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Reactors-Production

A SAFETY ROD ACTUATOR

by

D. Baker, Jr., W. E. Llewellyn, J. P. Maloney

Pile Engineering Division

December 1954

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E. I. du Pont de Nemours & Co.
Explosives Department — Atomic Energy Division
Technical Division — Savannah River Laboratory

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REACTORS-PRODUCTION

A SAFETY ROD ACTUATOR

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ABSTRACT

A windlass that operates a safety rod for a nuclear reactor was developed to decelerate the rod after it drops under emergency conditions into the reactor. The windlass is designed to convert the kinetic energy of the falling rod as it nears its limit of travel to rotational energy in the windlass. The conversion is accomplished without the aid of an external power source or an auxiliary snubbing mechanism.

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INTRODUCTION

Safety rod actuators for nuclear reactors frequently utilize gravitational force for emergency insertion of the safety rods. In such designs the rods must be decelerated before reaching the end of their travel to prevent damage to the reactor and to the auxiliary components.

In the Savannah River reactors, where the safety rods are supported vertically by cables and long slender tubes, the snubbing force is applied at the top of the cable to avoid buckling these supports. The cable is wound on a drum that is coupled with an electric clutch to a gearmotor. The clutch is released to permit the rods to fall and is electrically re-engaged near the bottom of the rod's travel to decelerate the rod.

Ideally, an actuator should not depend on an external source of power to activate the snubbing mechanism, since failure of the power can result in serious damage.

This report describes an improved design for a safety rod actuator which has a snubbing device that requires no external power source for its activation.

SUMMARY

The actuator developed at SRL for decelerating a safety rod employs a windlass that is designed to dissipate the energy of the falling rod during its last few feet of travel by rapidly accelerating the windlass. The snubbing is accomplished by permitting the last few turns of the cable to unwind from a spiral groove that is cut in a conical surface on one end of the windlass or drum. As the cable unwinds from the spiral groove and approaches the apex of the cone, the downward velocity of the rod approaches zero and the drum is accelerated to a high angular velocity. The cable is anchored to a shaft that serves as the axle of the conical drum. The drum can rotate freely relative to the shaft, thereby permitting the rod to remain in its down position after an emergency drop without the cable being rewound by the rapidly rotating drum.

On the basis of the conical drum concept, a prototype of a safety rod actuator for the Savannah River Plant was designed and constructed. The actuator, shown in Figure 1, will permit a safety rod to be inserted in the reactor in two seconds.

DISCUSSION

ACTUATOR REQUIREMENTS

The Savannah River Plant standards require that in an emergency, safety rods be inserted to within two feet of the bottom of the 15-foot pile in three seconds. Under normal operation, the rods must be withdrawn and inserted at a rate not greater than 7-1/2 feet per minute, with the provision that a scram (emergency insertion) be possible regardless of the rod position.

Because of the method of loading and unloading the SRP piles, the actuators are located 130 feet above the top of the reactor. Cables and pairs of concentric tubes, ("long latch assemblies"), connect the actuators to the safety rods. After seating the safety rod in the pile, an actuator must lower its long-latch assembly an additional two inches to permit the long latch to be disconnected from the rod. The long-latch assemblies are then removed from the top of the pile to permit charging and discharging.

CONICAL DRUM CONCEPT

In view of the foregoing requirements, one of the simplest and most reliable methods for quick insertion of a safety rod is to allow the rod to fall freely. Damage to the reactor, or buckling of the rod and slender long-latch assembly must be prevented by decelerating these components with a snubbing force applied at the actuator. The snubbing device described in this report is a cable windlass designed in such a way that the energy of the falling rod is dissipated by accelerating the windlass during the last 2-1/2 feet of rod travel. The snubbing is accomplished by providing a conical surface on one end of the windlass or drum that supports the cable. The last 1-1/2 turns of the cable groove form a spiral on the conical surface and terminate at the apex of the cone.

When the rod is in the up position, its cable is fully wound on the drum. When the rod drops, the drum is accelerated at a constant rate by the unwinding cable until the cable leaves the cylindrical surface of the drum and begins to unwind from the spiral groove. At this point the angular acceleration of the drum begins to increase rapidly and the velocity of the falling rod decreases.

The cable fits in a groove that is continuous from the drum to the shaft that serves as the axle of the drum. The terminating point of the groove is at the center of rotation of the shaft. As the unwinding cable approaches this point, the downward velocity of the cable and rod approaches zero, but the angular velocity of the conical drum reaches a maximum. Since the drum can rotate freely relative to the shaft, the cable merely hangs from the shaft while the drum rotates and expends its energy in overcoming bearing friction.

DESIGN CONSIDERATIONS

In the design of a conical drum actuator for a particular application, the weight of the safety rod and the distance through which the rod operates are generally specified. In most cases there are specifications that require the rod to be partially inserted a given distance and/or fully inserted within a given time. In addition, there are often special requirements that limit the size and weight of the actuator. The designer must choose the parameters of the actuator so that the desired performance will be obtained. The parameters that must be chosen are (1) radius of the drum, (2) effective inertia of the drum, (3) snubbing distance, and (4) shape of the spiral on the conical portion of the drum. Finally, the maximum tension that is developed in the cable as the rod is snubbed should not exceed a safe value, nor should the snubbing action cause excessive "bounce" that might result in backlash of the cable.

For a particular actuator, the exact calculation of the position of the rod and the tension in the cable as a function of time would require taking into account frictional effects and the elastic properties of the cable. Such a calculation would be much more complicated than is normally required for practical purposes. The calculation is much simplified if friction and cable stretch are neglected. The necessary equations are developed in the following section on "Idealized Analysis". Subsequently, an "Approximate Analysis" is given that will suffice for practical purposes of design.

Idealized Analysis

At any instant the kinetic energy of the rod, E_R, plus the kinetic energy of the drum, E_D, equals the weight of the rod, W, times the distance it has dropped, S:*

$$E_R + E_D = WS$$

Dividing by E_R and rearranging, one obtains:

$$E_R = \frac{WS}{1 + E_D/E_R}$$

Since E_D equals $\frac{1}{2} I\omega^2$ where ω is the angular velocity of the drum; and E_R equals $\frac{1}{2} Wv^2$ where v is the linear velocity of the rod, then:

* Symbols are listed in Appendix C.

$$E_R = \frac{WS}{1 + \frac{I\omega^2}{Wv^2}}$$

Since the linear velocity, v, of the rod and cable equals the angular velocity, ω, times the torque radius, r, of the cable as it unwinds from the drum, then:

$$E_R = \frac{WS}{1 + \frac{I}{Wr^2}} \qquad (1)$$

The net force, F, acting on the rod times an incremental distance, dS, that the rod has dropped equals the kinetic energy in the rod, therefore:

$$F = \frac{d}{dS}\,(E_R)$$

or

$$F = \frac{d}{dS}\left(\frac{WS}{1 + \frac{I}{Wr^2}}\right) \qquad (2)$$

The net force on the rod at any time is the difference between the force of gravity and the cable tension, T, so:

$$F = W\text{-}T$$

or

$$T = W - \frac{d}{dS}\left(\frac{WS}{1 + \frac{I}{Wr^2}}\right) \qquad (3)$$

$\frac{d}{ds} = \left(\frac{ds}{dt}\right)^{-1} \frac{d}{dt}$

$r = f(s)$

The path of the spiral determines r as a function of S. For a given spiral, the tension in the cable and the net force on the rod can be computed from equations (3) and (2) as a function of S. In particular, the maximum tension can be found.

Since the acceleration is given by $a = \frac{Fg}{W}$, the relationship between acceleration and distance S is also known. The instantaneous velocity of the rod is then determined as follows:

[redacted]

$$a = \frac{dv}{dt} = v\frac{dv}{dS}$$

or

$$v^2 = 2\int_0^S a dS$$

The time of travel to any given position can then be computed from:

$$t = \int_0^S \frac{dS}{v}$$

Approximate Analysis

Before snubbing begins, the cable unwinds from the portion of the drum that has a constant diameter and the rod falls with a constant acceleration:

$$a = \frac{g}{1 + \frac{I}{Wr_o^2}}$$

The time for the rod to fall to the position (S_1) where snubbing begins is:

$$t_1 = \sqrt{\frac{2S}{a_1}} = \sqrt{\frac{2S_1(I + Wr_o^2)}{gWr_o^2}}$$

The additional time for the rod to reach the end of its travel, after snubbing has begun, is generally small compared to t_1. A satisfactory approximation of this time interval is given by the assumption that the rod is brought to rest with constant deceleration in the interval. The velocity of the rod at the beginning of the interval is:

$$v_1 = at_1 = \frac{gt_1}{1 + \frac{I}{Wr_o^2}}$$

For uniform deceleration over the distance $S_2 - S_1$ the time will be:

[redacted]

$$t_2 - t_1 = \frac{2(S_2 - S_1)}{v_1} = \frac{2(S_2 - S_1)(1 + \frac{I}{Wr_o^2})}{gt_1}$$

The total time of insertion can therefore be approximated by:

$$t_2 = \sqrt{\frac{2S_1(I + Wr_o^2)}{gWr_o^2}} + 2(S_2 - S_1)\sqrt{\frac{I + Wr_o^2}{2S_1 gWr_o^2}} \qquad (4)$$

Sufficient information about the tension in the cable can be obtained by a consideration of appropriate average tensions. Ordinarily, the maximum tension will occur as the rod approaches the position of full insertion. The reason for this is that there is a maximum curvature that can be practically used with a given cable. When the cable has unwound from the spiral to the point of maximum curvature, there is little control that can be exercised over the remaining distance of travel.

If the position of the rod is S_m and the torque radius is r_m when the cable has unwound to the point of maximum curvature, the kinetic and potential energy of the rod are:

$$\text{Kinetic Energy} = \frac{WS_m}{1 + \frac{I}{Wr_m^2}}$$

$$\text{Potential Energy} = W(S_2 - S_m)$$

The total energy of the rod must be expended by doing work on the cable in the remaining distance of travel. The average tension in the cable over the distance S_m to S_2 is:

$$T_{avg}\ (\text{terminating}) = W + \frac{WS_m}{(S_2 - S_m)(1 + \frac{I}{Wr_m^2})} \qquad (5)$$

It is possible to control the termination of the cable in such a way that the tension is theoretically constant over the interval from S_m to S_2, but the effect of cable stretch is generally so great that such pains are unwarranted. The average tension given by equation (5) should be made substantially less than the ultimate strength of the cable.

The average tension in the cable for the distance the rod moves during snubbing is given by:

$$T_{avg} \text{ (snubbing)} = W + \frac{WS_1}{(S_2 - S_1)\left(1 + \frac{I}{Wr_o^2}\right)} \qquad (6)$$

The maximum tension in the cable will exceed the larger of the two average tensions given by equations (5) and (6) by a factor of two or three.

Performance

The actual performance of two different actuators (Figures 1 and 2) is compared with the quantities computed by means of the equations given under "Approximate Analysis."

Experimental Model

Spiral is shown in Figure 3

W = 30 lbs
I = 14.1 lb-ft^2
S_1 = 12 ft
S_2 = 16 ft
S_m = 15.97 ft

r_o = .292 ft
r_m = .042 ft

Time of insertion	= 2.9 seconds	observed
t_2	= 2.94 seconds	equation (4)

Maximum tension in cable	= 120 lbs	observed
T_{avg} (snubbing)	= 44 lbs	equation (6)
T_{avg} (terminating)	= 91 lbs	equation (5)

Prototype Model

Spiral is shown in Figure 4

W = 75 lbs
I = 42.6 lb-ft^2
S_1 = 13.5 ft
S_2 = 16 ft
S_m = 15.96 ft

r_o = 0.458 ft
r_m = 0.042 ft

Time of insertion = 2.07 seconds observed
t_2 = 2.15 seconds equation (4)

Maximum tension in cable = 400 lbs observed
T_{avg} (snubbing) = 184 lbs equation (6)
T_{avg} (terminating) = 167 lbs equation (5)

THE DESIGN OF A PROTOTYPE MODEL FOR SRP

In order to meet the requirements stated previously and to require a minimum of changes to existing equipment, several unique features which could normally be omitted in most installations were incorporated in the design of a prototype actuator for the Savannah River Piles. Therefore, the following description of this design treats only those features necessary for a workable machine that satisfies the requirements of most safety rod actuators. The mechanical features that apply only to the actuators for SRP are described in Appendix A.

The prototype model for the Savannah River production reactors is shown in section view in Figure 1. The conical drum (F) is attached to a hub (E) that is seated on bearings. The bearings are mounted on the shaft (H) in which the cable is anchored, and the shaft in turn is seated in bearings that are pressed into a supporting frame (J). The cable and rod are moved normally by driving the drum in either direction by a gearmotor connected through an electric clutch (B). The purpose of the clutch is to release the drum from the gearmotor, and allow the rod to drop freely when an emergency drop is required or when the power supply fails.

When the cable and rod are to be moved upward, the shaft must turn and wind up the cable until it pays onto the drum. The torque is transmitted from the drum to the shaft by a key (K), which engages the drum in the up direction only. The drum can rotate freely in the opposite direction on the shaft after an emergency drop.

The safety rod and long-latch assembly weigh 75 pounds, and must drop 16 feet. The moment of inertia neccessary to absorb this amount of energy is provided by a flywheel (N) connected to the drum and hub through a 3 to 1 gear ratio. Since the effective moment of inertia of the flywheel varies as the square of the gear ratio, the gearing permits the use of a flywheel having only 1/9 the moment of inertia of one connected directly to the drum, and allows a reduction in the weight of the actuator.

The prototype model shown in Figure 1 permitted the safety rod to drop 16 ft in 2.3 seconds. This time was measured from the instant the "scram" signal was placed in the control circuit until the rod reached its limit of travel. A curve of the height vs. time of fall is shown in Figure 5.

This curve neglects the time delay in the relays of the control circuit.

The remaining details of the actuator as shown in Figure 1 are significant only in so far as they meet the special requirements of SRP. These details, such as the lowering mechanism within the hub and the eccentric in the shaft, are described in Appendix A.

A description of an actuator for operating gangs of safety rods is given in Appendix B.

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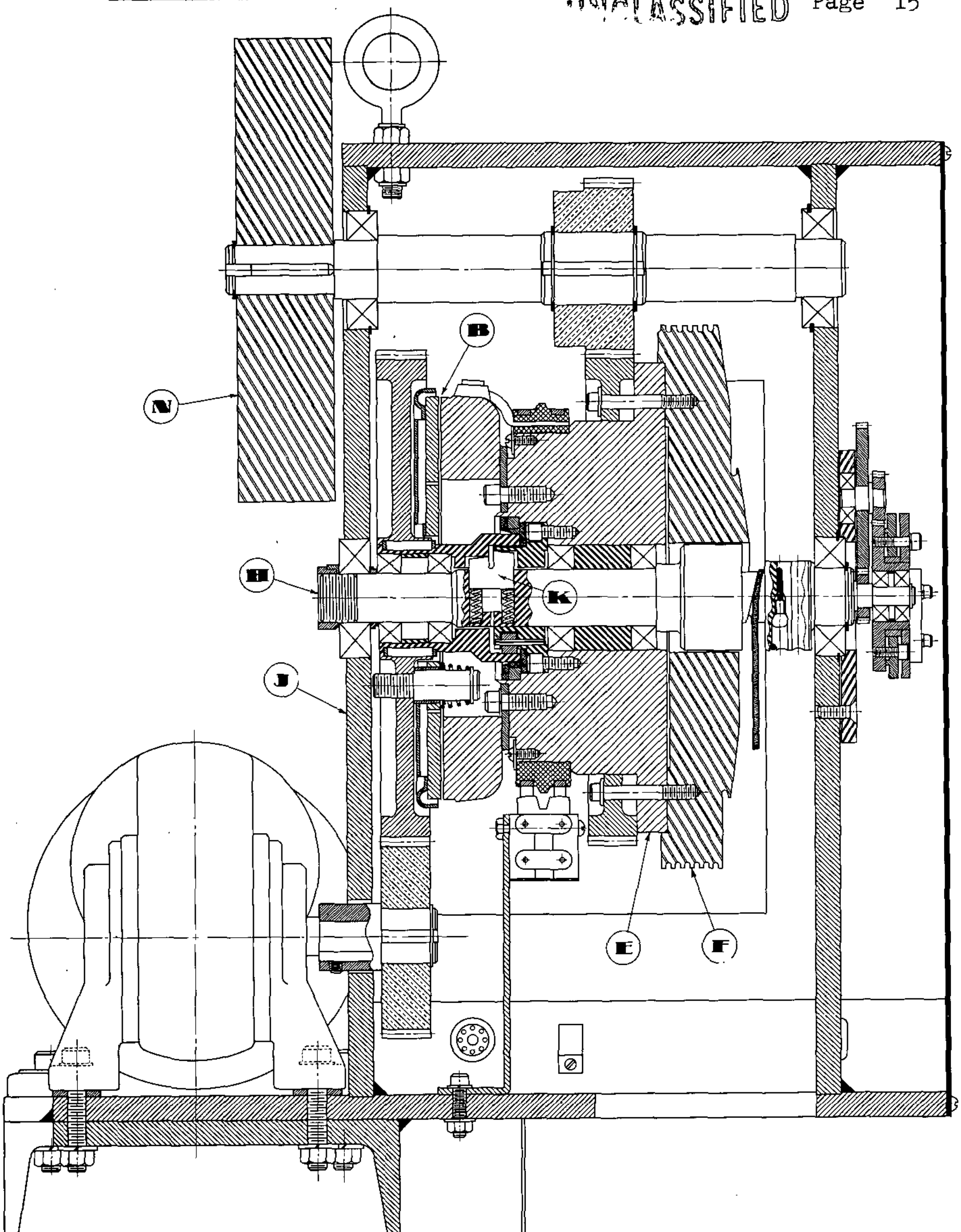
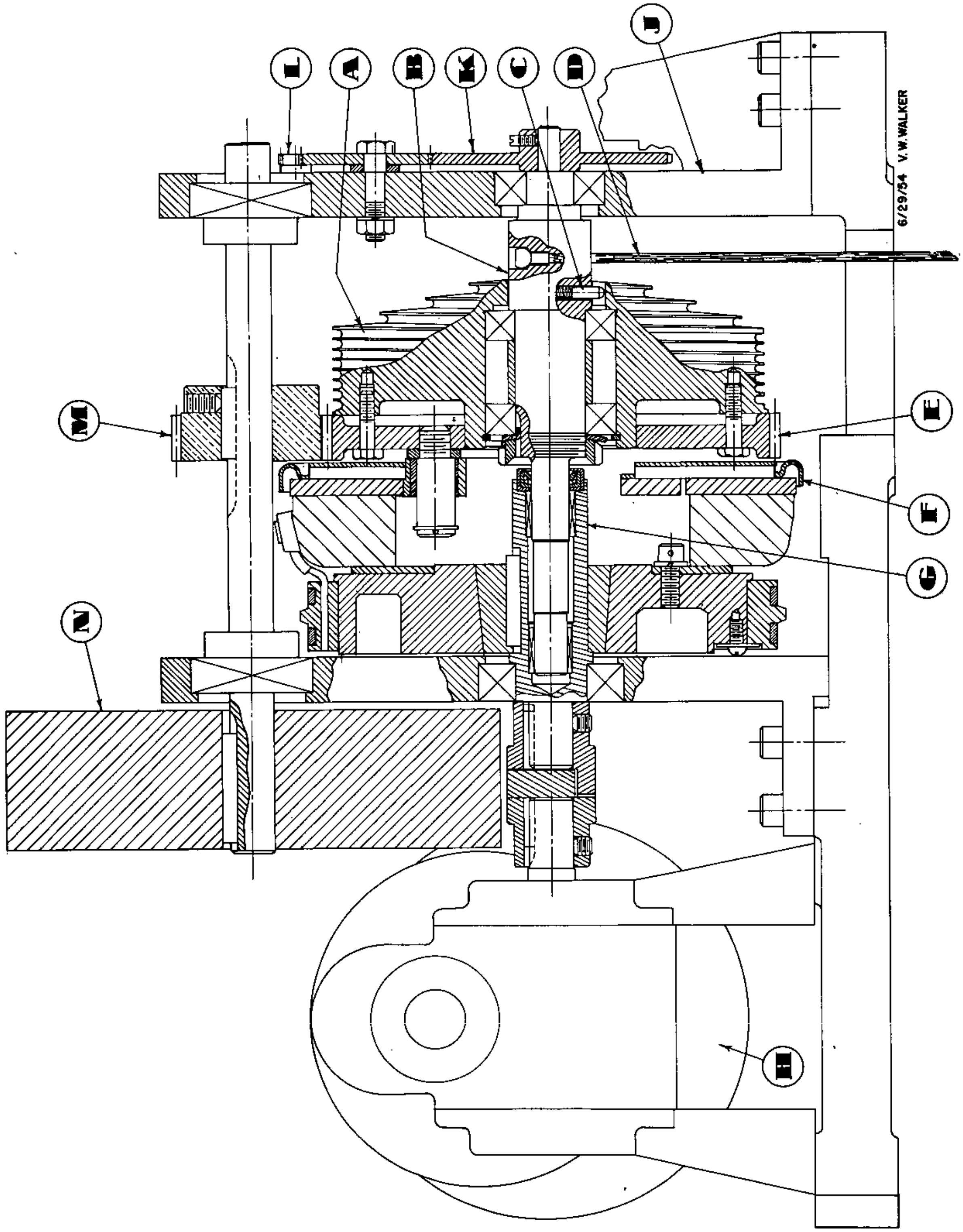
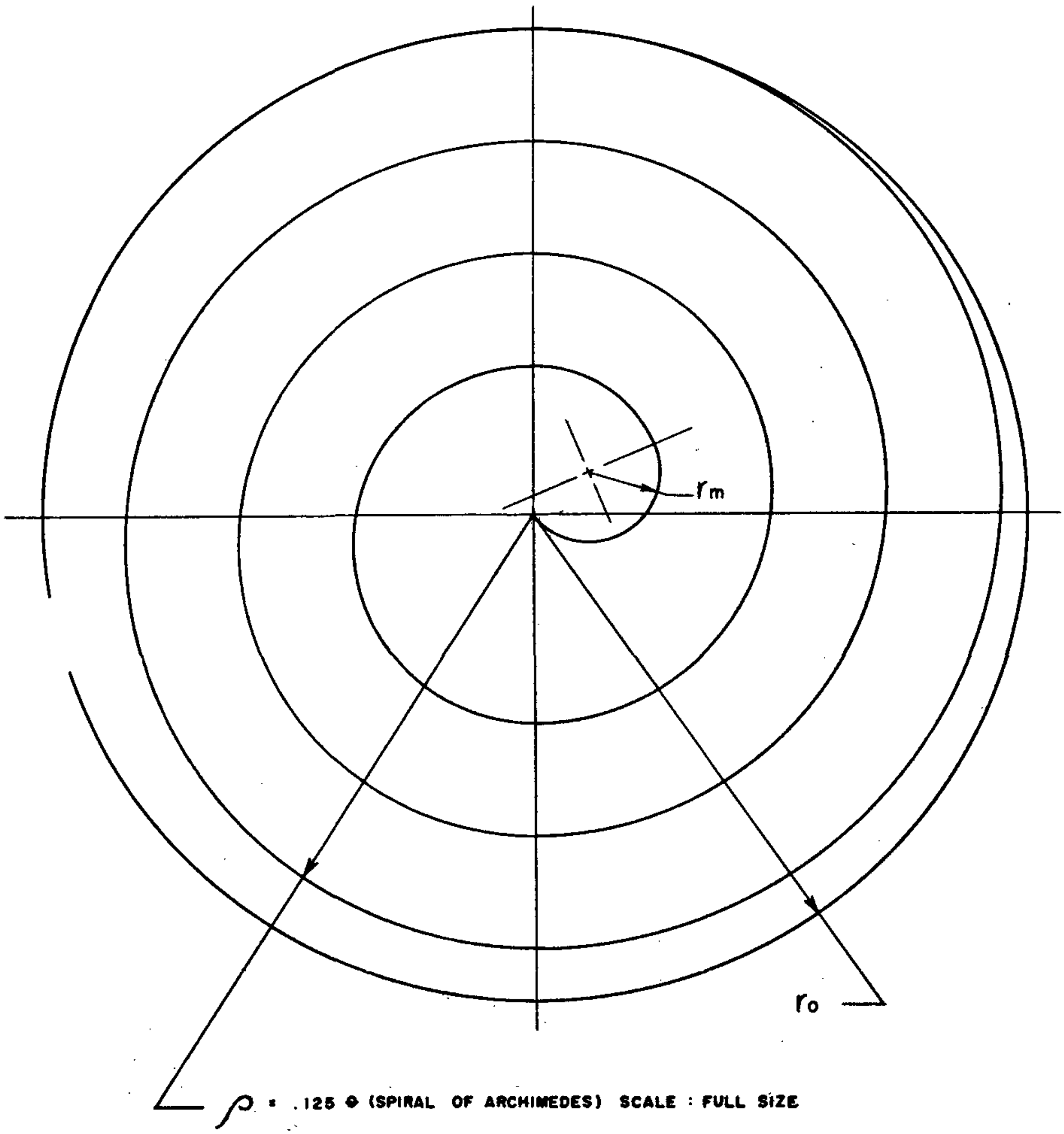


PROTOTYPE MODEL OF THE CONICAL DRUM ACTUATOR

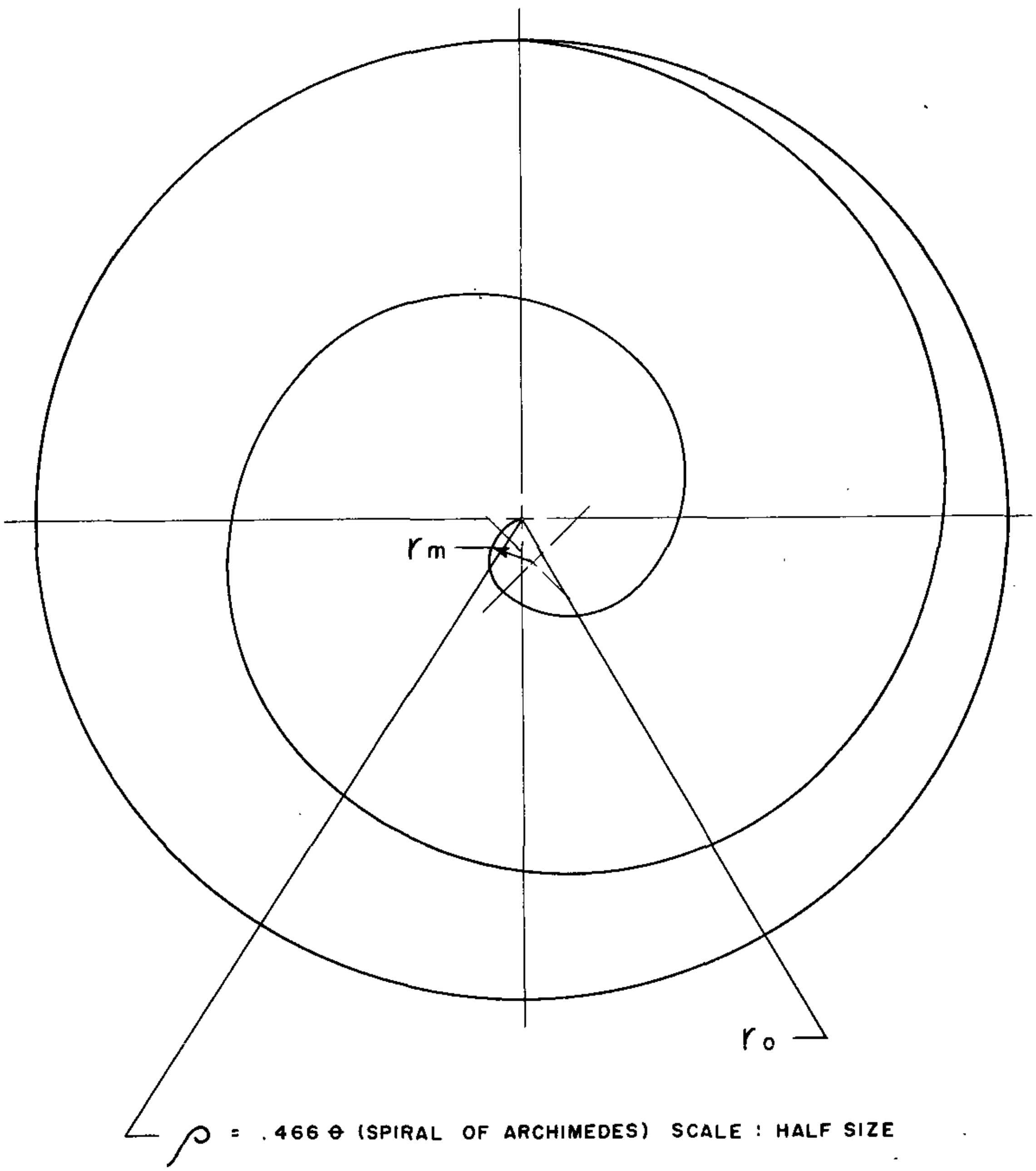


EXPERIMENTAL DESIGN OF CONICAL DRUM ACTUATOR

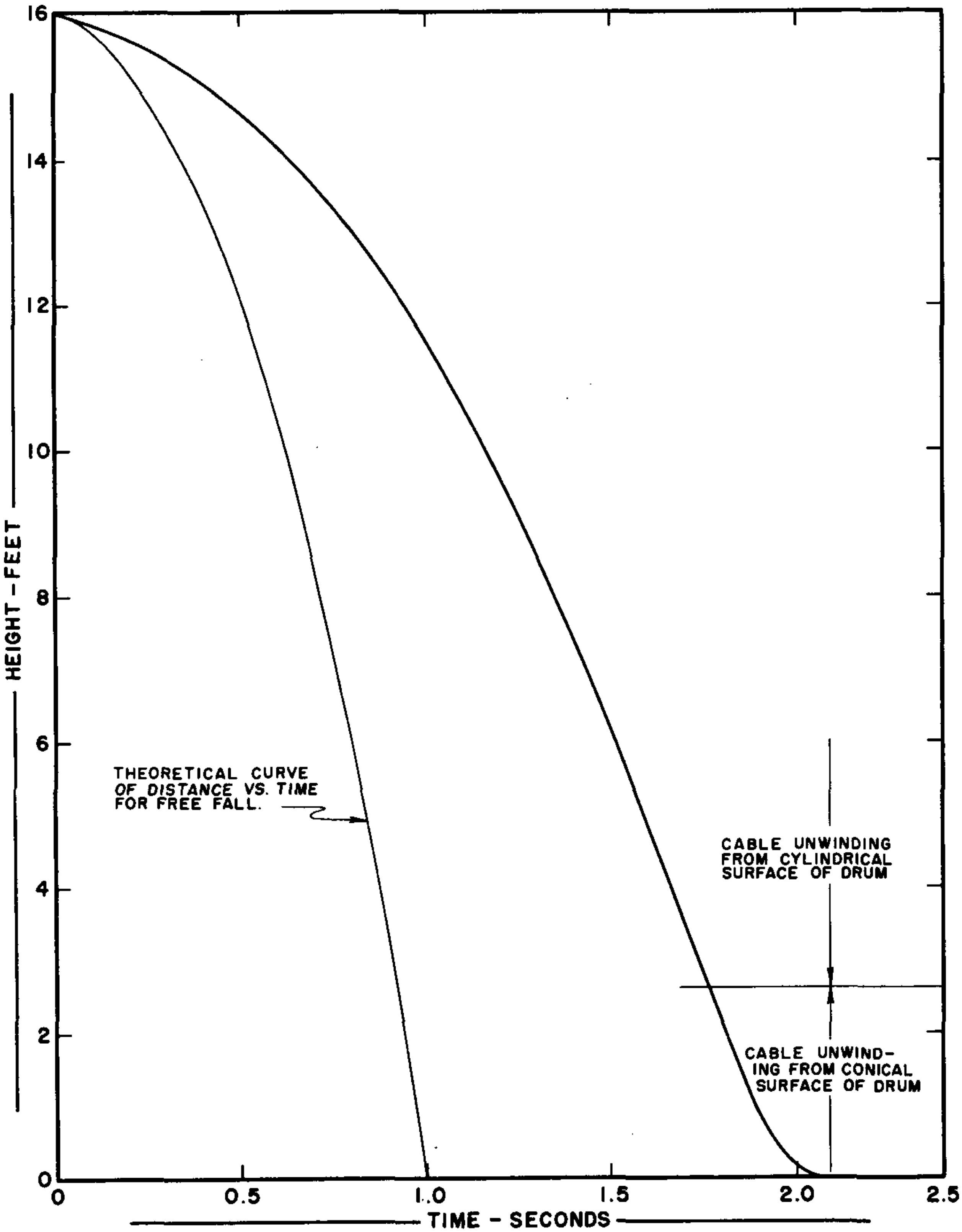
FIGURE 3



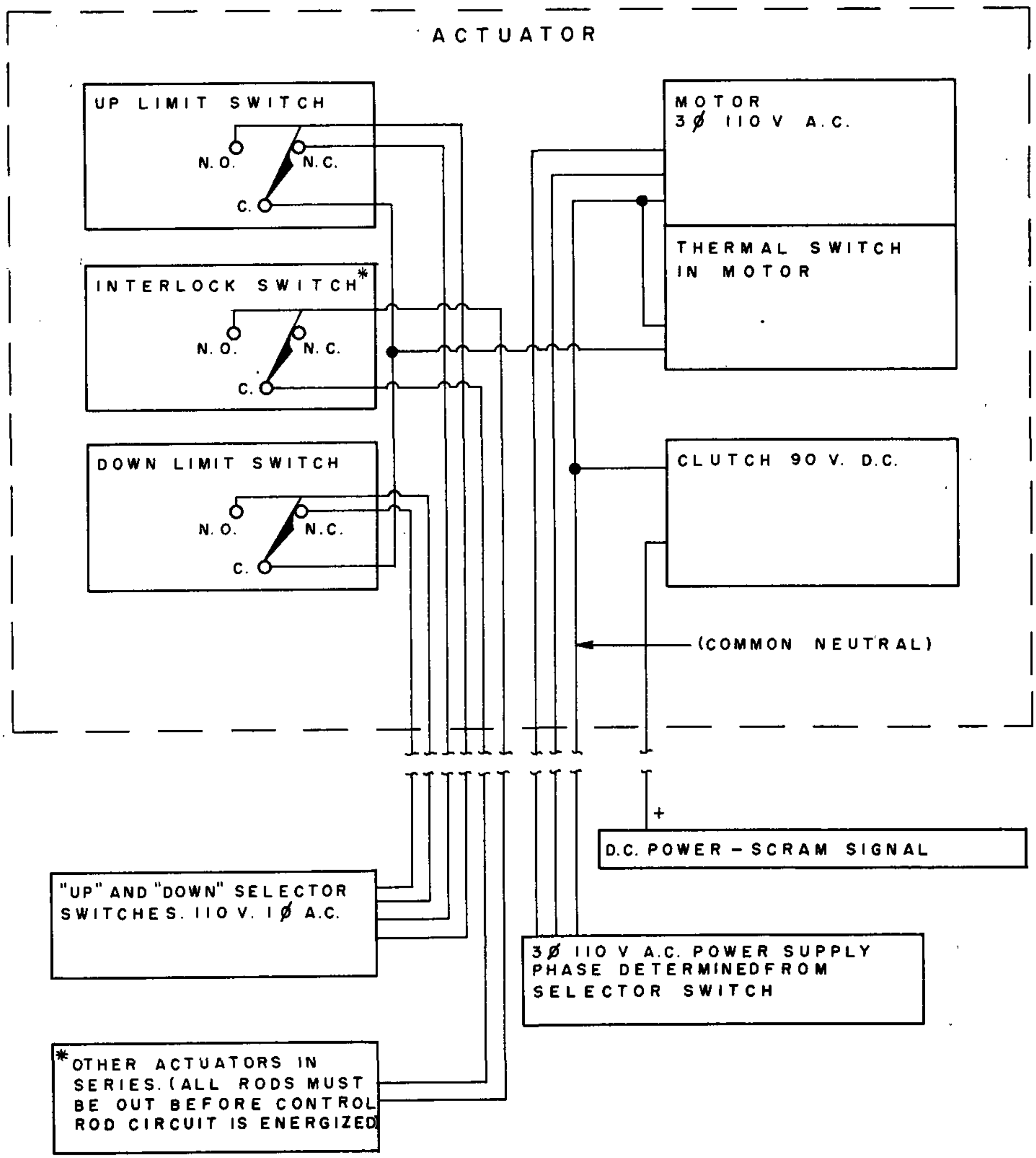
SPIRAL ON EXPERIMENTAL MODEL



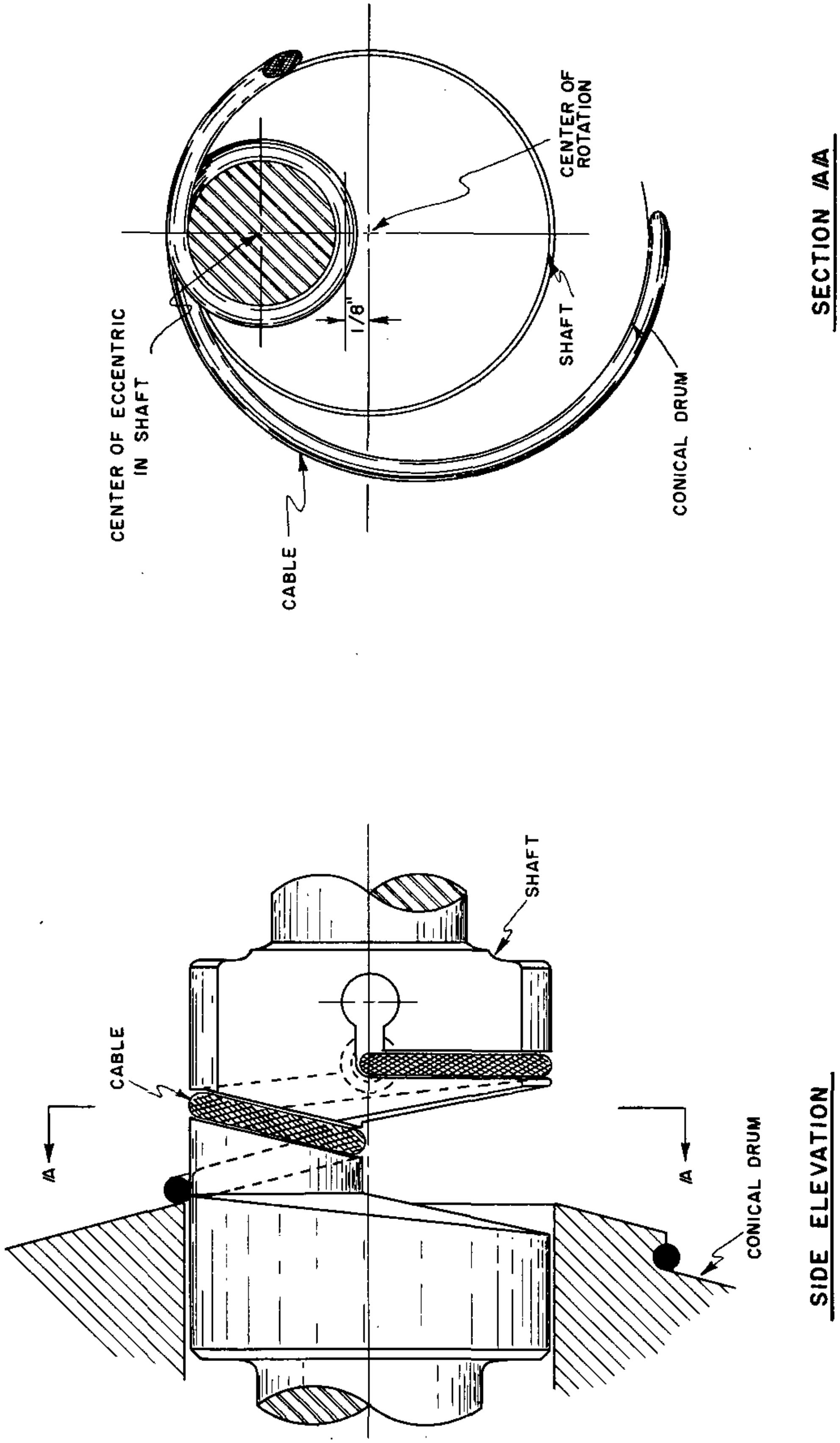
SPIRAL ON PROTOTYPE



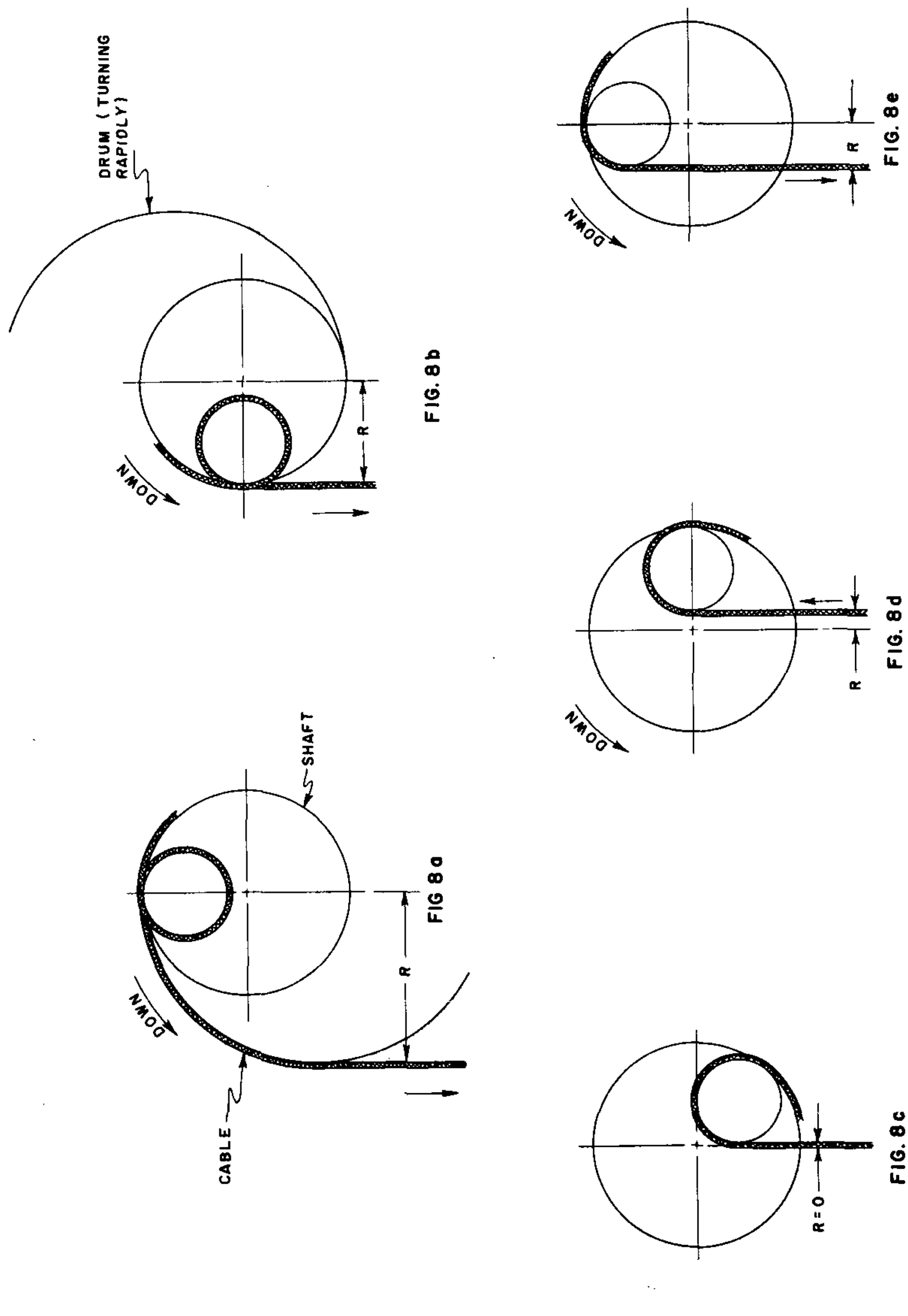
INSERTION OF SAFETY ROD - CURVE OF DISTANCE vs. TIME -
CONICAL DRUM SAFETY ROD ACTUATOR PROTOTYPE MODEL, FIGURE 1



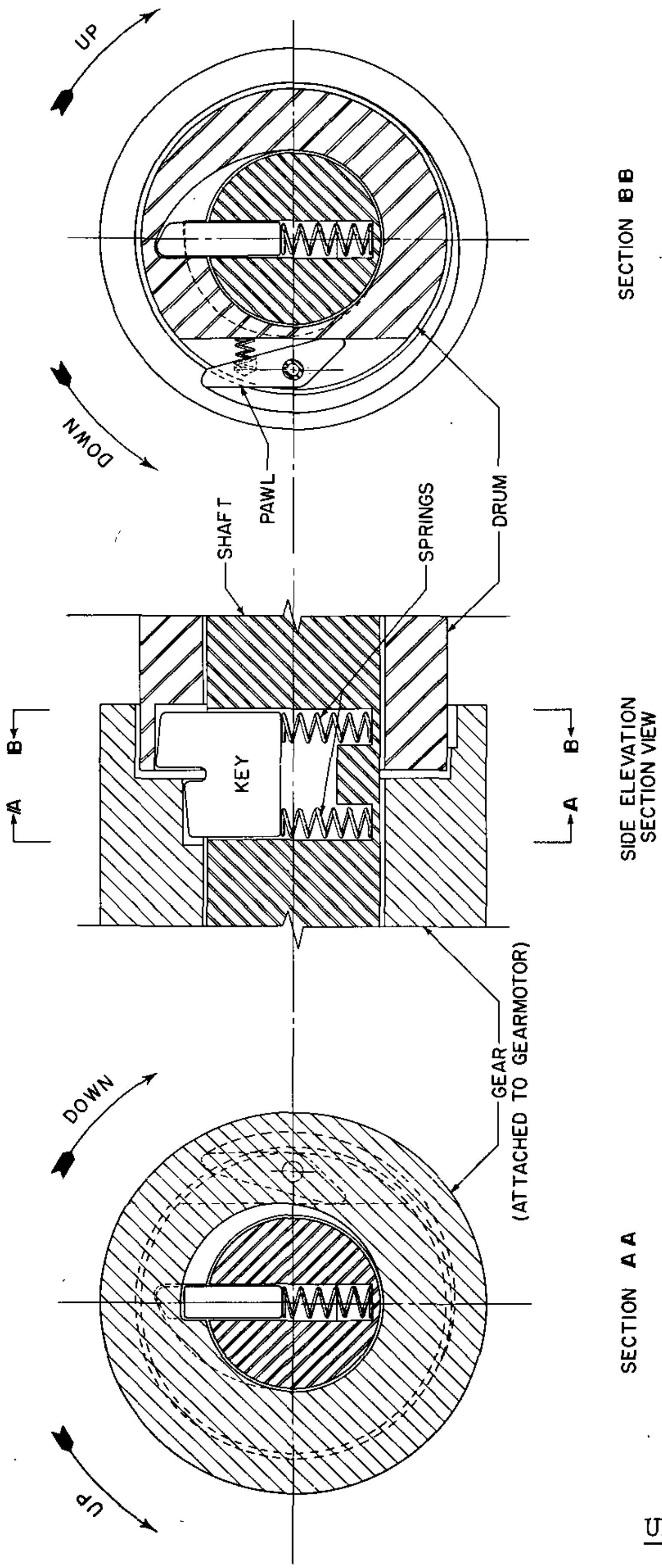
POWER CIRCUITS IN CONICAL DRUM ACTUATOR



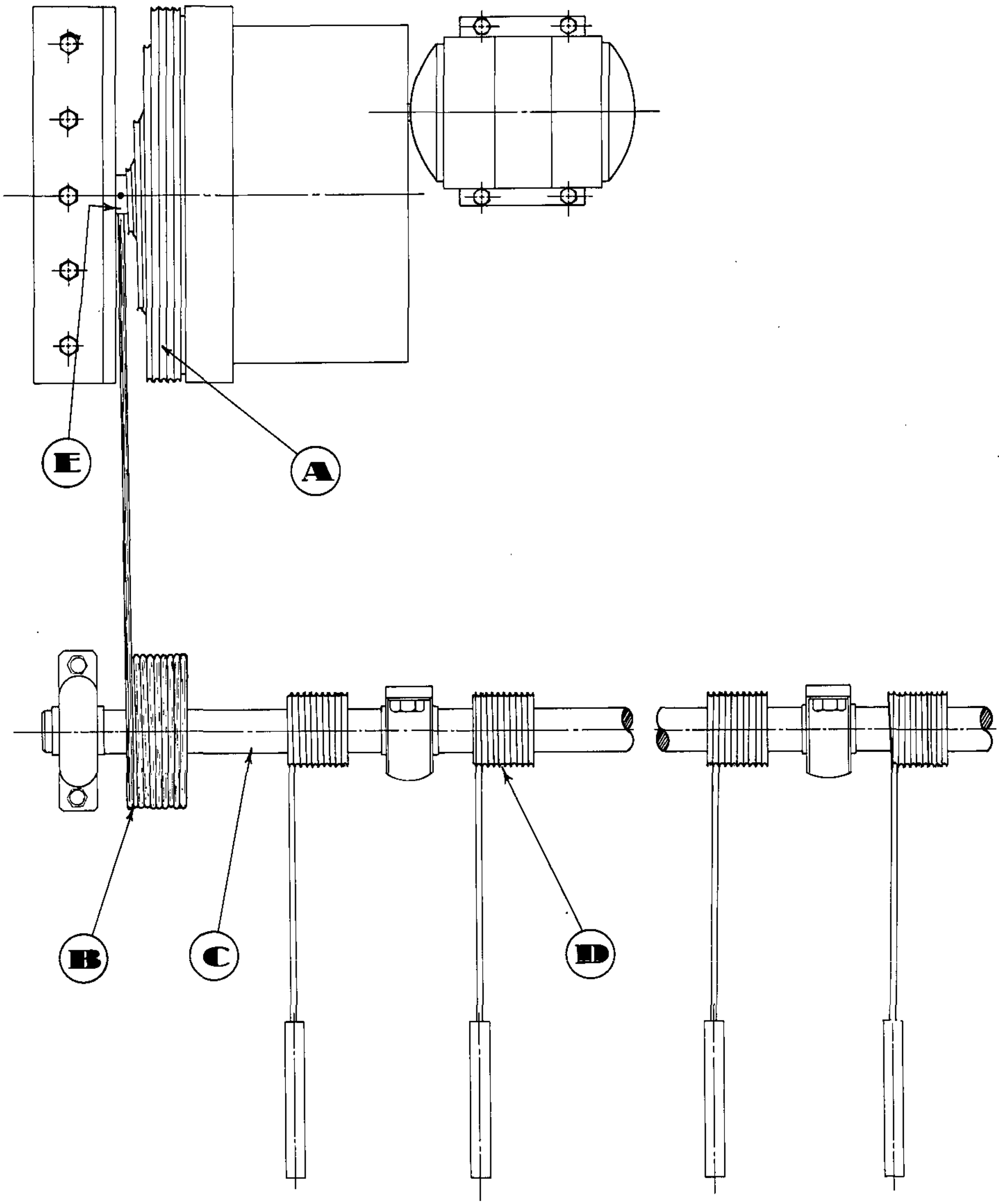
DETAIL OF THE ECCENTRIC IN THE SHAFT, CONICAL DRUM ACTUATOR



SCHEMATIC ARRANGEMENT, UNWINDING CABLE



LOWERING MECHANISM



CONICAL DRUM ACTUATOR FOR GANGED SAFETY RODS

[redacted]

APPENDIX A

SPECIAL FEATURES REQUIRED FOR SRP

The most significant details of the prototype actuator for the production piles are the compactness in design, the electrical circuitry, and the lowering mechanism. These features are incidental to the conical drum concept, but they are a prerequisite for installation at SRP. A description of these details is included in this report to show the feasibility of adapting the conical drum concept to the special requirements of a particular reactor installation.

The actuators at SRP rest on pin supports that are distributed among clusters of control rods, the lattice arrangement of both being determined by the geometry of the reactor. The limited space which is formed by this configuration and method of support requires an actuator of extremely compact design.

The electrical circuitry of the prototype actuator had to conform to that installed at SRP. Also, the actuator had to perform its proper sequence of operations with the input signals that are now consistent with control room procedures. These requirements were met by designing the power circuits as shown in Figure 6.

The lowering feature gently seats the safety rod in the reactor and lowers the long-latch assembly two inches over the top of the rod. This action is accomplished by an eccentric, similar to a connecting rod journal on a crankshaft, in the shaft that serves as the axle for the conical drum. The cable which unwinds from the spiral groove in the conical drum is wound around the eccentric in the shaft in such a way that at one point the cable is 1/8 inch from the center of rotation of the shaft as shown in Figure 7.

During an emergency drop, the cable unwinds from the spiral groove and then from the eccentric in the shaft as shown in Figures 8a through 8e.

Figure 8a shows the drum and shaft moving together as the cable unwinds. Figure 8b shows the relative positions of the components as the cable begins unwinding from the shaft. At this time the downward velocity of the cable is low and the angular velocity of the drum is high due to the short unwinding radius, R. When R reaches zero, as shown in Figure 8c, the cable merely hangs from the shaft while the drum continues to rotate until stopped by bearing friction. Also, for this relative position between cable and shaft, the safety rod is four inches from being fully seated in the reactor. To lower the cable (and safety rod) an additional amount, the shaft must be turned by the gearmotor, because the cable must be lifted slightly to pass through the position

[redacted]

shown in Figure 8d. Having passed this position and having reached the position shown in Figure 8e, the cable, due to the weight of the hanging rod, can rotate the shaft. The slight impact that would occur during this final lowering is avoided by making the drum rotate with the shaft and by terminating the cable at the center of rotation of the shaft.

The drum is made to rotate with the shaft by designing two pickup points on the key which is used to engage the drum to the shaft for upward movement of the cable. As shown in Figure 9, the higher of the two points permits drum-to-shaft engagement for up direction of rotation only, and the lower point permits gearmotor-to-shaft engagement for down direction of rotation only. Also, the gearmotor or gear cannot pick up the shaft until the gear has engaged itself to the drum with the pawl and turned the drum to the point where it is perfectly aligned with the shaft. In this way the shaft will not rotate rapidly and independently from the drum during the six-inch lowering cycle, but will be required to move slowly due to the high inertia of the drum. When the gear is connected to the drum through the electric clutch for up direction of rotation, the drum will pick up the shaft regardless of the relative position of the gear and shaft because of the difference in height of the pickup points on the key.

The lowering mechanism described above requires no additional power signals from the control room. The mechanism operates automatically with the normal "up", "down", and "scram" electrical signals.

APPENDIX B

ARRANGEMENT FOR GANGED SAFETY RODS

If the geometry of a particular reactor and the available space permit operation of a number of safety rods from one prime mover, the conical drum concept offers an attractive method for snubbing the rods. In addition to the advantages gained by the absence of an external power source for snubbing, the system can be designed with very few moving parts and little auxiliary equipment. A schematic arrangement of a ganged system is shown in Figure 10.

The effect of the conical drum snubbing could be compounded by replacing the cylindrical drum "B" with a conical drum, so arranged that as the unwinding cable approached the apex of the conical drum "A", the winding cable would approach the base of conical drum "B". This in turn would result in relatively lightweight drums with only the cable connecting the drums being of substantial strength.

APPENDIX C

NOMENCLATURE - SYMBOLS

S = distance that rod has dropped, feet

S_1 = distance that rod has dropped before snubbing begins, feet

S_2 = full distance of rod travel, feet

S_m = distance rod has dropped when torque radius equals r_m (see r_m below)

t = time since rod was dropped, seconds

t_1 = time required for rod to fall to the position when snubbing begins, seconds

t_2 = full insertion time, seconds

r = torque radius of cable as it unwinds from the drum, feet

r_o = radius of constant diameter portion of drum, feet

r_m = torque radius at which maximum curvature of the cable on the conical portion of the drum occurs, feet

W = weight of rod, pounds

I = effective moment of inertia of the drum, pound-feet^2

ω = angular velocity of drum, radians/sec

E_R = kinetic energy of rod, foot-lbs

E_D = kinetic energy of drum, foot-lbs

v = velocity of rod, feet per second

v_1 = velocity of rod when snubbing begins, feet per second

v_m = velocity of rod when torque radius r_m is reached, feet per second

a = acceleration of rod in direction of fall, feet per second^2

g = acceleration of gravity, 32 feet/sec^2

T = tension in cables, pounds

F = net force acting on the rod, pounds