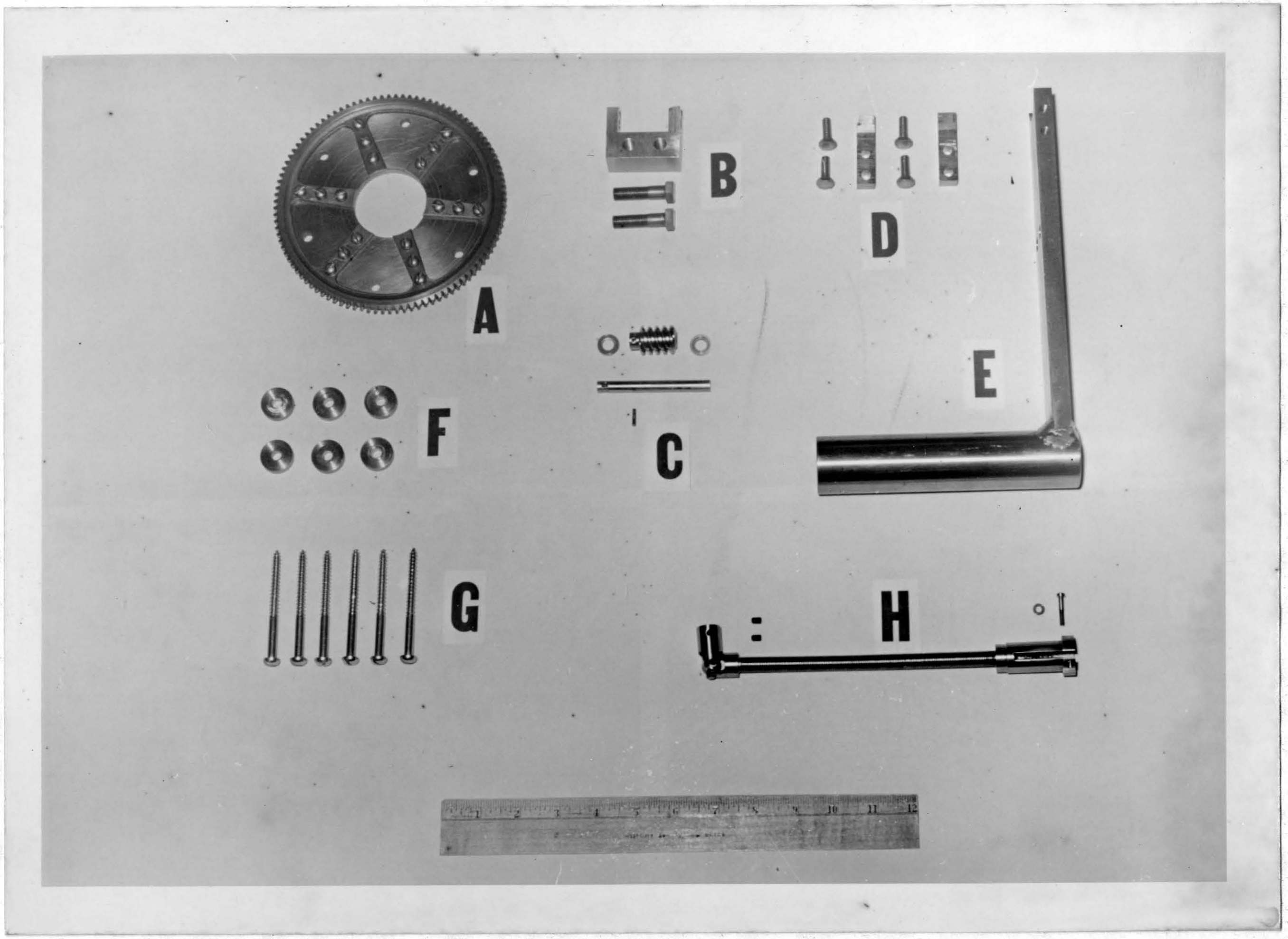


Figure 11. Components of Control Rod Drive Mechanism.

Symbols for Figure 11

A	Worm Gear and Backing Plate
B	Worm Housing
C	Worm and Worm Shaft
D	Brass Bar Bearings
E	Worm Guide and Guide Arm Unit
F	Drum-Worm Gear Spacers
G	Worm Gear Mounting Screws
H	Motor-Drum Coupling Shaft

The indicator incorporates two lengths of rod, one of which is threaded along its length. The rods are supported at each end by bearing blocks and are held parallel to one another in a horizontal position. The unthreaded rod or guide rod is held stationary while the threaded rod is free to rotate in the bearing blocks. The guide rod is equipped with a slider which is free to move along the length of the rod. A bar which has a tapped hole with threads that match those of the threaded rod is attached to the slider. The tapped bar is made to engage the threaded rod in such a way that rotation of the rod will produce uniform horizontal movement of the slider on the guide rod. The completed indicator mechanism is mounted on the stationary frame in a position where the threaded rod can be driven through right angle gears by a flexible shaft connected to the free end of the worm shaft. The ratio of the right angle gears and the gauge of the threads used is chosen to produce an overall ratio as large as possible between the control rod movement and slider movement. The resulting ratio is 1.67 inches of slider movement per foot of control rod. A scale is mounted on the indicator mechanism using this ratio with each foot on the scale divided into tenths. A vernier is attached to the slider, thereby enabling a direct reading of control rod position to within one hundredth of a foot. Figure 12 is a disassembled view of the indicator mechanism.

Mounting Track

When the stationary frame containing the completed control rod apparatus is placed in its position on top of the reactor, only two inches of the two foot clearance between the ceiling and the top of the reactor remains. It is then necessary that a provision be made for removing the frame from its operating position to a position where working space is available. This is for the purpose of changing the neutron absorbing material of the control rod and performing any maintenance that may be necessary.

To accomplish this, a double rail track is constructed and mounted in the ceiling above the reactor. This track extends from the center of the reactor to approximately two feet over the edge of the reactor, thereby providing the working space necessary. The stationary frame is equipped with rollers at each of its upper four corners and then mounted on the track. Limit stops are used to correctly position the frame at each end of the track.

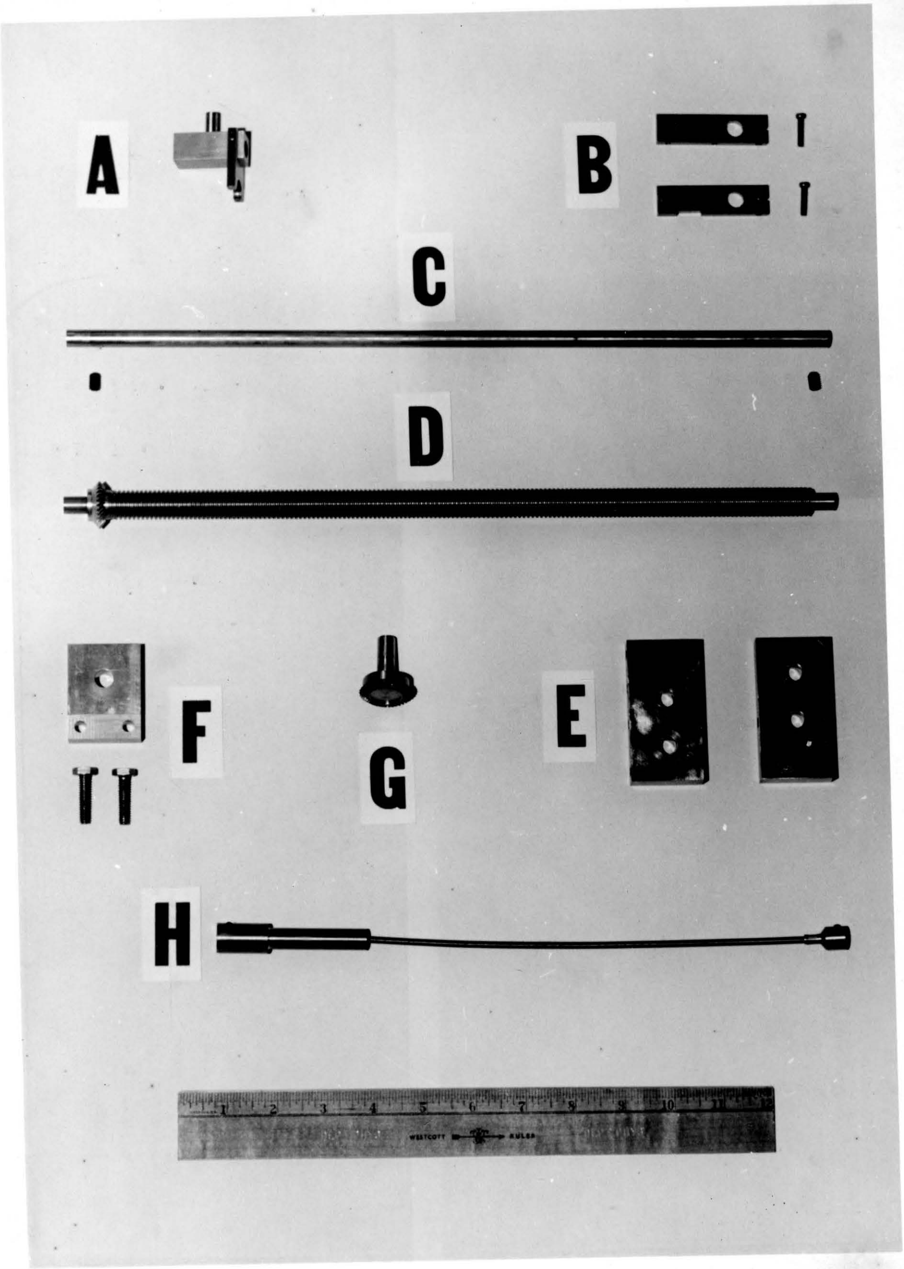


Figure 12. Components of Indicator Mechanism

Symbols for Figure 12

A	Guide Rod Slider
B	Limit Switch Mounts
C	Guide Rod
D	Threaded Rod
E	Bearing Blocks
F	Drive Gear Housing
G	Drive Gear
H	Flexible Drive Shaft

To move the frame from one position to another along the track, a motor drive is used. This incorporates an 1800 r.p.m. reversible electric motor mounted on the frame with a gear reduction of 35 to 1 from the motor to a 1-3/8 inch diameter chain sprocket. The sprocket is made to engage a taut chain extending the length of the track and attached at each end of the track. Operation of the motor will then move the frame along the track by means of the chain to the desired position. Figure 13 shows the mounting track in its location above the reactor.

Electrical System

In distributing the electrical power to the control rod drive motor and the frame drive motor, it is necessary that the wiring system incorporate a means of operating the motors at specified times within specified limits. This is primarily to prevent damage to the apparatus.

The switching arrangement for the power distribution is accomplished with five single pole, double throw limit switches and two four-pole, double throw control switches. The motors are wired for reversibility through control switches. The limit switches are then

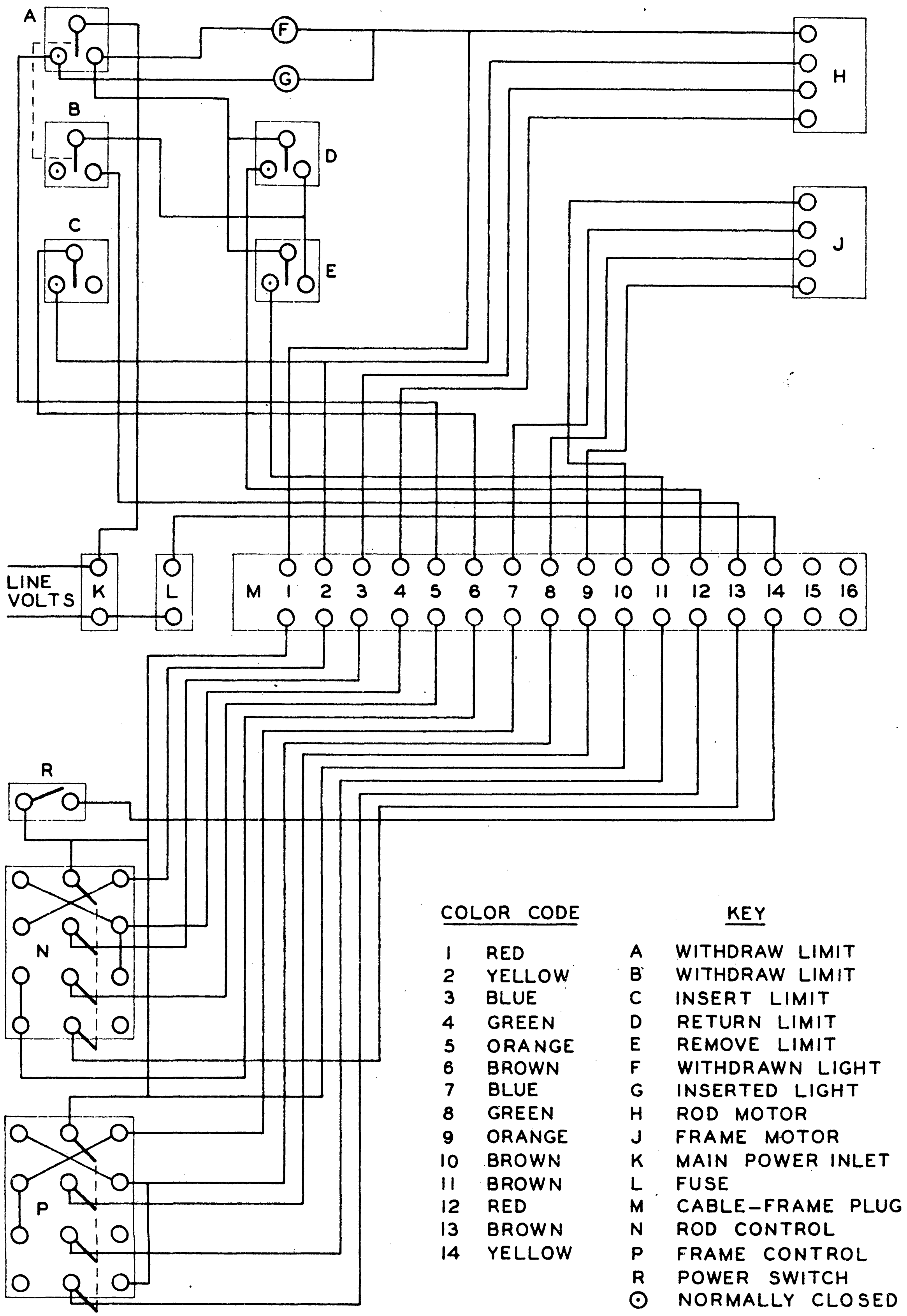
Figure 13. Mounting Track in Position Over Reactor.

placed in the circuit between the motors and the control switches. Two of the limit switches, which are mounted on the indicator mechanism and operated by the slider, serve to limit the extreme inserted and withdrawn positions of the control rod. The frame positions at each end of the track are governed by limit switches mounted on the frame and operated by the limit stops at each end of the track. The fifth limit switch is mounted together with the switch limiting the withdrawn position of the control rod and serves to switch the power between the control rod motor and the frame motor.

With this wiring system, the frame position over the reactor hole is necessarily correct before the control rod will operate. The system also prevents any movement of the frame while the control rod is inserted in the reactor or unless it is fully withdrawn.

A five ampere fuse is placed in the circuit to prevent damage to the switches and motors. Power-on is indicated by either one of two lights mounted on the indicator mechanism; a red light if the control rod is in the reactor, or a green light if the rod is fully withdrawn.

Due to the frame position over the reactor and its length of travel, a cable carrying the necessary electrical leads is brought from the frame to a hand control box housing the two control switches and the main power switch. This enables the operator to operate the apparatus from the ground level at any position within the vicinity of the reactor. Figure 14 shows a wiring diagram of the system.



COLOR CODE

1	RED
2	YELLOW
3	BLUE
4	GREEN
5	ORANGE
6	BROWN
7	BLUE
8	GREEN
9	ORANGE
10	BROWN
11	BROWN
12	RED
13	BROWN
14	YELLOW

KEY

A	WITHDRAW LIMIT
B	WITHDRAW LIMIT
C	INSERT LIMIT
D	RETURN LIMIT
E	REMOVE LIMIT
F	WITHDRAWN LIGHT
G	INSERTED LIGHT
H	ROD MOTOR
J	FRAME MOTOR
K	MAIN POWER INLET
L	FUSE
M	CABLE-FRAME PLUG
N	ROD CONTROL
P	FRAME CONTROL
R	POWER SWITCH
⊙	NORMALLY CLOSED

FIGURE 14. WIRING DIAGRAM FOR ELECTRICAL SYSTEM

CONSTRUCTION

Control Rod

A major portion of the construction time was required in the fabrication of the control rod and its associated components. Each of the operations necessary to produce a completed rod section was performed separately on all sections before subsequent operations were attempted. Throughout the construction appropriate jigs were used to insure the uniformity of rod section components.

Eighteen six-inch sections are cut from a two-inch diameter aluminum rod at an angle of 45 degrees. A 1/2 x 3 inch slot is milled in the end of each section to accept the pivoting arms, after which the opposite ends are faced for the coupling pin location. A 1/2 x 1/2 inch groove milled in the side of each section serves as the expansion plug recess. Drilling the coupling pin and pivot pin holes completes the rod base sections as shown in Figure 3.

The pivoting arms are made from four-inch lengths of a 1/2 x 1-1/2 inch cold rolled steel bar. These lengths are stacked and placed in the milling machine in such a way that each cut necessary to form the pivoting arms is performed on all arms at one time. After the required number of cuts, the arms are drilled and reamed for the pivot pins and coupling pins as indicated in Figure 4.

All pins are cut from a 3/8 inch diameter cold rolled steel rod. A 1/32 x 1/32 inch annular groove is added to the free end of the coupling pins as a retaining clip seat. Figure 4 gives the pin dimensions.

The rod sleeves consist of six-inch sections cut from 2-1/4 inch diameter aluminum tubing at an angle of 45 degrees. The wall thickness of the tubing is 1/8 inch.

The sleeves are lined with 0.02 inch cadmium (the neutron absorbing material). With the aid of a templet, the liners are marked and cut from cadmium sheet, rolled into cylinders having a butted edge seam, and inserted into the rod sleeves.

Circular shims, rolled from 4 x 6 inch sections of 0.018 inch aluminum sheet, are used to eliminate the slack between the cadmium lined sleeve and the rod base. Figure 5 shows a cross-section of the lined sleeve and shim assembled.

The expansion plugs consist of two-inch lengths of 1/2 inch diameter rubber tubing through which a 2-1/4 inch 10-32 machine screw is inserted. The expansion action occurs as the nut is tightened on the machine screw, thus compressing the tubing between two thrust washers and expanding the diameter.

The control rod components are assembled by positioning the pivoting arm in the rod base and inserting the pivot pin. The coupling pin is pressed in place, and the expansion plug is recessed in its groove. The shim and cadmium lined sleeve are slipped over the rod base and are held in place by expanding the expansion plug. Figures 1 and 6 show a control rod section assembled and disassembled, respectively.

Control Rod Drum and Threading Cam

The control rod drum is constructed as a hollow, wooden hexagon one foot long with wooden ends. The end pieces and six faces of the drum are cut from two-inch thick white pine with the face edges beveled 30 degrees. These sections are assembled with glue and reinforced with wood screws to form a drum having the dimensions given in Figures 7 and 8.

The drum bearings are turned to size using the lathe and are made to accommodate the steel drum shaft which is 23 inches long and one inch in diameter. The bearings are recessed in the drum ends and secured with bolts through the bearing flanges.

The cam followers consist of small roller bearing housings for which the dimensions are shown in Figures 7 and 8. To form the housings, sections are sliced at a 4-1/2 degree angle (lead angle of the helix) from a steel bar onto which the housing profile has been milled. The bearing slot is then milled in each section, and the holes for the bearing shafts (1/8 inch drill rod) and mounting holes are drilled. After assembling the components, the cam followers are arranged on the drum as shown in Figure 8 and held in place with wood screws.

The threading cam, having a contoured surface as shown in Figure 7, is cut from a 1 x 2 x 4-1/2 inch steel block. To protect the cam contour and increase the resistance to wear, a 0.02 inch stainless steel replaceable cam surface is used. Brass strips, 1/8 inch thick and extending 1/4 inch above the cam surface along its length, form the cam sides. The distance between the cam sides is equal to the thickness of a cam follower plus 0.01 inch.

Housing Frames

The material used in fabricating the housing frames is 1-1/4 x 1-1/4 inch angle iron. Sections of the material cut at the required angles and lengths are assembled by means of welded construction. Dimensions of the completed frames are shown in Figure 10.

The pivoting pins at each end of the pivoting frame are made from a 1/2 inch diameter steel rod and welded in place. These pins operate in pivot blocks bolted to the stationary frame and are removable to provide the means of assembly and disassembly of the frames.

The stationary frame wheels are equipped with roller bearings and made with a 9 degree taper to coincide with the flange angle of the mounting track. The wheels are mounted on 1/2 inch steel axles welded in place at each of the upper four corners of the frame.

Control Rod Drive Mechanism

The six-inch diameter worm gear is mounted on a circular steel plate 1/4 inch thick with machine screws through the worm gear spokes and threaded into the plate. Additional strength and a means of mounting the worm gear on the drum is obtained with the mounting plate. The plate and worm gear unit is secured to the end of the drum with six 1/4 x 2-1/2 inch wood screws.

The worm guide shaft, made from one-inch diameter steel rod, is positioned in the pivoting frame parallel to and 9-3/4 inches from the drum shaft by means of shaft brackets welded to the frame.

Riding on the worm guide shaft between the shaft brackets is the worm guide and guide arm unit. This unit consists of a six-inch steel cylinder machined for a sliding fit on the guide shaft and a nine-inch length of 1/2 x 1-1/2 inch steel bar. The two pieces are welded together at a 90 degree angle forming an "L" shaped unit. The free end of the guide arm is equipped with 3/8 x 1/2 inch brass bar bearings (bolted in place) which engage a 1/2 x 1/4 inch annular groove in an extension of the drum bearing at the worm gear end. This arrangement allows the guide arm to maintain a stationary position with respect to the plane of the worm gear as the drum and worm guide traverse their respective shafts.

The worm housing is machined from a 1 x 1-1/2 x 2 inch steel block. After cutting the 1 x 3/4 x 1-3/8 inch worm recess, the block is drilled and tapped for two 1/4-28 mounting bolts and drilled and reamed to accept the 5/16 inch diameter worm shaft. The worm, with thrust washers at each end, is inserted in the housing recess and held in place with a tapered pin through the worm and worm shaft. The unit is bolted to the guide arm in such a way that the worm engages the worm gear.

The torque necessary to drive the drum is supplied by an 1800 rpm synchronous, split-phase, reversible motor with a shaft output of 21 inch-pounds of torque. The motor is bolted to a 6 x 6 inch mounting plate welded to the stationary frame.

The torque is transmitted from the motor to the worm shaft by means of a coupling device having transverse movement. This coupling or slip-shaft consists of a four-inch length of 5/8 inch diameter steel rod and a five-inch length of 5/8 inch inside diameter steel tubing. A 3/16 x 1-1/2 inch slot is milled through the rod at one end. The tubing is slipped over the rod and connected by a 3/16 inch steel pin through the tubing and rod slot. This enables axial torque to be transmitted as the coupling varies in length. Universal joints are used to connect the respective ends of the coupling shaft to the motor and worm shaft. Figure 11 shows the components necessary for the control rod drive mechanism.

Indicator

A 5/8 inch diameter steel rod 16 inches in length is threaded with 11 threads per inch. The ends of the rod are turned to 3/8 inch in diameter and allowed to rotate in bearing blocks made from 1/2 x 1-1/2 inch steel bar. A 90 degree bevel gear is pressed on one end of the threaded rod and is meshed with the driving gear housed 90 degrees to the threaded shaft.

The guide rod, a 3/8 inch diameter steel rod 16 inches in length, is mounted in the bearing blocks parallel to and one inch above the threaded rod. A 5/8 x 5/8 x 1-1/2 inch brass slider is drilled and reamed through the long axis for a sliding fit on the guide rod. Attached to the slider is a 3/16 x 1 x 1-5/8 brass bar having two 180 degree threads which match those of the threaded rod cut in the free end of the bar.

With the slider on the guide rod, the bar is adjusted in such a way that its threads engage those of the threaded rod. As the driving gear is rotated, the slider will traverse the guide rod.

The indicator mechanism is bolted to the stationary frame by means of the tapped mounting holes in the bearing blocks and is driven by a flexible shaft connected between the free end of the worm gear and the driving gear of the indicator. Figure 12 shows a disassembled view of the indicator mechanism.

Mounting Track

Channel iron having a three-inch web and 1-1/2 inch flange is used for the mounting track. The material is cut in lengths in such a way that the final shape will be a rectangle with an inside length and width of 105 inches and 22 inches, respectively. The corners are welded together with the web vertical, thus allowing the bottom flange to be used as the wheel bearing surface.

The track is secured to the ceiling at each end with 1/2 x 14 inch bolts through the ceiling and recessed in the above floor. Figure 13 shows the mounting track in place over the reactor.

Electrical System

The five microswitches used in the circuit are attached to mounting blocks properly located on the stationary frame and indicator mechanism. The fuse holder, the indicator lights, and the female side of a 16-pin polarized quick-disconnect plug are attached to the frame. The system is then wired according to the diagram given in Figure 14 using six colors of 20 gage, insulated, stranded wire and soldered connections. The wires are tied in bundles and secured to the frame with clips.

Fourteen eleven-foot lengths of the wire are sheathed to form the control cable. The cable leads at one end are attached to the male side of the 16-pin polarized plug; the opposite end leads to a 2 x 2 x 4 inch control box containing the two 4-pole double throw switches and the main power switch. Figure 15 shows the control box and cable assembly.

Assembly

Figure 16 shows a disassembled view of the complete control rod apparatus. Figures 17, 18, and 19 show various views of the apparatus after being assembled without the control rod. The lettered parts in Figures 17, 18, and 19 correspond to those in Figure 16.

The procedure for assembling the major sections into a single unit is as follows:

1. The drum and drum shaft are mounted in the pivoting frame.
2. The worm guide shaft and worm guide unit are positioned in the pivoting frame with the guide arm engaging the drum bearing groove.
3. The pivoting frame is mounted in the stationary frame.
4. The control rod drive motor is secured to the frame and the coupling shaft installed.
5. The indicator mechanism is attached to the frame and connected.
6. The electrical system is installed.

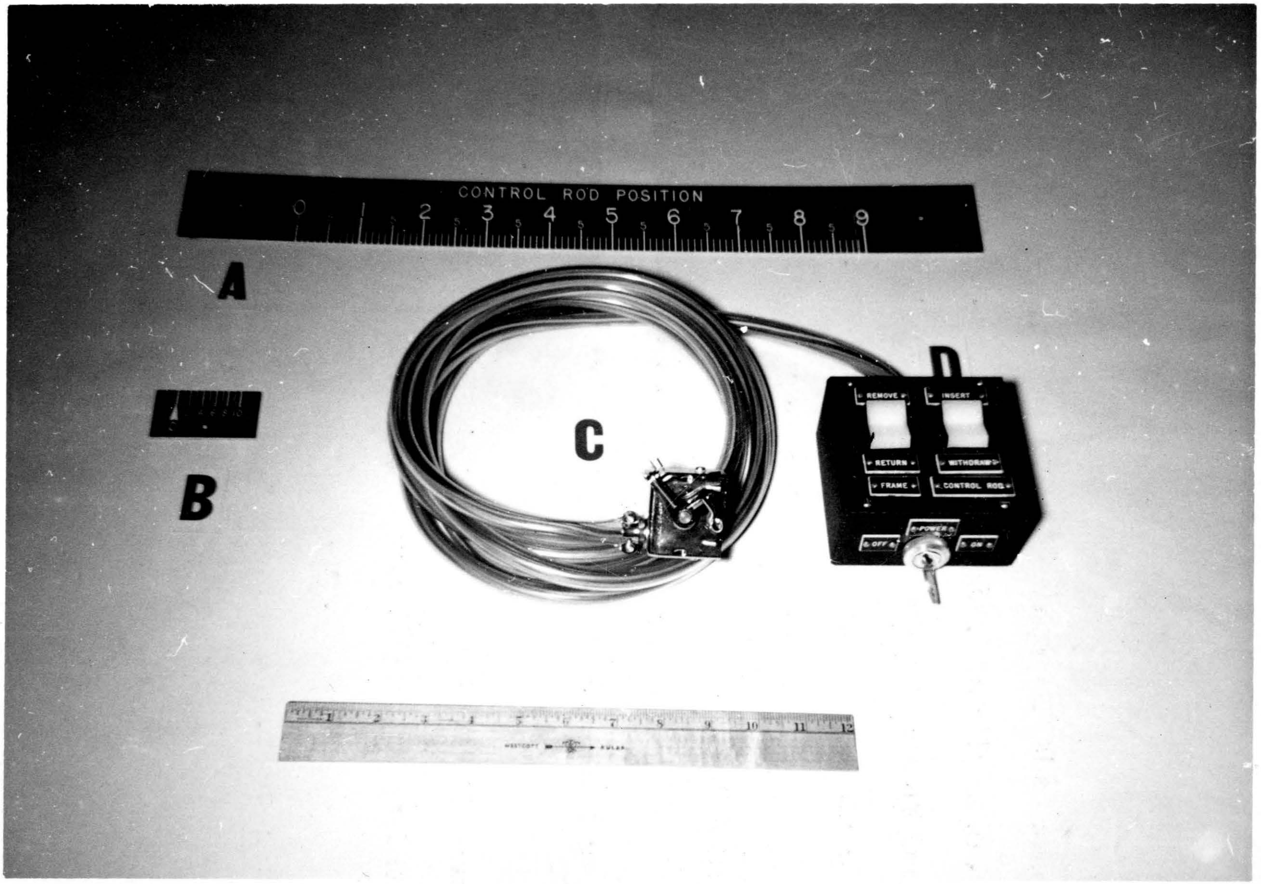


Figure 15. Control Box and Cable Assembly.

Symbols for Figure 15

A	Indicator Scale
B	Vernier
C	Control Cable
D	Control Box

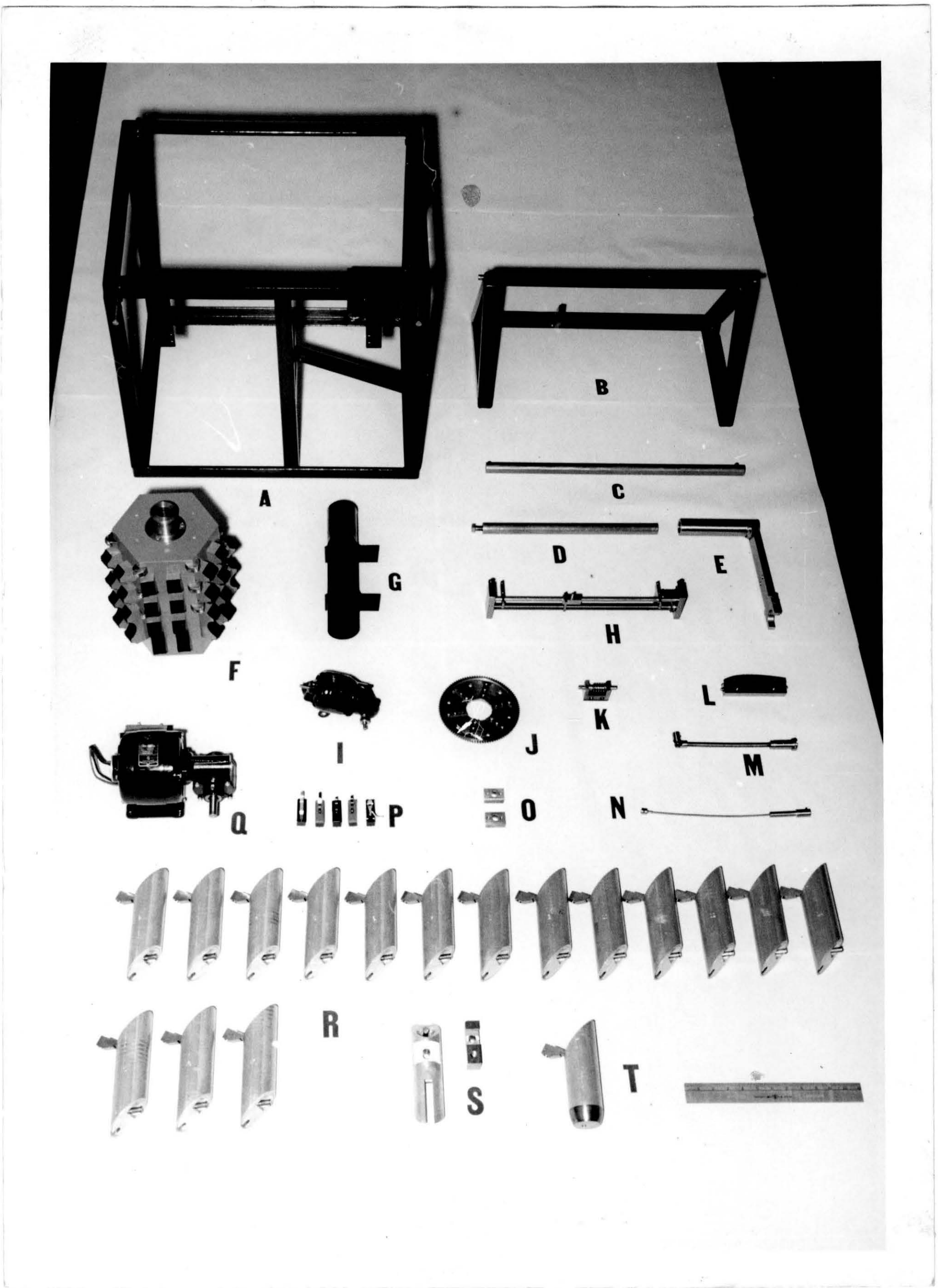


Figure 16. Components of Complete Control Rod Apparatus.

Symbols for Figure 16

A	Stationary Frame
B	Pivoting Frame
C	Control Rod Drum Shaft
D	Worm Guide Shaft
E	Worm Guide and Guide Arm Unit
F	Control Rod Drum
G	Control Rod Guide Tube
H	Indicator Mechanism
I	Frame Drive Motor
J	Worm Gear and Backing Plate
K	Worm and Housing
L	Threading Cam
M	Motor-Drum Coupling Shaft
N	Indicator Drive Shaft
O	Stationary Frame Pivot Blocks
P	Limit Switches
Q	Control Rod Drive Motor
R	Control Rod Sections
S	Rod-Drum Connecting Section
T	Control Rod End Section

Figure 17. Front View of Control Rod Apparatus Assembled Without Control Rod.

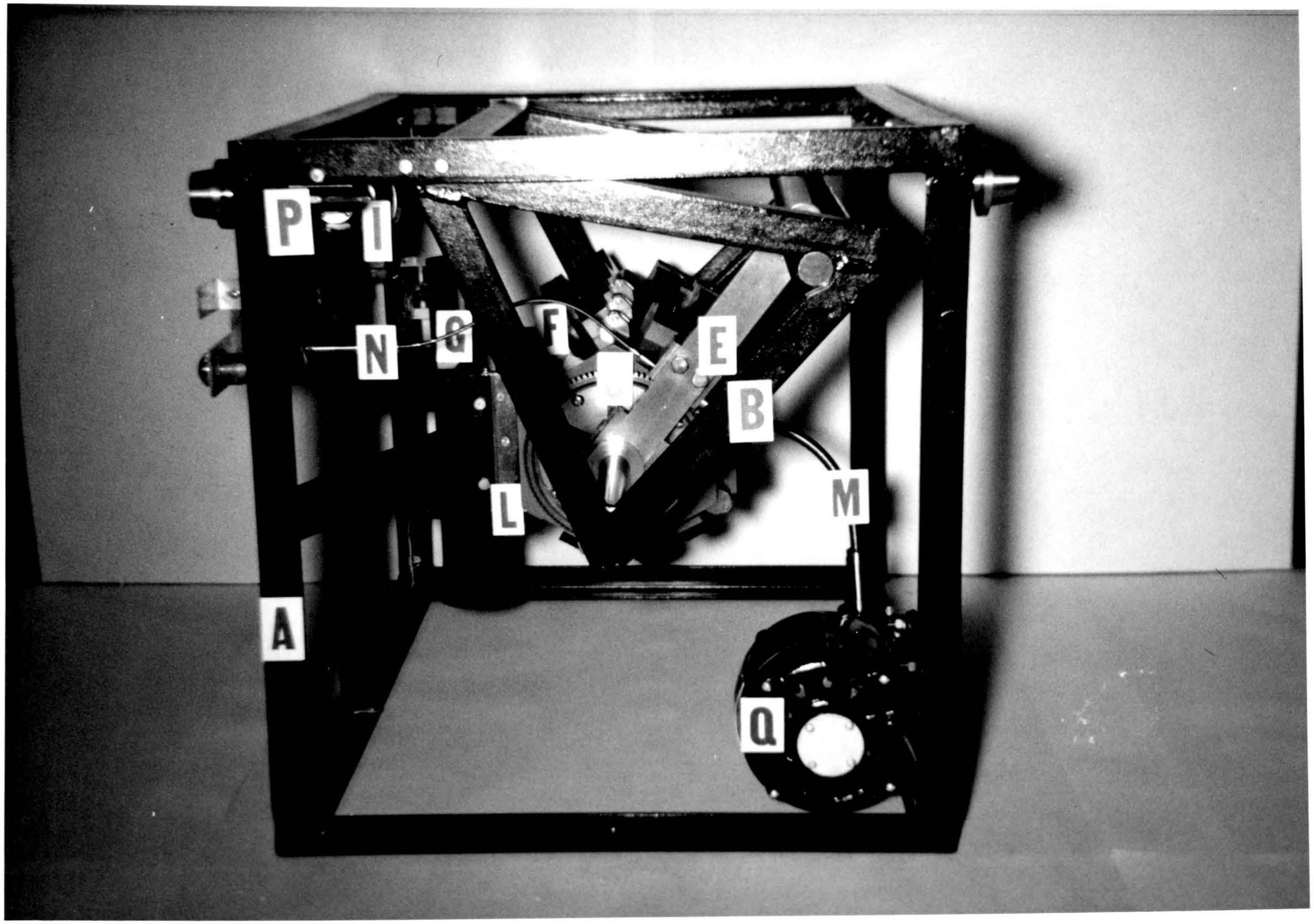


Figure 18. Side View of Control Rod Apparatus Assembled Without Control Rod.

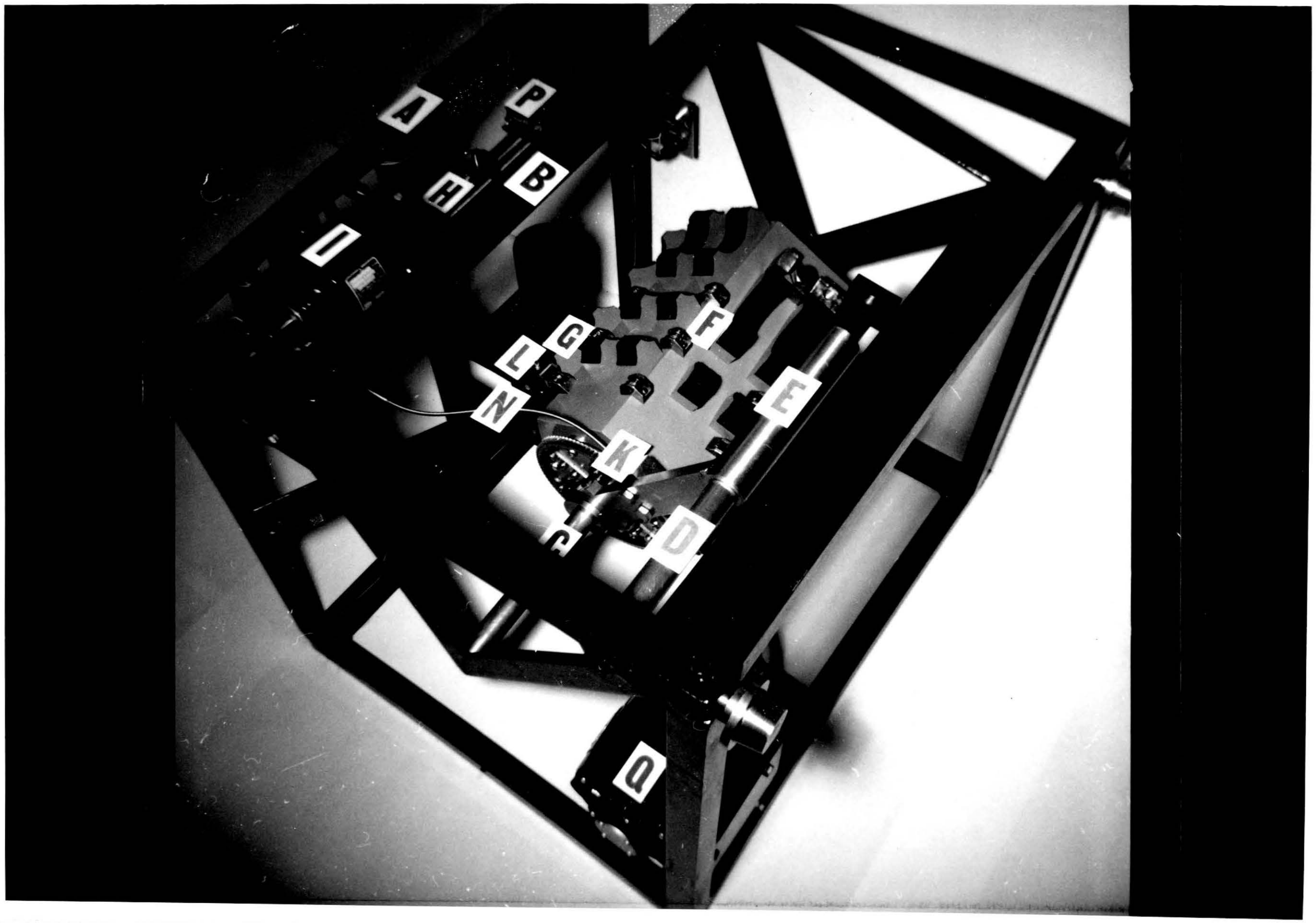


Figure 19. Top View of Control Rod Apparatus Assembled Without Control Rod.

7. The mounting track is secured to the ceiling over the reactor.
8. The frame wheels are attached and the frame is positioned on the mounting track.
9. The frame traversing motor and drive mechanism are installed.
10. The control cable and main power lead are connected.

Figures 20 and 21 show the completed control rod apparatus removed from its operating position with the control rod in the inserted position and the withdrawn position, respectively. Figure 22 shows the apparatus in its operating position over the reactor.

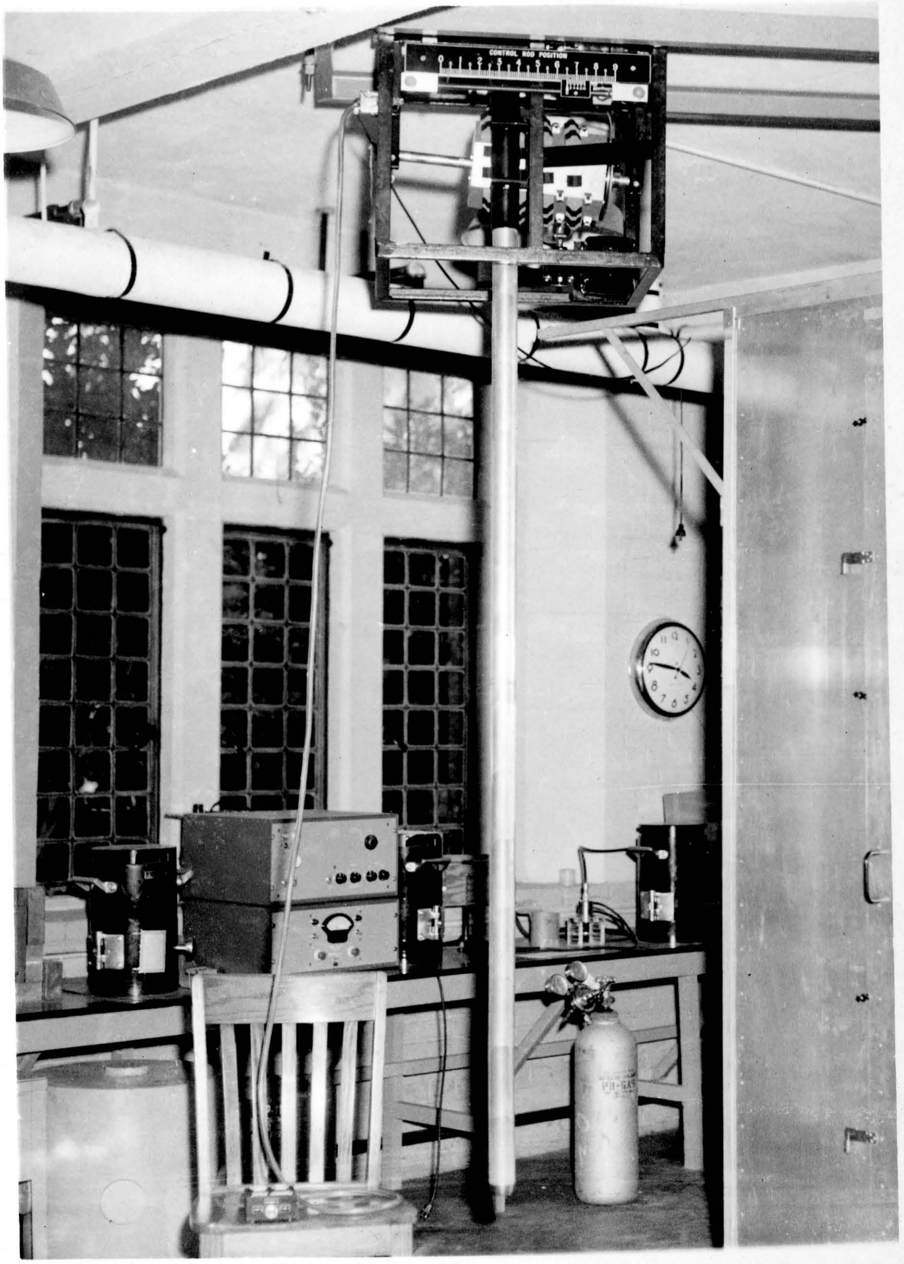


Figure 20. Control Rod in Inserted Position (Apparatus Removed from Operating Position).

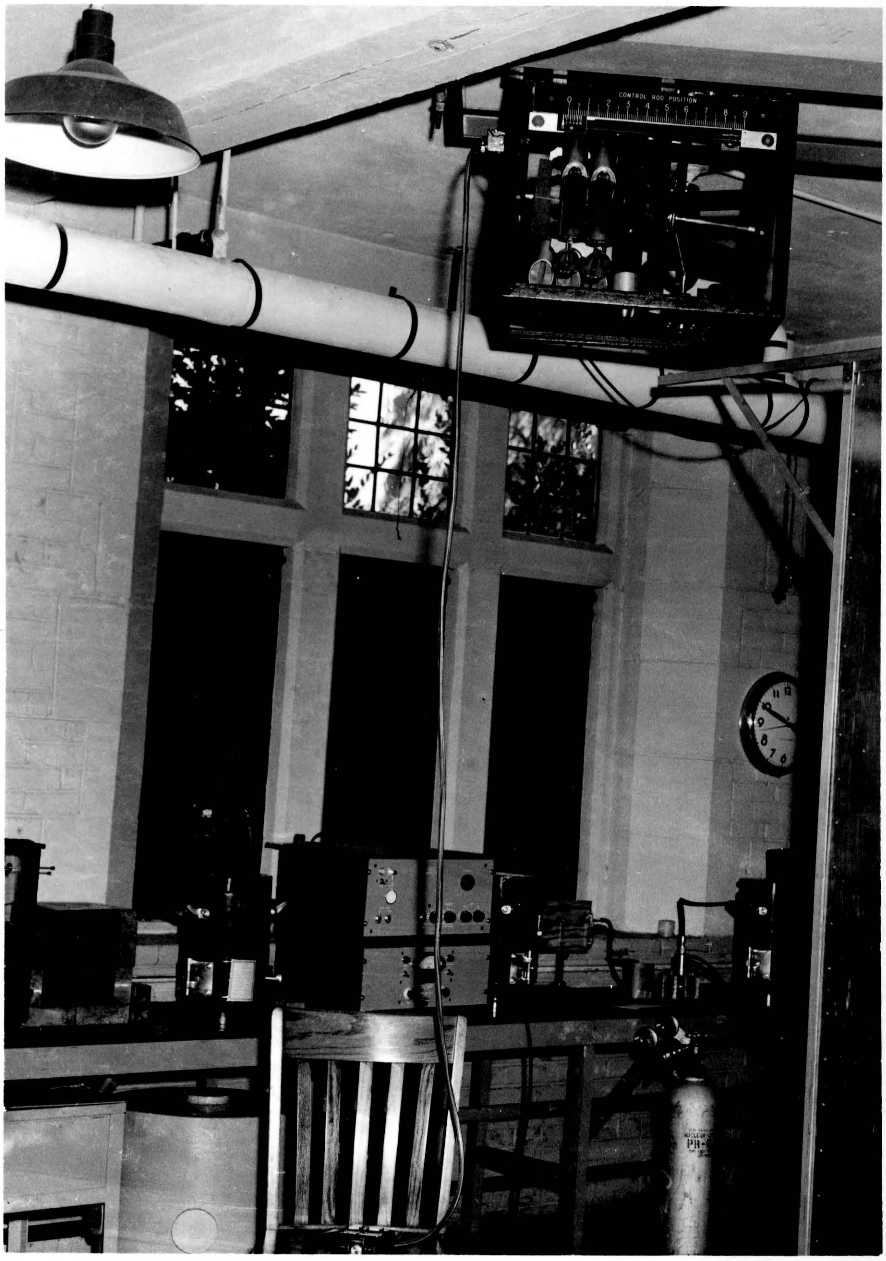


Figure 21. Control Rod in Withdrawn Position (Apparatus Removed from Operating Position).

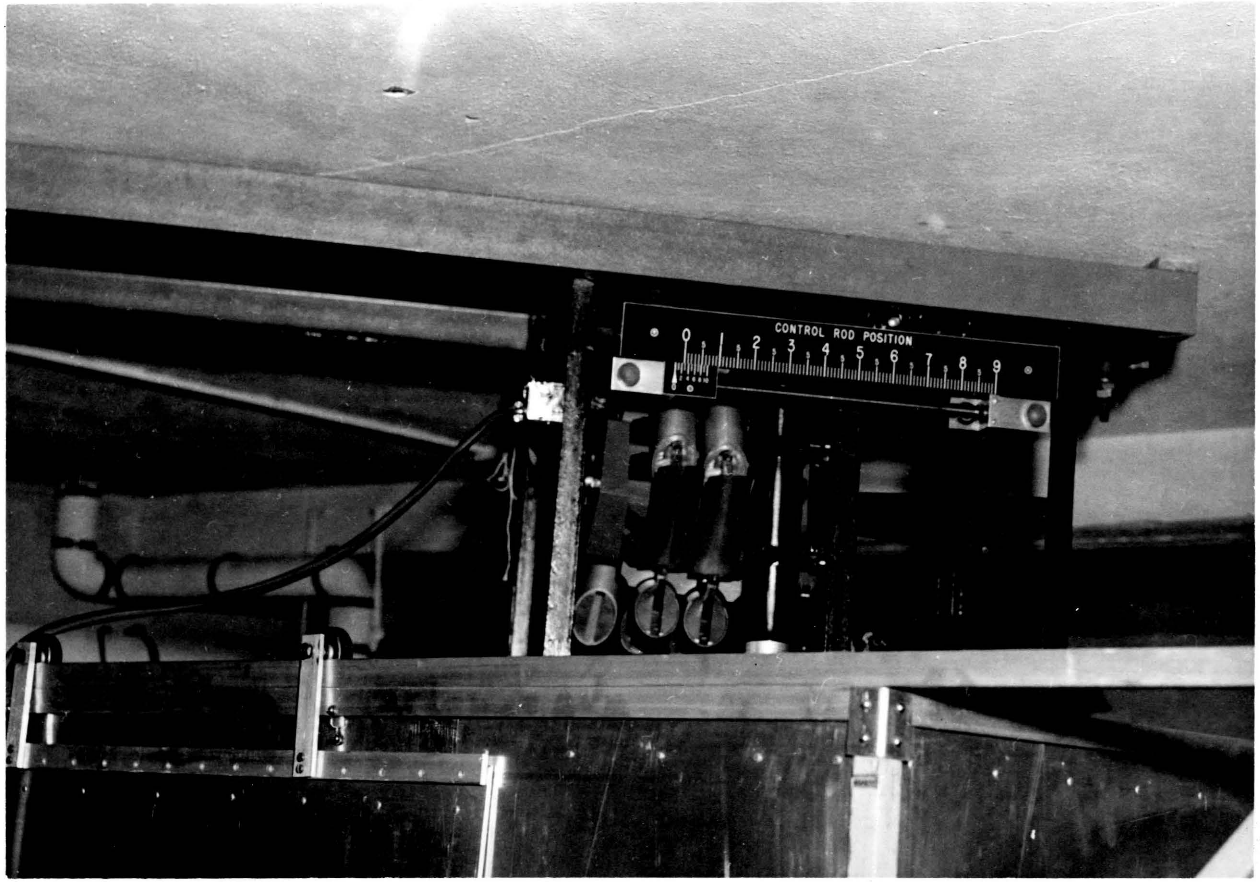


Figure 22. Control Rod Apparatus in Operating Position Over Reactor.

TERMINOLOGY AND BASIC CONCEPTS OF REACTOR CONTROL

Basically, a nuclear reactor is a system consisting of a moderator, a fissionable material, a geometric structure in which a nuclear chain reaction can be maintained, and a means of controlling the chain reaction. The chain reaction takes place within the geometric structure or reactor core where there exists an initial source of neutrons from some radioactive decay process. When a neutron of a given energy is absorbed or captured by the fuel (uranium 235 or uranium 238), there is a finite probability of the resultant compound nucleus splitting into two or more smaller nuclei. This process is called fission and is accompanied by the concurrent release of a relatively large amount of energy (approximately 200 Mev per fission)(58).

In the act of fission two to three neutrons are released from the fragmentation, and these neutrons are capable of creating more fissions in other uranium nuclei under the proper conditions. These neutrons that are produced may take part in several reactions, all of which are competitive. A neutron may undergo (1) fission capture by the uranium, (2) non-fission capture by the uranium, (3) "parasitic capture" by other materials present in the core, and (4) "leakage" or loss by escaping from the system(16)(28). In any event, for a chain reaction to take place, each uranium nucleus capturing a neutron and undergoing fission, must produce, on the average, a minimum of one neutron which in turn causes the fission of another nucleus. Formulating, let

P_f ≡ the fraction of neutrons in a reactor at a given instant which will ultimately cause a fission, i.e., the fission probability.

ν ≡ the average number of neutrons released per fission. (2.5 ± 0.1 in the case of U^{235})(26)

Then, for a stable condition or self-sustaining reaction(38),

$$\nu P_f = 1. \tag{1}$$

The quantity νP_f is referred to as the "multiplication factor" of the reactor denoted by "k" and is defined as the ratio of the number of neutrons of any one generation to the number of corresponding neutrons of the immediately preceding generation(27). When $k = 1$ the chain reaction is stable and the reactor is defined as critical. When $k < 1$ the chain reaction is unable to sustain itself and the neutron population will decrease to zero. The reactor is then said to be subcritical. If $k > 1$ the neutron population will increase essentially without limit and the reaction is then referred to as supercritical.

Since the condition of the reactor is a function of the amount the multiplication factor varies from unity, the quantity $k - 1$ is introduced and is defined as "excess k" or Δk(17).

$$k_{ex} = \Delta k \equiv k - 1 \qquad (2)$$

From this, the term "reactivity" denoted by ρ may be defined as(20)

$$\rho \equiv \frac{k-1}{k} = \frac{k_{ex}}{k} = \frac{\Delta k}{k}. \qquad (3)$$

The reactivity change is a means of expressing the degree to which the condition of the reactor is altered and is accomplished by varying the ratio (k) of the neutrons from one generation to another.

The neutrons released from the fission fragments fall into two categories: prompt neutrons and delayed neutrons. The prompt neutrons, representing approximately 99.25 per cent(18) of the total fission neutrons, are emitted from the fragments within an extremely short interval of time after fission (about 10^{-14} seconds)(26). The remaining 0.75 per cent are the delayed neutrons and are given off in six distinct groups at different times and in different quantities(59).

Table 1.(59) Delayed Neutrons from U^{235}

Mean Life t_i sec.	Decay Constant λ_i sec^{-1}	Fraction of Total Neutrons β_i per cent
0.071	14.0	0.025
0.62	1.61	0.084
2.19	0.456	0.24
6.50	0.151	0.21
31.7	0.0315	0.17
80.2	0.0124	0.026

Reactor control both depends upon and is made possible by these delayed neutrons.

To illustrate the importance of delayed neutrons, the time rate of change of neutron density is(17)

$$\frac{dn}{dt} = \frac{n\Delta k}{L} \qquad (4)$$

where L is the average time between successive neutron generations. The "period" denoted by "T" is then defined as(59)

$$T \equiv \frac{1}{(\frac{1}{n})(\frac{dn}{dt})} \,. \qquad (5)$$

And upon substituting equation (4), equation (5) becomes(29)

$$T = \frac{L}{\Delta k}. \tag{6}$$

The period, T, is the time required for the neutron population to change by a factor of e(2.718).

Considering all the neutrons to be prompt, the average time between successive neutron generations (prompt neutron lifetime) would be approximately 0.001 seconds. Then, if a reactivity, say $\Delta k = 0.001$, is inserted into a reactor, the resulting period from equation (3) is one second. With this rate of increase, reactor control by regulated reactivity would be extremely difficult.

The period is considerably increased when the delayed neutrons are taken into account. Letting β_i represent the fraction of delayed neutrons in the i-th group and t_i the average life of each neutron in that group (Table 1.), the weighted mean delay time is(30)

$$\sum_{i=1}^{6} \beta_i t_i \;. \tag{7}$$

The average time between neutron generations, L, would now be(31)

$$L = \sum_{i=1}^{6} \beta_i t_i + L' \tag{8}$$

where:

L' = average prompt neutron lifetime.

The quantity $\Sigma\beta_i t_i$ is found to be 0.0942(31) and thus L is approximately 0.1 seconds. Using this value in equation (3) and $\Delta k = 0.001$ (as before), a period of one hundred seconds is obtained--the magnitude of which is sufficient to permit adequate control of the reactor.

Advantage is taken of the delayed neutron fraction, β, by dividing k into two parts; $k(1-\beta)$, representing the prompt neutron multiplication factor and $k\beta$, the contribution made by delayed neutrons. If $k(1-\beta)$ is adjusted to unity (or slightly less), the neutron population will essentially be determined by the delayed neutrons. Since β is approximately equal to 0.75 per cent, adequate control is possible for values of k between 1.0 and 1.0075. However, for values of k greater than 1.0075, the chain reactions can be maintained by prompt neutrons alone. This condition is described as "prompt critical"(22), and the neutron density is capable of increasing extremely fast as discussed previously.(15)(25)(57)(69)

It is convenient for the purpose of control calibration to combine the period and reactivity into one expression accounting for the effect of both prompt and delayed neutrons. The time rate of change of neutron density becomes(47)

$$\frac{dn}{dt} = \frac{k(1-\beta)n}{L} + \sum_{i=1}^{6} \lambda_i C_i \tag{9}$$

where:

n = neutron density

L = average time between neutron generations

C_i = concentration of the precursor producing the i-th group of neutrons

λ_i = decay constant of the i-th precursor.

The first term is the prompt neutron contribution to the neutron density. The second term is the formation of delayed neutrons as a result of precursor decay. The rate of this decay (Table 1) determines the neutron delay time.

The time rate of change of percursor concentration is given by(47)

$$\frac{dC_i}{dt} = \frac{k\beta n}{L} - \lambda_i C_i \ . \tag{10}$$

The first term is the rate at which the precursor is being formed and the second is its rate of disintegration through decay.

The time rate of change of neutron density may also be expressed as(48)

$$\frac{dn}{dt} = \frac{n}{T} \tag{11}$$

where:

T = period.

Similarly, the precursor concentration is(48)

$$\frac{dC_i}{dt} = \frac{C_i}{T} \; . \tag{12}$$

Substituting equation (12) into equation (10)(48)

$$C_i = \frac{k\beta_i n}{L(1/T + \lambda_i)} \; . \tag{13}$$

If this expression and equation (11) are combined with equation (9) and then rearranged, the result is(49)

$$\frac{k-1}{k} = \frac{L}{kT} + \sum_{i=1}^{6} \frac{\beta_i}{1 + \lambda_i T} = \rho \; . \tag{14}$$

This is known as the "inhour" equation and may be justified by inserting a period of $T = 3600$ seconds. The resulting amount of reactivity (ρ) is called the inhour (inverse hour) and causes the reactor to have a stable period of one hour(50). Other units of ρ are the "dollar" which is equal to a reactivity of $\beta = .0075$, and the "cent" which is 1/100 of the dollar(21)(22)(46)(57)(70).

To accomplish the necessary control for maintaining the desired flux level, four general methods are usually considered. They involve the addition or removal of the fuel, the moderator, the reflector, or a neutron absorber. Also, a combination of these is sometimes considered in the interest of neutron economy. Of these methods, some are limited in use depending upon classification of the reactor in which they are to be employed. Thermal, intermediate, and fast type reactors each pose different problems in control. For the fast reactor, only the addition or removal of the fuel and/or reflector are considered due to mechanical shortcomings of mechanisms for moving control elements quickly. The most common method employed because of its simplicity and convenience (for thermal reactors) is the insertion or withdrawal of a neutron absorbing material.

To facilitate the use of this absorber material, it is usually fabricated into one of several shapes; i.e., rods, slabs, strips, crucifixes, etc., depending upon the space requirement and position of the control element in the reactor. The absorber is generally alloyed with a more structural material to increase the mechanical and geometric stability, resistance to attack by environment, and resistance to damage by whole pile radiation. The concentration of the absorber material in the control element together with the exposed area is governed by the particular function for which it is intended in the reactor.

The problem of obtaining an optimum control element is also influenced by the choice of neutron absorbing material. Bach and Kitchen(3) present experimental data regarding the effect on reactivity of control elements having various shapes and using several types of neutron absorbers. Properties of materials used for reactor control will be discussed in the next section.

The functions of control elements are coarse control, fine control, and safety; referred to as shim rods, regulating rods, and safety rods respectively.

The shim rods are used to bring the reactor approximately to the desired power level when the system is started up. They must, therefore, have a fairly large reactivity equivalent, the amount depending on the particular reactor. Shim rod movement must be slow and closely regulated because of the large reactivity increase possible.

After the approximate power level has been achieved with the shim rods, the control responsibility is passed to the regulating rods. The reactivity equivalent of these rods is small--not exceeding the fraction of delayed neutrons (0.75 per cent) when uranium 235 is the fissionable material.

This eliminates the possibility of the reactor becoming prompt critical by complete withdrawal of the rod due to operator error or mechanical failure. The regulating rod not only maintains the desired power level, but also compensates for the small changes in reactivity due to fuel depletion, accumulative poisons, temperature effects, etc. These rods must be capable of moving rapidly in order to provide quick response, when necessary, to changes affecting the reactor.

The purpose of the safety rod is to shut down the reactors immediately in the event of an emergency. The rod must be capable of moving very rapidly and its reactivity equivalent must be appreciably greater than the maximum excess reactivity built into the reactor in order to insure complete shut down.(23)(51)(60)(71)

ABSORBER MATERIALS FOR REACTOR CONTROL RODS

The best absorber material for control elements would be one whose cross section is high for all energies of neutrons. However, absorbers which have sharp epithermal cutoffs but relatively high thermal cross sections have frequently been used.

Most desirable is an absorber which reacts with neutrons by radiative capture rather than by fission or particle emission. The (n,α) reaction, a common type of particle emission, results in embrittlement, swelling, deformation, and other damaging effects. It is desirable that the element used not only be one where successive (n,γ) reactions or radiative captures occur, but that the reactions also produce a chain of neutron-born daughter isotopes of appreciable cross section so that a chain of captures can result from each high cross section atom in the original material. Low atomic mass and high density are also desirable since this permits a high number of absorbing nuclei per unit volume(1).

Boron, cadimum, hafnium, gadolinium, samarium, and europium are the most commonly selected materials which satisfy these requirements; although such elements as silver, iridium, gold, and mercury are sometimes considered.

Boron

Boron, although having only 18.8 per cent B^{10} as its only absorbing isotope, has a low atomic weight and extremely good cross section behavior. The absorption cross section of boron extends over the entire spectrum and is essentially proportional to the reciprocal of the neutron velocities. This is very desirable and makes it the first element considered for most neutron absorber applications. However, boron reacts with neutrons by the (n,α) reaction producing lithium and helium as the products. Both of these elements have larger atoms than the original boron atom and produce large internal strains in the lattice. The irradiation of boron-containing alloys to any appreciable burnup, i.e., in excess of 0.5 total atom per cent burnup, produces appreciable growth to the linear dimensions of the samples and drastically embrittles the materials. To attain long-life slabs for use in high-power reactors isotopic enrichment is usually required.(1)(5) Cost: approximately $450 per pound.(40)

Cadmium

Cadmium, which has Cd^{113} at a concentration of 12.26 per cent as its only absorbing isotope has a sharp cutoff on the low epithermal region. In addition, its low melting point (310 degrees C), coupled with the poor metallurgical properties of its known alloys has limited its application to small experimental reactors where little or no heat is produced.(1)(5) Cost: approximately $1.75 per pound.(41)

Hafnium

Hafnium has several advantages. It has a five-member series of absorbing mother-daughter isotopes, connected through (n,γ) reactions. It has good capture behavior in the epithermal ranges due to a family of resonances, and has a fair resistance to radiation damage together with good corrosion resistance. However, the thermal cross section of all absorbing isotopes is low, and although of high density, it is also of high atomic mass. Hence, relatively thick and extremely heavy slabs of pure hafnium are required for long-life high-power reactors. The use of hafnium for control purposes is restricted by its commercial scarcity and thus high cost, especially since large quantities are required.(1)

Samarium

Samarium is of little use for long-life high-power reactors due to the rapid burnout rate resulting from an extremely high thermal cross section of 50,000 barns. Its one absorber isotope is low in concentration (13.84 per cent) and no chain relationship exists.(1)(5) Cost: approximately $300 per pound.(76)

Gadolinium

Gadolinium is one of the first materials considered for control purposes after boron. This is due to its extremely high thermal cross section. There are two isotopes of gadolinium with appreciable absorption cross sections; Gd^{155} with a thermal cross section of approximately 70,000 barns and Gd^{157} with a thermal cross section of approximately 160,000 barns. These high cross sections indicate complete blackness to neutrons for slabs at low concentrations. However, upon closer examination it is noted that the material has essentially no effectiveness in the epithermal spectrum and that large quantities of gadolinium would be required due to the fast burnout rate associated with the high cross sections. Since the two isotopes comprise only 30.41 per cent of the naturally occurring material and no chain relationship exists, additional material must be added to provide for the control requirements. The results of these factors is that in general the use of gadolinium for control would be limited by the large initial loadings to short-life reactors or to applications where insertion of new control elements is possible.(1)(5) Cost: approximately $400 per pound.(76)

Europium

Europium possesses several advantages. It has two naturally occurring isotopes, each near 50 per cent in concentration and both having appreciable thermal cross section. Europium also has a five-member chain of absorber isotopes in mother-daughter relationship through the (n,γ) reaction. This cross section is much higher than that of hafnium; the concentration required for blackness is much lower. Below is shown the cross section behavior of the chain of europium isotopes.(5)

Table 2.(1) Nuclear Properties of Europium Isotopes

Mass No.	Per cent natural abundance	Mode of decay	Half-life	Cross sections barns
151	47.8	--	--	9,000
152	--	K,B-	13 yrs.	5,000
153	52.2	--	--	420
154	--	B-	16 yrs.	1,000
155	--	B-	1.7 yrs.	13,000

This enables it to have a long endurance or slow burnout rate at high power densities. It has one nuclear disadvantage of low epithermal absorption which can be overcome by an increase in concentration or slab area. Methods of fabricating the oxide into usable control slabs having desirable properties have been developed. The material, though among the more scarce elements, is still sufficiently plentiful to meet most needs. Endurance and control worth being adequate for high power, long-life applications appear to make europium one of the more desirable control materials.(1) Cost: approximately $1200 per pound.(76)

CALIBRATION METHODS

The complete calibration of a reactor control system is more difficult than most calibrations due to the complexity and interdependence of reactor phenomena. The calibration of a control rod consists of determining the reactivity change associated with any given motion of the control rod under any reactor condition. The methods of accomplishing this calibration are frustrated by a number of different effects. One example of the limitations is in the measurement of the total rod worth; that is, the reactivity change due to moving the rod from the fully inserted position to the fully withdrawn position. Generally it is not possible to fully withdraw the rod in one step due to the unsafe condition that could result from the addition of such a large amount of reactivity. Therefore, to measure the total rod worth, if sizeable, it is necessary to measure it in small increments while adjusting the reactivity to a safe value by some other means. However, this amounts to changing the reactor condition. Thus, it is not possible to measure the reactivity change of any motion under any condition but only of limited motions under limited conditions. Several specific methods have been developed for control rod calibration and are discussed here.

Exponential Period

The time behavior of a neutron population in a reactor with k not equal to one is described by a sum of exponentials. After a sufficient time has elapsed one of the exponentials will dominate the expression so that the neutron population follows an exponential law.

The exponential period method of calibrating an unknown reactivity is to introduce the reactivity into a critical reactor and then follow the neutron population with a neutron detecting device. The period or e-folding time of the final exponential is determined from the response of the detector, and this quantity is used in the inhour equation to calculate the value of the reactivity.

The calibration of a control rod having considerable worth may be determined by the following method: the reactor is made critical with the rod at a given position. The rod is then moved or "bumped" an amount sufficient to give a convenient period and the reactivity corresponding to the observed period calculated. This reactivity is then divided by the amount of the rod bump so that an average reactivity per inch is determined over the range of the bump. The rod is then moved to another position and the reactor made critical through some other means. The rod is bumped again, and a reactivity per inch calculated for the new position. This procedure is repeated at various positions over the complete range of rod motion, thereby enabling a curve to be obtained of reactivity per inch versus rod position. This curve is called a differential rod worth curve and may be integrated to find the approximate total worth of the rod.

The neutron level will behave in an exponential manner only when the reactivity is constant. This imposes the limitation that the method be used when the reactivity can be held constant during the calibration or when changes due to fast-neutrons and temperature effect can be corrected for.(6)(7)(11)(33)(35)(36)(42)(53)

Intercalibration

Once a single rod has been calibrated it is possible to calibrate other rods against it by determining how much reactivity must be added by the calibrated rod in order to maintain criticality after a given movement of the uncalibrated rod. This method is not confined to calibrating one rod in terms of another rod but can be used to calibrate any control device in terms of any other control device.(4)(6)(36)(42)(53)(64)

Subcritical Multiplication

If a burst of neutrons, S in number, is introduced into a subcritical reactor, by the definition of multiplication the next neutron generation will contain kS neutrons. The generation after that will contain k^2S, the next, k^3S, etc. If now a source of neutrons is inserted into the reactor which introduces neutrons continuously at the rate of S per generation, the neutron population in the reactor will become

$$S(1 + k^2 + k^3 + \dots + k^n)$$

or

$$\frac{S}{1-k} \tag{15}$$

where $k < 1$.

The subcritical multiplication factor is defined as

$$m \equiv \frac{1}{1-k} \quad . \tag{16}$$

Since the counting rate (R) of a neutron detector is proportional to the neutron population in the reactor,

$$R = \frac{\varepsilon S}{1-k} \tag{17}$$

where ϵ is the proportionality constant of the counter. To perform a subcritical calibration the reactor is made subcritical by a known amount and a source of neutrons inserted. A counting rate is obtained and the quantity ϵS calculated.

$$\epsilon S = R_1(1-k_1) \tag{18}$$

An unknown amount of reactivity is then inserted into the reactor, another counting rate taken and the new multiplication calculated using the ϵS determined before.

$$(1-k_2) = \frac{\epsilon S}{R_2} = \frac{R_1}{R_2}(1-k_1) \tag{19}$$

If the initial known reactivity was removed before taking R_2, then k_2-1/k_2 is the value of the unknown reactivity. If the initial reactivity was left in the reactor, the added unknown reactivity is

$$\Delta k = \frac{k_3-1}{k_3} \tag{20}$$

where

$$(k_3-1) = k_2-k_1 = \frac{R_2-R_1}{R_2}(1-k_1). \tag{21}$$

This method assumes that the quantity ϵS does not change when the reactivity is changed. Experimentally this may be hard to achieve, especially for large reactivity changes.(7)(64)

Distributed Poison

In this method a known amount of poison is distributed throughout the reactor and the change in control rod position for criticality noted. The worth of this rod motion is equivalent to the worth of the distributed poison. The worth of the poison can usually be calculated, and thus the reactivity worth of the rod motion found. An approximate method of calculating the poison worth for small amounts of poison is to assume that the added poison affects the multiplication only through the thermal utilization. Thus

$$\rho = \frac{\Delta k}{k} \approx \frac{\Delta f}{f} \approx -\frac{\Delta \Sigma_a}{\Sigma_a} \tag{22}$$

where:

f = thermal utilization factor

Σ_a = macroscopic absorption cross section

The distributed poison can be added by dissolving it in the moderator or coolant, or inserting it in the form of foils or wires. This method requires considerable time and effort for a single calibration and is only as good as the calculation.(7)(36)(44)

Transient Response

If a positive reactivity is inserted into a reactor which is operating at a sizeable power level, the heat generation will increase and the mean reactor temperature will rise as the neutron population increases. If the reactor has a negative temperature coefficient of reactivity, as the temperature rises the reactivity will decrease until at some temperature it will be zero and then become negative. The power level will then start to decrease. The temperature will pass through a maximum and start to decrease, but as temperature decreases the reactivity will increase. The net result of inserting a positive reactivity into a reactor with a negative temperature coefficient is to produce a series of oscillations in power level. These oscillations are damped by the action of delayed neutrons.

This effect has been used to find control rod "sensitivity" or relative differential rod worth. The rod to be calibrated is brought to the desired position, with the reactor critical, and bumped as in the exponential period method. However, instead of increasing exponentially the power level will oscillate.

The height of the first peak is then divided by the amount of the bump to obtain sensitivity. This procedure is repeated for various rod positions to obtain a sensitivity versus rod position curve. This curve should have the same shape as a differential rod worth curve. In order to minimize errors due to the non-linearity of the relation between reactivity and peak height, the magnitude of rod bumps is such that the initial power peaks are kept at about the same height.

The sensitivity curve can be converted into a differential rod worth curve. It has a scale factor that may be found by integrating the sensitivity curve over a range of rod positions for which an absolute calibration is known.

For a reactor that is operating at a high power level it is difficult to use the exponential period method. This is because the rising neutron level represents a substantial increase in power. This increase in power raises the temperature and magnifies the effect of the temperature coefficient, thus altering the original reactivity. The transient response method can only be used on a reactor which is producing a fair amount of heat and, therefore, is especially useful when it is desirable to perform the calibration while the reactor remains at high power.(42)

Rod Drop

If a negative reactivity is instantaneously inserted into a reactor which has been operating in a steady critical state, the neutron level will decrease exponentially producing a decay curve. The reactor is then subcritical with a distributed source of delayed neutrons being multiplied by a subcritical multiplication factor.

$$m' \equiv \frac{1}{1-k(1-\beta)} \tag{23}$$

where β is the delayed neutron factor.

Let the neutron level prior to the insertion of reactivity represent the birth of N_o neutrons per second. The number born per second which are delayed neutrons is then βN_o. Immediately after insertion of reactivity the delayed neutron birth rate is still βN_o since there has been insufficient time for the delay precursor level to change. The total neutron birth rate immediately after the drop is

$$N_1 = \frac{\beta N_o}{1-k(1-\beta)} \, . \tag{24}$$

Therefore

$$\frac{N_1}{N_o} = \frac{\beta}{1-k(1-\beta)} \, . \tag{25}$$

The ratio N_1/N_0 is determined experimentally by inserting reactivity and extrapolating the delay curve back to the time of insertion.

To obtain a differential rod worth curve by this method the reactor is made critical with the rod at the desired position. The rod is then driven into the core a fixed amount and the ratio N_1/N_0 found from the neutron level detectors. The change in multiplication due to the rod motion is determined from the above equation and the differential rod worth is this change divided by the amount of the rod bump. The above equation for N_1/N_0 also applies when inserting a positive reactivity or withdrawing the rod subject to the limitation that $k(1-\beta) < 1$ (not prompt critical).

The reactivity may also be found from the decay curve by extrapolating the final exponential portion of the curve back to a point N_2 and using the formula

$$\frac{N_2}{N_0} = \frac{\beta_i}{1-k(1-\beta_i)} \tag{26}$$

where β_i is the production fraction for that group of delayed neutrons having the longest half life.(35)(43)

Source Jerk

The source jerk method is similar to the rod drop method in that it makes use of the reactor decay curve. Rather than starting at a critical condition, the reactor is initially subcritical and contains a neutron source. If the source strength is S per second, the number of neutrons born into the reactor per second is

$$N_o = \frac{S}{1-k} \, . \tag{27}$$

Of these, the number coming from fission is

$$\frac{S}{1-k} - S = \frac{Sk}{1-k} \, . \tag{28}$$

Of these, the number which are delayed is

$$\frac{\beta Sk}{1-k} = \beta k N_o . \tag{29}$$

At time zero the source is instantly ejected from the reactor. The reactor is then subcritical with a distributed source of delayed neutrons being multiplied by

$$\frac{1}{1-k(1-\beta)} \, . \tag{30}$$

The neutron birth rate immediately after the source is removed is

$$N_1 = \frac{\beta k N_o}{1-k(1-\beta)} \tag{31}$$

$$\frac{N_1}{N_o} = \frac{\beta k}{1-k(1-\beta)}, \quad \frac{N_o-N_1}{N_1} = \frac{1-k}{\beta k} = \frac{-\Delta k}{\beta} \tag{32}$$

The quantity N_o/N_1 is determined experimentally as in the rod drop method and the reactivity calculated.

To determine the worth of a given motion of a control rod source jerk measurements are made of the reactivity before and after the motion. The worth of a motion is the difference in the two reactivities.

The source jerk method may be preferred to the rod drop method in that the source, being small and light, can be ejected from the reactor in less time than it takes to move a rod.(35)

Subcritical Reactors

The control rod calibration methods discussed above apply primarily to critical assemblies. Since these calibrations are a measure of the reactivity change, ρ, and depend upon the amount the multiplication factor, k, varies from unity, it is necessary that the reactor operates with $k < 1$, $k = 1$, and $k > 1$.

In view of this and the fact that the k of subcritical assemblies can not exceed $k < 1$, the normal procedures for control rod calibration are not applicable for subcritical reactors.

The calibration of a subcritical control rod, rather than being a function of Δk, is therefore limited to some measurement of the effect of the control rod on the neutron flux. Since a means of control is not required for subcritical reactors in order to maintain a safe mode of operation, the procedures for determining control rod effect are not standard and are accomplished in a manner depending upon the extent to which the effect must be known. The method used in this thesis is one means of establishing the effect of a subcritical control rod.

CALIBRATION OF THE CONTROL ROD

Fuel and Source

The Virginia Polytechnic Institute natural uranium-graphite subcritical reactor(55), when fully loaded, contains 576 fuel rods which measure eight inches in length and one inch in diameter and are canned in aluminum. The uranium rods are loaded into the 72 horizontal fuel slots provided for the fuel with each slot holding eight rods. The lattice is arranged in the graphite moderator in such a way that the fuel slots are parallel and are spaced on eight inch centers both in the horizontal and vertical directions. The length, width, and height of the total lattice are 64 inches, 64 inches, and 72 inches, respectively.

Four one-curie plutonium-beryllium sources (plutonium half-life: 2.8×10^4 years) having a neutron emission of approximately 1×10^7 neutrons per second are used. The sources are placed 16 inches (approximately one diffusion length) below the lattice in the vertical axis of the reactor, thereby permitting the majority of the source neutrons to be thermalized by the time they reach the lattice structure.

Both the fuel and the sources are on loan from the United States Atomic Energy Commission.

Counting Equipment

The experimental procedures for establishing the control rod effect on the flux distribution are accomplished with the following equipment.

1. Scaler: "Ultrascaler", pre-set time, pre-set counts, decade counting, 5 micro-seconds resolving time, 500 to 5000 regulated high voltage supply, 1 mv to 0.8 v input sensitivity, manufactured by Nuclear-Chicago.
2. Detector: Boron triflouride detection tube, Mk 2, Model 3, 96 per cent enriched boron-10, six inch active anode length, 0.032 inch aluminum cathode wall, 2 mil diameter tungsten anode, one inch over-all diameter, 13-1/4 inches over-all length, detection energies below 0.1 Mev, manufactured by Radiation Counter Labs.
3. Detector: Geiger-Muller end-window detection tube, Mk 1, Model 5, one inch active anode length, 1.5-2.0 mg/cm^2 mica window, 1-5/8 inch diameter, 4 inches in length, operating voltage around 1400 v, manufactured by Radiation Counter Labs.
4. Counting shield: iron pig, two inch wall thickness, 170 pounds in weight, manufactured by Radiation Counter Labs.

5. Foil holders: (1) lucite stand with aluminum sample tray, used with counting shield, manufactured by Radiation Counter Labs; (2) graphite strips having foil recesses, used for horizontal foil irradiation, locally made; (3) wire frame, used for vertical foil irradiation, locally made.

Method of Procedure

To determine the effect of the control rod on the neutron flux in the vicinity of the rod, tests are performed using 0.020 inch cadmium as the neutron absorbing material. When the control rod is inserted into the reactor, a cylinder of absorber material two inches in diameter and covered with 3/32 inch aluminum is presented to the neutron flux.

The effect of the aluminum covering may be determined from the expression(24)

$$\text{Atn.} = 1 - e^{-N\sigma_a x} \qquad (33)$$

where:

Atn. = attenuation of neutrons due to absorption in material

N = number of nuclei per cm^3 of material

σ_a = absorption cross section of material (cm^2)

x = thickness of material through which the
neutrons pass (cm).

Using a value of σ_a equal to 230 millibarns for aluminum(5), the attenuation of thermal neutrons due to the aluminum cover is only 0.35 per cent of the original neutron intensity. Hence, the aluminum has a negligible effect on the removal of thermal neutrons.

The thermal neutron absorption cross section for naturally-occurring cadmium is approximately 2550 barns and is due to Cd^{113}--the only absorbing isotope (12.26 per cent in abundance)--which has a cross section of 20,800 barns(5). When this value (2550 barns) and a cadmium thickness of 40 mils (since the neutrons must pass through two surfaces of the control rod) are used in equation (33), essentially all thermal neutrons (99.999 per cent) encountering the control rod are absorbed. The reaction taking place is ${}_{48}Cd^{113}(n,\gamma){}_{48}Cd^{114}$ where ${}_{48}Cd^{114}$ is a stable isotope(14). The cadmium cutoff energy for a thickness of 40 mils is 0.66 ev(9); i.e., neutrons above this energy will pass rather freely through the rod. It is concluded that the control rod is "black" to thermal neutrons and that all thermal absorptions are attributed to the cadmium.

The effect of the control rod is determined by a series of horizontal traverses at three different levels in the pile using various control rod positions. The data at each level is taken as the control rod position is varied in one foot increments beginning with the 6.5 foot position (six inches from the source). Traverses are made until the control rod movement produces no appreciable effect on the flux.

Two separate counting techniques are used in taking the data. The flux distribution from the surface of the control rod (or from the center of the pile as the case may be) to a distance of four inches from the rod is obtained at 1/2 inch intervals by using indium foils containing 95.77 per cent In^{115}(5). The foils, 1.00 inch in diameter and 0.005 inches thick, are hand picked for a weight of approximately .505 mg per foil. The foils, together with one inch diameter graphite spacers, are placed vertically in a holder and inserted into the pile. The activation time of the foils ranges from 3 to 10 hours, after which they are removed from the pile. The activities are then determined using an "Ultrascaler" and end-window Geiger-Muller detector. The induced foil activity is a result of the ${}_{49}In^{115}(n,\gamma){}_{49}In^{116}$ reaction, where ${}_{49}In^{116}$ is radio-active (half-lives of 13 seconds and 54.1 minutes) and decays to ${}_{50}Sn^{116}$ by β^- emission(52).

Records of time of insertion, location in pile, time of withdrawal, delay time before counting, total counting time, and total counts are kept for each foil. Saturated activities are then determined from (75)

$$A_s = \frac{\lambda C}{(1-e^{-\lambda t_e})(e^{-\lambda t_w})(1-e^{-\lambda t_c})} \tag{34}$$

where:

A_s = saturated activity (counts/minute)
λ = decay constant (min^{-1})
C = counts minus background (counts/minute)
t_e = exposure time (minutes)
t_w = waiting time before counting (minutes)
t_c = counting time (minutes).

Counting times to obtain two per cent probable error range from two to ten minutes. A minimum waiting time of one minute is allowed in order to permit the 13 second half-life isomer to decay to a negligible counting rate.

The saturated activity is converted to thermal flux with the relation

$$\phi_{th} = \frac{A_s f_{th}}{N\sigma_a V \epsilon f_{cd}(60)} \tag{35}$$

where:

ϕ_{th} = thermal neutron flux ($\text{neuts/cm}^2\text{/sec}$)

A_s = saturated foil activity (counts/min)

f_{th} = portion of foil activity induced by thermal neutrons

N = number of nuclei per cm^3 of foil

σ_a = absorption cross section of foil (190×10^{-24} cm^2)(5)

V = volume of foil (cm^3)

ε = counter efficiency

f_{cd} = cadmium correction factor.

That portion of the foil activity resulting from thermal neutrons is determined by comparing the saturated activity of a bare foil to that of a foil sandwiched between cadmium discs. 86.1 per cent of the foil activity is found to be induced by thermal neutrons. In connection with this method--since cadmium also absorbes some epithermal neutrons--a cadmium correction factor which is a function of indium-foil thickness and cadmium thickness, 1.065 in this case, is used(52). With the aid of a standard source ($_{83}Bi^{210}$; 0.85×10^{-5} mc; 1.17 Mev β^-; 22 year half-life) a counter efficiency of 14.9 per cent is obtained.

Since the changes in flux distribution as a function of distance are less at points greater than four inches from the control rod, a second method of neutron detection is used to continue the traverses between the distances of four inches and 20 inches from the rod. These counting rates are obtained directly at two inch intervals with an enriched boron triflouride (BF_3) detection tube and associated scaling apparatus. Of interest is the ${}_5B^{10}(n,\alpha){}_3Li^7$ exothermic reaction which has an energy release of 2.78 Mev. The ground state of ${}_3Li^7$ may be formed directly, or an intermediate state of ${}_3Li^7$ may be formed followed by the emission of a 0.48 Mev gamma(52). The BF_3 counting rates, being directly proportional to the neutron density, made it possible to normalize the BF_3 data to the foil data for the complete thermal neutron distribution curves.

The results of the counting data (Figures 23, 24, and 25) show a noticeable decrease in the flux at distances of four inches and 12 inches from the control rod. This decrease is more predominate for the traverses with higher flux values, and it is attributed to the proximity of the counter to the fuel rods at these points. The presence of less moderator between the fuel and counter reduces the probability of the neutrons from the fuel being thermalized or slowed down to energies detectable by the counter. In drawing the curves, however, the flux depressions are not considered and a smooth curve is drawn through the points.

Data and Results

A graphical representation of the data obtained at each pile level is made using a semi-log plot. The thermal neutron flux distribution is a function of the distance from the control rod and the various control rod positions within each level. Figures 23, 24, and 25 are the results of these plots for pile levels 8, 12, and 16, respectively.

The flux curves representing the control rod positions within each pile level are averaged over a distance of 20 inches from the control rod. The rate of change of the flux averages for each level is plotted as a function of control rod motion and is found to follow the exponential law. The powers to which e must be raised in order to satisfy the points are determined by obtaining the slopes of the lines resulting from semi-log plots. These slopes or powers of e for pile levels 8, 12, and 16 are - 0.234 per foot, - 0.177 per foot, and - 0.134 per foot, respectively. These values in turn are plotted as a function of pile level, and again the points represent a straight line when using a semi-log plot. The line is extrapolated back to the zero level and a value of 0.41 obtained. Using this point, together with an additional point arbitrarily

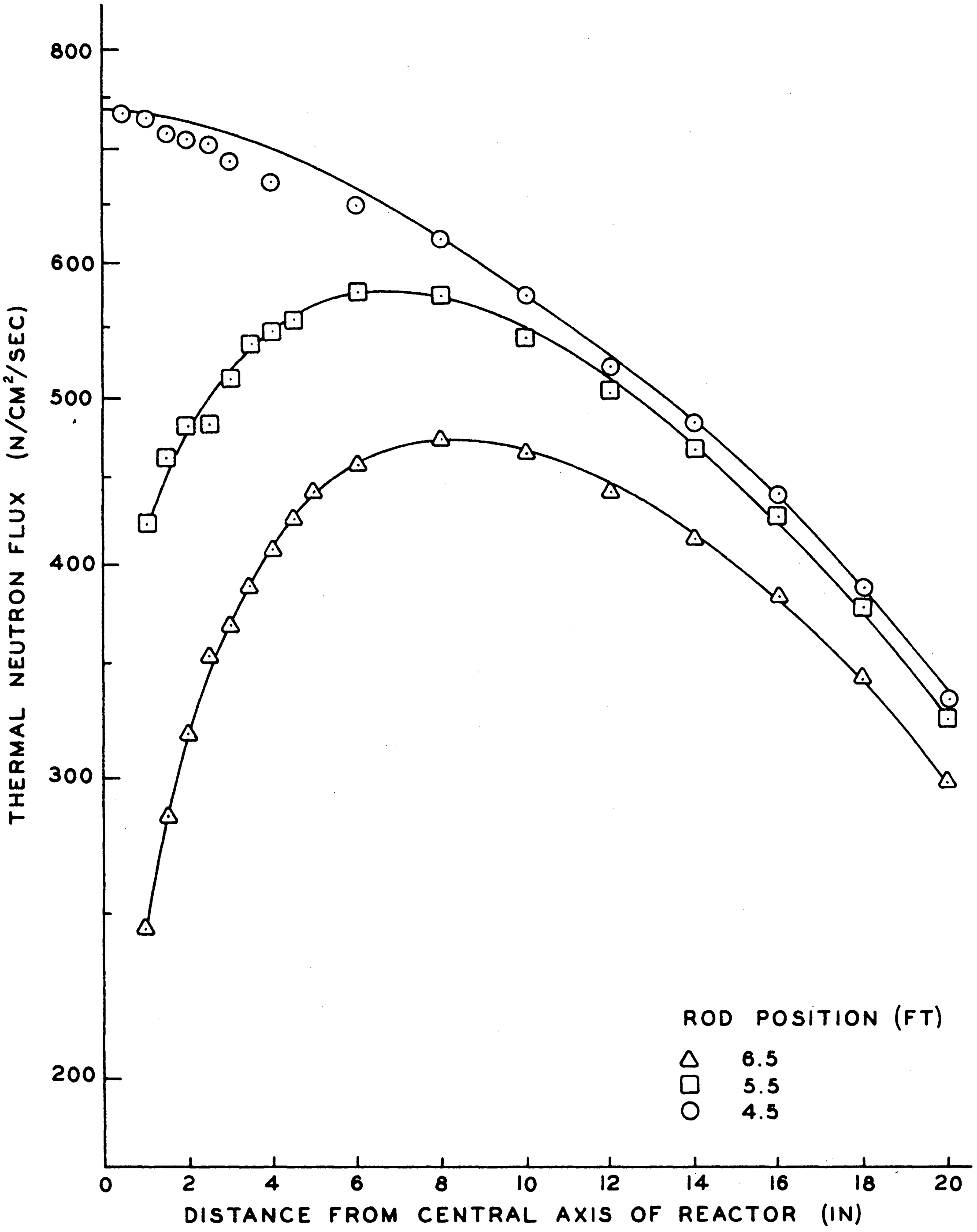


FIGURE 23. FLUX DISTRIBUTION AT REACTOR LEVEL 8

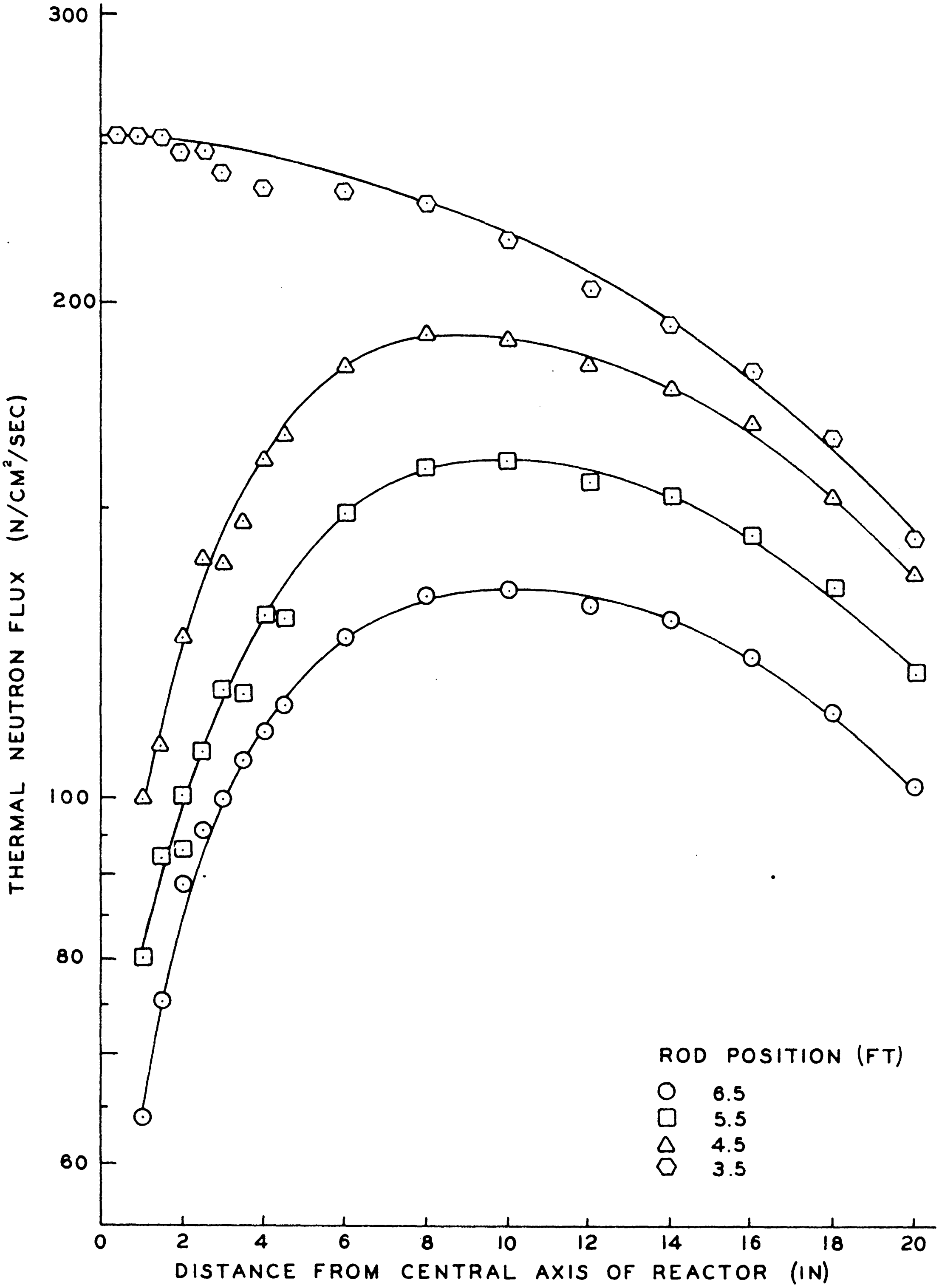


FIGURE 24. FLUX DISTRIBUTION AT REACTOR LEVEL 12

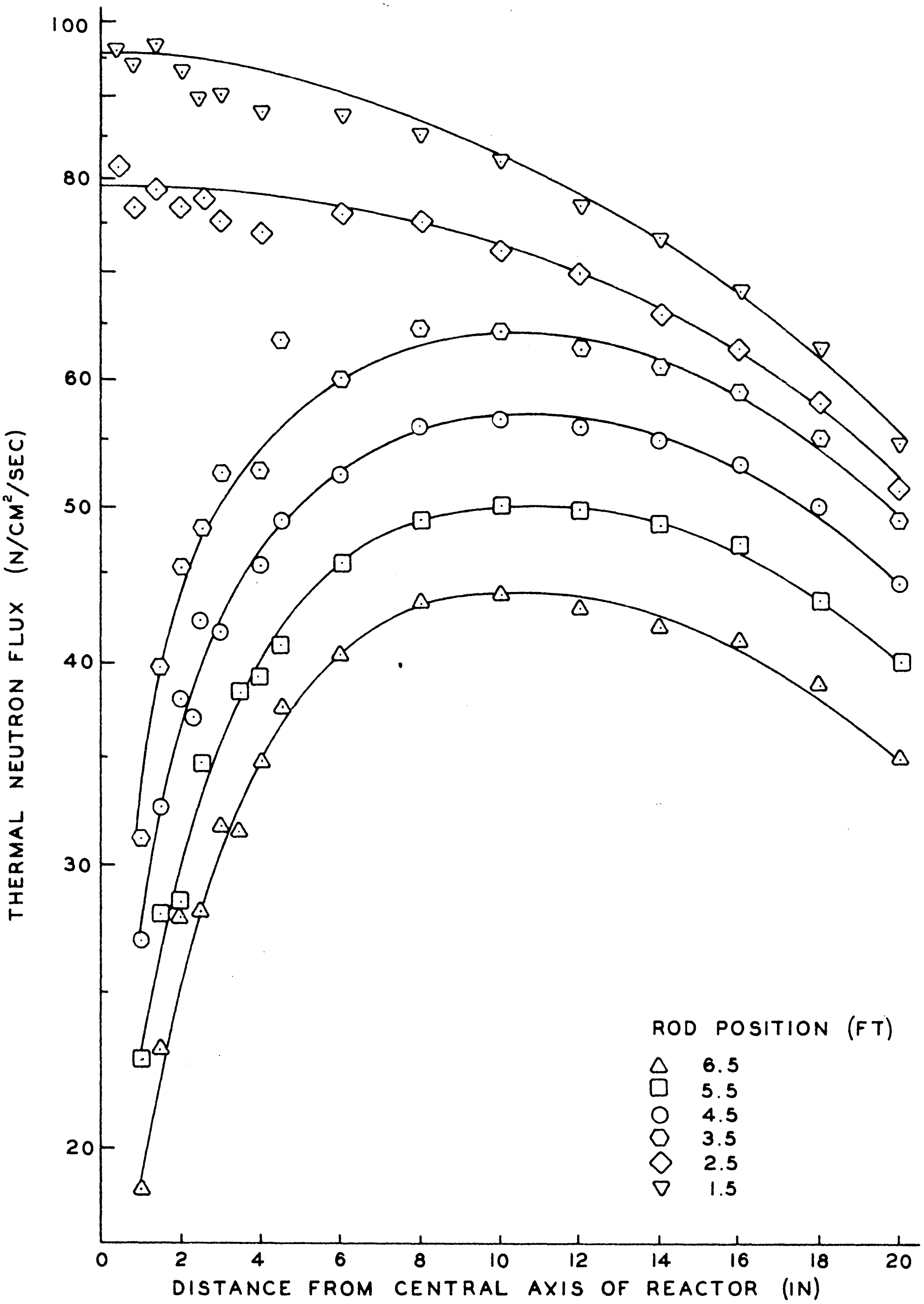


FIGURE 25. FLUX DISTRIBUTION AT REACTOR LEVEL 16

chosen, the power of e satisfying the curve is determined and found to be - 0.07 per level.

In view of the above relations, the data, representing the effect of the control rod as a function of pile level and control rod position, may be reduced to the following expression.

$$f_{\phi} = 1 - e^{-.41(e^{-.07L})\Delta R} \qquad (36)$$

where:

f_{ϕ} = factor by which the average neutron flux changes

L = pile level in question (4 inches = 1 level)

ΔR = change in control rod position (feet) (insert = + ΔR; withdraw = - ΔR)

The above equation is limited in that (1) the flux values used must be the average flux over a distance of 20 inches from the center of the pile, and (2) the value $(24 - L)/3$ must be equal to or less than the control rod position as read from the indicator. The latter is due to the fact that the rod effect at distances below the rod does not conform to the flux pattern used in obtaining the equation.

It is felt that with the aid of more extensive data expression (36) can be expanded for determining the change in flux at a point rather than average flux.

SUMMARY

A flexible control rod was designed and constructed for the Virginia Polytechnic Institute subcritical reactor. The control rod is motor driven and remotely operated. Aluminum, steel, and cadmium absorber are the materials used in construction. Provision is made for changing the absorber material in the control rod to permit the investigation of materials having various neutron absorbing properties.

Tests were performed using cadmium as the absorber material to determine the effect of the control rod on the neutron flux. Results indicate that the control rod, although flexible, is effectively a solid, straight rod. An equation is obtained for expressing the control rod effect as a function of pile level and control rod position.

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APPENDIX I

TORQUE REQUIREMENT FOR THE CONTROL ROD DRIVE MOTOR

1. Torque due to pivoting frame and control rod drum--T_1(in-lbs)

$$T_1 = \frac{(W_1)(D_1)(D_3)}{D_2}$$

where:

W_1 = weight of frame and drum (lbs)

D_1 = horizontal distance between frame pivot and drum shaft (inches)

D_2 = vertical distance between frame pivot and contact point of cam follower on threading cam (inches)

D_3 = vertical distance between drum shaft and contact point of cam follower on threading cam (inches)

$$T_1 = \frac{(38)(5.6)(2)}{8.75} = 48.6 \text{ in-lbs.}$$

2. Torque due to control rod--T_2(in-lbs)

$$T_2 = (W_2)(N)(D_4)$$

where:

W_2 = weight of control rod section (lbs)

N = number of control rod sections

D_4 = horizontal distance between drum shaft and control rod line of action (inches)

$$T_2 = (2.52)(18)(6) = 272 \text{ in-lbs.}$$

3. Tangential force on worm gear--F_{tg}(lbs)

$$F_{tg} = \frac{T_1 + T_2}{R_{wg}}$$

where:

R_{wg} = radius of worm gear (inches)

$$F_{tg} = \frac{48.6 + 272}{3.125} = 102.5 \text{ lbs.}$$

4. Tangential force on worm--F_{tw}(lbs)(10)

$$F_{tw} = F_{tg} \frac{\cos \phi \sin \lambda + f \cos \lambda}{\cos \phi \cos \lambda - f \sin \lambda}$$

where:

ϕ = pressure angle of worm (14.5 degrees)

λ = lead angle of worm (11.316 degrees)

f = coefficient of friction (0.15)(10)

$$F_{tw} = 102.5\,\frac{(.968)(.196) + (.15)(.98)}{(.968)(.98) - (.15)(.196)}$$

$$= 38 \text{ lbs.}$$

5. Torque on worm shaft and thus torque required by motor--T_w(in-lbs)

$$T_w = \frac{F_{tw}}{R_w}$$

where:

R_w = radius of worm (inches)

$$T_w = \frac{38}{.3125} = 12.2 \text{ in-lbs.}$$

A motor was chosen with 21 in-lbs of torque, yielding a factor of safety of 1.72.

Motor Number: B4218-10; Bodine Electric Company, Chicago, Illinois.

APPENDIX II

LIMITING LOADS ON WORM GEAR TEETH

Gear Number: D1147; Boston Gear Works, Quincy, Mass.

1. Limiting tangential load--W_{max}(lbs)(63)

$$W_{max} = s_d p_n f_g y$$

where:

s_d = design stress (24,000 psi for phosphor bronze)(63)

p_n = normal circular pitch (inches)

f_g = face width of gear (inches)

y = tooth form factor (0.1 for 14.5 degrees pressure angle)(63)

$$W_{max} = (24{,}000)(.196)(.312)(.1) = 147 \text{ lbs.}$$

147 lbs > 102.5 lbs required and is satisfactory.

2. Limiting load for wear--W_w(lbs)(63)

$$W_w = D f_g K$$

where:

D = pitch diameter of gear (inches)

K = load stress factor (80 for phosphor bronze gear and hardened steel worm having 11.316 degrees lead angle)(63)

$W_w = (6.25)(.312)(80) = 156$ lbs.

156 lbs $>$ 102.5 lbs required and is satisfactory.

The Design, Construction, and Calibration of a Flexible Control Rod for the V. P. I. Subcritical Reactor

Abstract

The problem of installing a control rod in the V. P. I. subcritical reactor is complicated by the limiting two foot clearance between the top of the reactor and the ceiling. Within this space it is necessary to insert and operate an effective seven foot, solid, straight rod along the vertical axis of the reactor.

The problem is overcome by cutting the rod in six inch sections at an angle of 45 degrees and installing an internal pivoting arm which allows the sections to break 60 degrees with respect to one another. The rod is wrapped on a drum which takes the shape of a hexagonal helix when withdrawn from the pile. When inserted, an effective solid, straight rod is presented to the neutron flux. The control rod is motor driven and remotely operated. Provision is made for changing the absorber material in the control rod to permit the investigation of materials having various neutral absorbing properties.

Tests were performed using cadmium as the absorber material to determine the effect of the control rod on the

neutron flux. Results indicate that the control rod, although flexible, is effectively a solid, straight rod. An equation is obtained for expressing the control rod effect as a function of pile level and control rod position.