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MASTER

FEASIBILITY OF A FULL CORE NUCLEAR POISON SYSTEM FOR USE DURING RIFT LAUNCH OPERATIONS

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FEASIBILITY OF A FULL CORE NUCLEAR POISON SYSTEM FOR USE DURING RIFT LAUNCH OPERATIONS

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FEASIBILITY OF A FULL CORE NUCLEAR POISON SYSTEM FOR USE DURING RIFT LAUNCH OPERATIONS

I. INTRODUCTION

One of the prime safety considerations associated with the RIFT vehicle assembly and launch at Cape Cavernal is preventing an accidental reactor excursion in the proximity of the launch site. In addition to the normal operations with the nuclear subsystem in the area, accidents resulting from malfunction of the lower chemical stages can lead to the production and release of fission product material. Several approaches have previously been investigated such as locked control drums or in-core poisons which prevented accidental criticality on the launch pad but were based on manual removal of the protection just prior to launch. This protection, on thorough review, is limited since it does cover the period of time between removal and launch, it must be replaced if the launch is delayed, and it affords no protection in the event of early abort. Maximum protection can be achieved with a system which maintains the reactor subcritical under all conditions which can credibly be postulated for the launch area including core compaction or flooding with water, lower stage propellant, or other hydrogenous material.

Two basic characteristics of the NRX reactor complicate the problem of safeguarding against accidental criticality. It is a relatively small reactor with fissioning due principally to intermediate energy neutrons. Hence, the neutron leakage is large and the uranium inventory is much greater than that for a comparable size thermal reactor. In addition, a considerable volume of the core is voided and since propellant must be discharged it is impossible to contain the reactor in a sealed vessel. Immersion of the reactor in water, which is in abundance near the launch pad, can add reactivity both by increased reflection externally and increased moderation internally. Increased internal moderation is so effective that small sections of the core can be independently critical.

The requirements for the system which will protect against accidental criticality follow from the discussion above. It must use a nuclear poison which is disbursed through out the core and must remain in the core during vehicle assembly, count down, and the initial period of booster operation. The system resulting from this study consists of approximately 2,000 boron-10 wires inserted in the coolant channels of the fuel elements and distributed uniformily throughout the core. A shutdown of 5% ΔK is achieved with the reactor fully immersed in water. The principal factors determining the feasibility of such a system were the potential damage that could be caused to the fuel element coolant channels and support blocks by rapidly removing the poison wires and the mechanical equipment required for the wire removal.

The experimental program initiated during the study established the feasibility of using poison wires if they are coated with teflon and demonstrated that the forces required for their removal are not excessive. About 2150 pounds is needed to pull the wires from the coolant channels. Initial attempts with uncoated wires were not successful. Three to four times the force was required to pull the uncoated wires and the fuel element cluster blocks were damaged in the process.

Conceptual designs of a poison wire retention device, a pull head, and an actuator system are presented. Although these designs are not definitive, no major problems are anticipated which would invalidate the feasibility of the basic poison wire system. Work will continue in the forth coming contract year to develop a prototype design of the pull head and an actuator system.

II. DESIGN CRITERIA FOR THE NUCLEAR POISON SYSTEM

The development of a poison system is based on the following criteria:

1. The K_{eff} for the reactor fully immersed in water or other hydrogenous liquid or fully compacted must be less than 0.95.
2. The poison must be retained in the core during an on-the-pad fire involving the reactor coolant or the propellant of the lower stages.
3. The poison must be completely removed from the core prior to second stage separation. Ten seconds are allowed for poison withdrawal.
4. No rigid connection can be made to the nozzle. A plastic ring that can easily be melted or burned out by the hot reactor coolant may be left in the nozzle throat after removal of the poison wires.
5. The poison must remain with the core in the event the 2nd stage is prematurely separated from the nuclear stage.
6. Removal of the poison from the core must not cause core damage. This is particularly important since damage of the niobium carbide coating on graphite in the hot reactor coolant stream can lead to accelerated corrosion of the components.
7. Poison withdrawal equipment must be mounted out of the nozzle with the nuclear stage, or on the second stage, so that the nozzle is clear after separation.
8. The system must be able to withstand powered flight environment.

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III. PRELIMINARY DESIGN

The first phase of the preliminary design process was to review different methods for providing poison in the core of an NRX-A reactor design and to review these in light of the system criteria. Major reactor redesign to incorporate increased control capability was considered but discarded becuase of its effect on the NRX-A program. A large number of in-core control elements with independent control actuators is conceivable but would be an integral part of the basic reactor design. Such methods have been reviewed for alternate or advanced reactor designs. Some of the approaches considered for the NRX-A and their limitations are given below. The use of fusible plugs to retain poison gases or liquids was eliminated because of their inability to survive launch pad fires, their high potential of poison loss in the event of mechanical damage to the core, and the requirement necessary for their removal. Reactor heat is not available until after the poison is removed. Pellets were considered to be undesirable because of their potential for packing, and because of the problem of providing plugs which could be removed on command but which would not shake loose prematurely. Segmented wires or "key chain" devices presented possible problems of damage to the support cookies of an NRX-A reactor design as they left the channel. Poison wires seemed to have the advantage of offering minimum development problems, good structural strength at elevated temperatures, and mechanical integrity. The major problems anticipated for the development were tendency of wires to cause damage to the support block and the challenge of holding a multiwire pull head in the nozzle without fasteners.

A conceptual version of a pull head for the poison wire system which is mounted in the nozzle throat is shown in Figure 3.1. The poison wires are clustered into groups and each group mounted in the retaining plate through a ball and socket device. The plate is fastened to a pull head, and the entire assembly held in place by a spring leaf structure. The spring characteristics of these leaves is determined by the "g" force during ascent acting on the combined mass of the head and poison wires. For the head shown and 2400 wires, the force corresponding to 6 "g's" is about 1000 pounds. The nozzle throat may have a telfon or similar overlay to minimize abrasion of the nozzle during retraction of the

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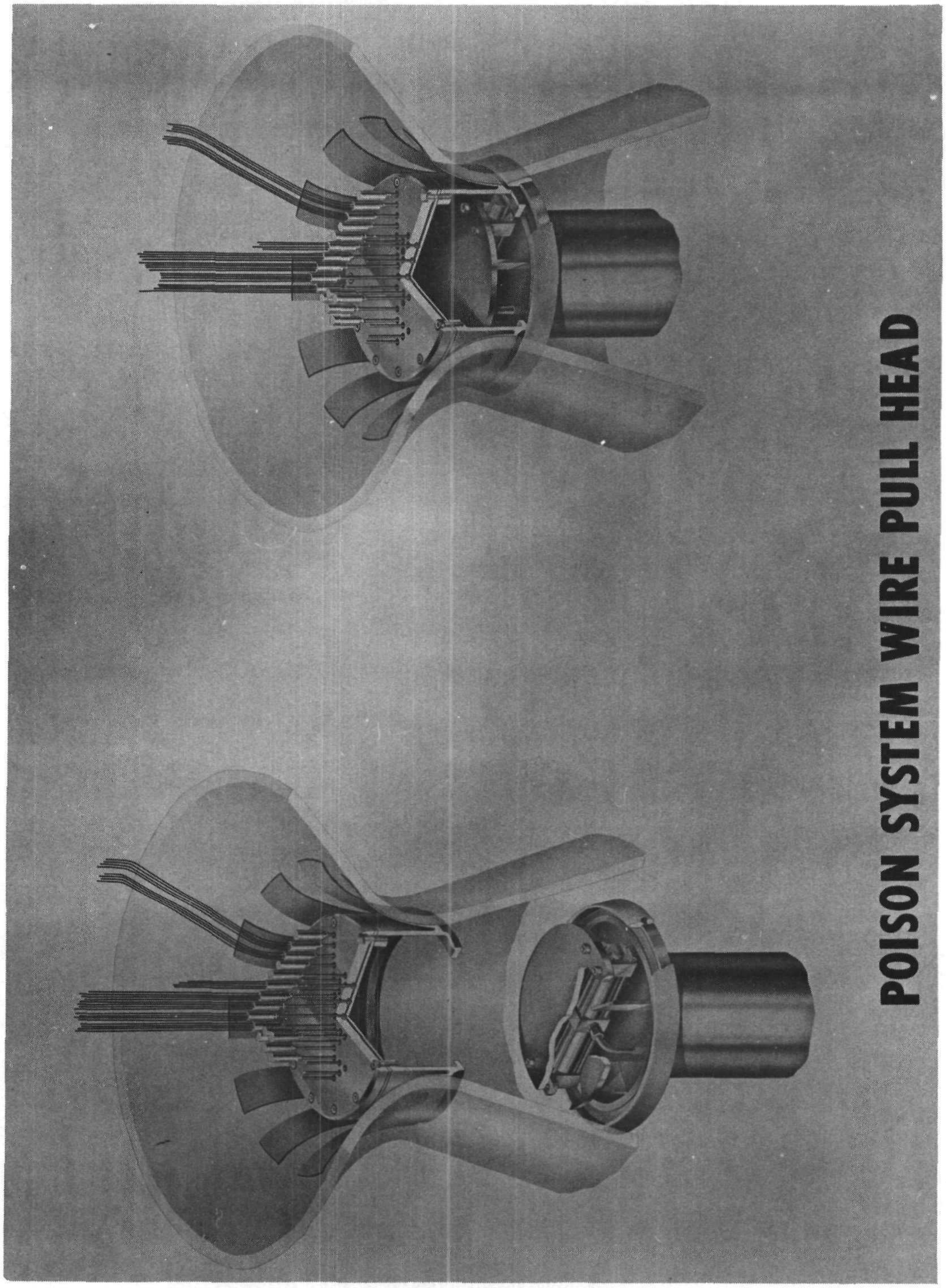

FIGURE 3.1 POISON WIRE SYSTEM PULL HEAD

head and wires if required. An alternate arrangement was examined which used pressure pads against the nozzle with a retracting device similar to an umbreallo, but the complexity of it compared to the passive spring approach made it less desirable. The object shown beneath the pull head is the top of the actuator. In practice, the actuator could be run up by gas pressure to a position just beneath the pull head during countdown. Here it could help support the pull head from below against "g" loads, but would break clear without the pull head if the 2nd stage or interstage structure failed. After the proper altitude was reached, an enabling signal would cause the actuator to be lifted into the pull head, but not engaged. An arming signal would cause the engagement of the ram plungers with the pull head. On the firing or withdrawal signal, high pressure gas to the actuator would effect withdrawal of the pull head and wires.

Figure 3.2 shows a lightweight, single stage piston and cylinder type high pressure actuator mounted on the top of the 2nd state of the vehicle. Redundant gas supplies are furnished to provide increased reliability. This arrangement provides maximum reliability at the expense of height required.

Figure 3.3 shows a two stage actuator which reduces the height requirements but results in somewhat greater complexity and consequent decrease in reliability. Here the first stage cylinder forms the 2nd stage piston and gas pressure is used to effect simultaneous withdrawal of both 1st and 2nd stage pistons.

Figure 3.4 shows a multistage actuator. It has the least height requirements, but is penalized by weight, complexity, and lower reliability. Unless space limitations are overly restrictive, the use of a multistage actuator is discourage.

The general configuration and dimensional limits of the core-nozzle-2nd stage complex are shown on Figure 3.5. The effect on the distance required between the nozzle and second stage for a 54 inch wire travel using a multistage actuator is shown on the accompanying table.

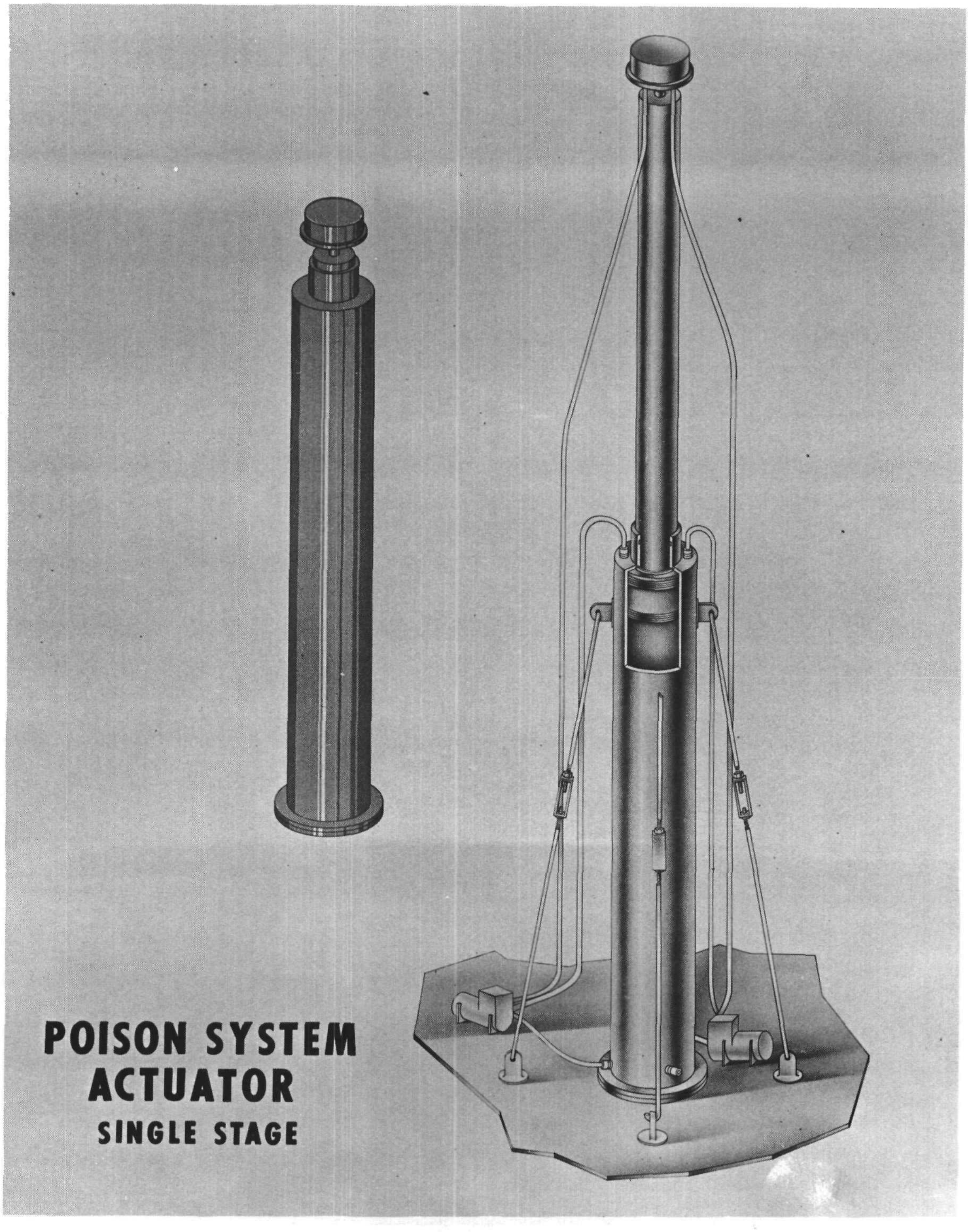

FIGURE 3.2 POISON WIRE REMOVAL ACTUATOR-SINGLE STAGE

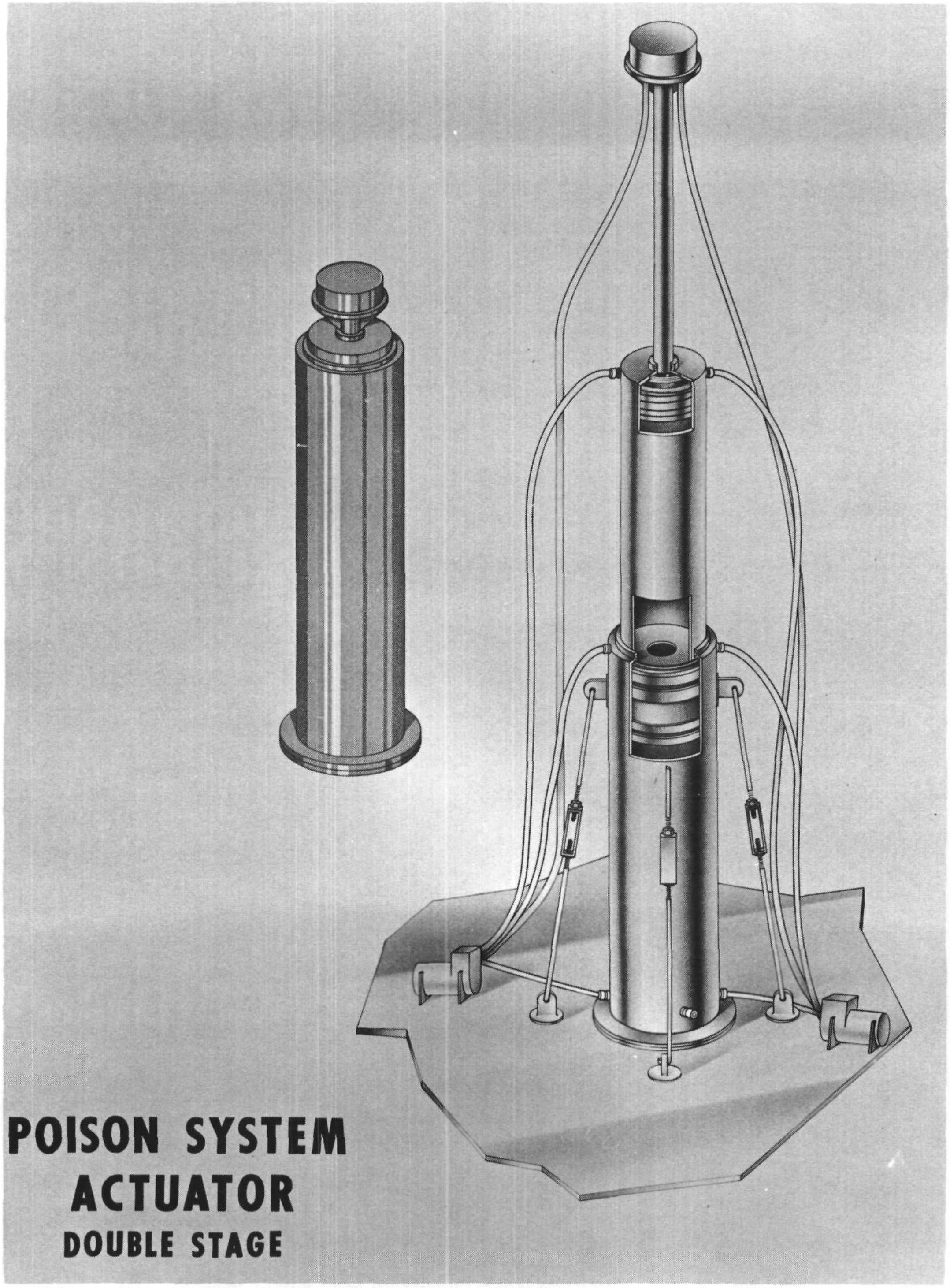

FIGURE 3.3 POISON WIRE REMOVAL ACTUATOR-TWO STAGE

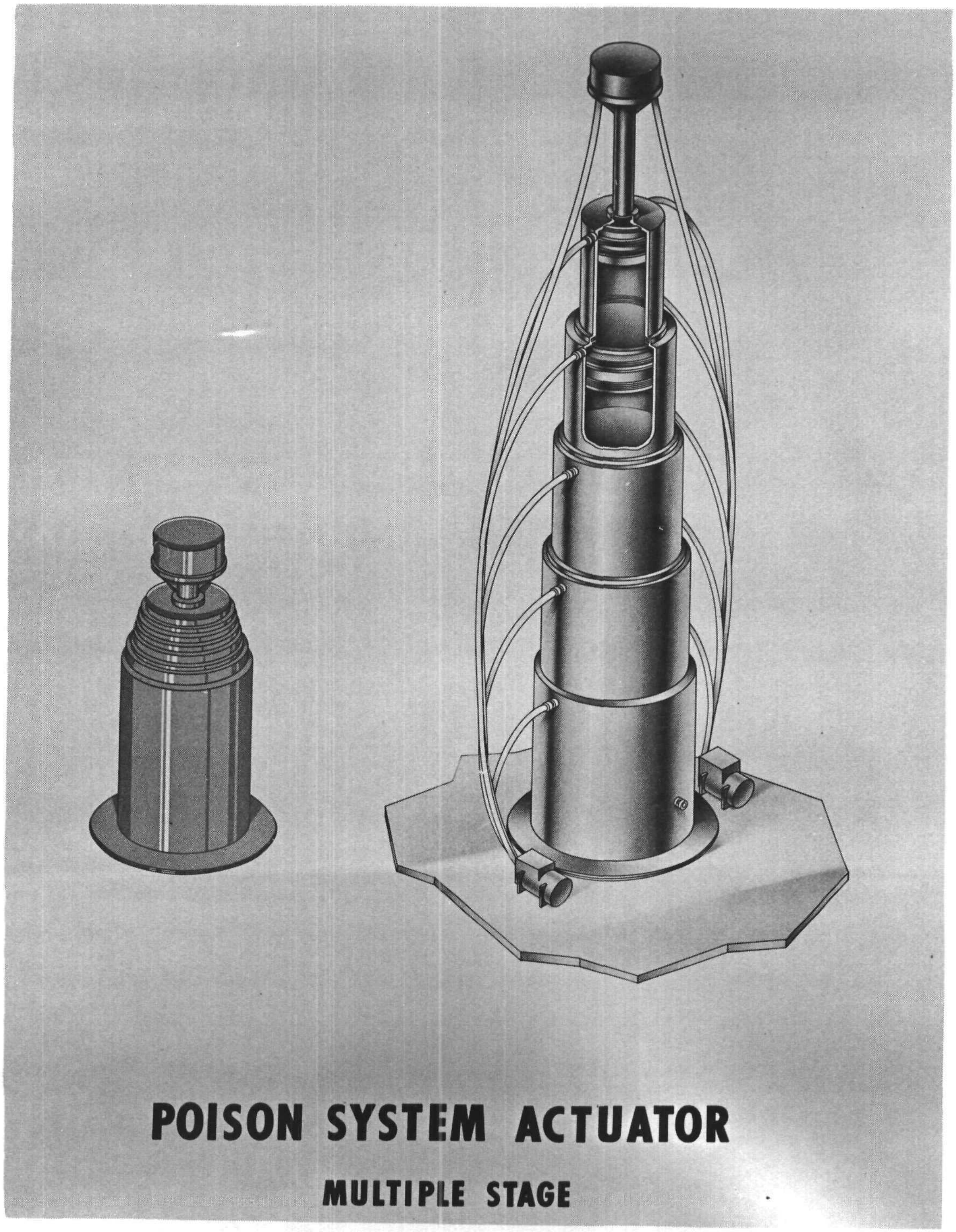

FIGURE 3.4 POISON WIRE REMOVAL ACTUATOR-MULTIPLE STAGE

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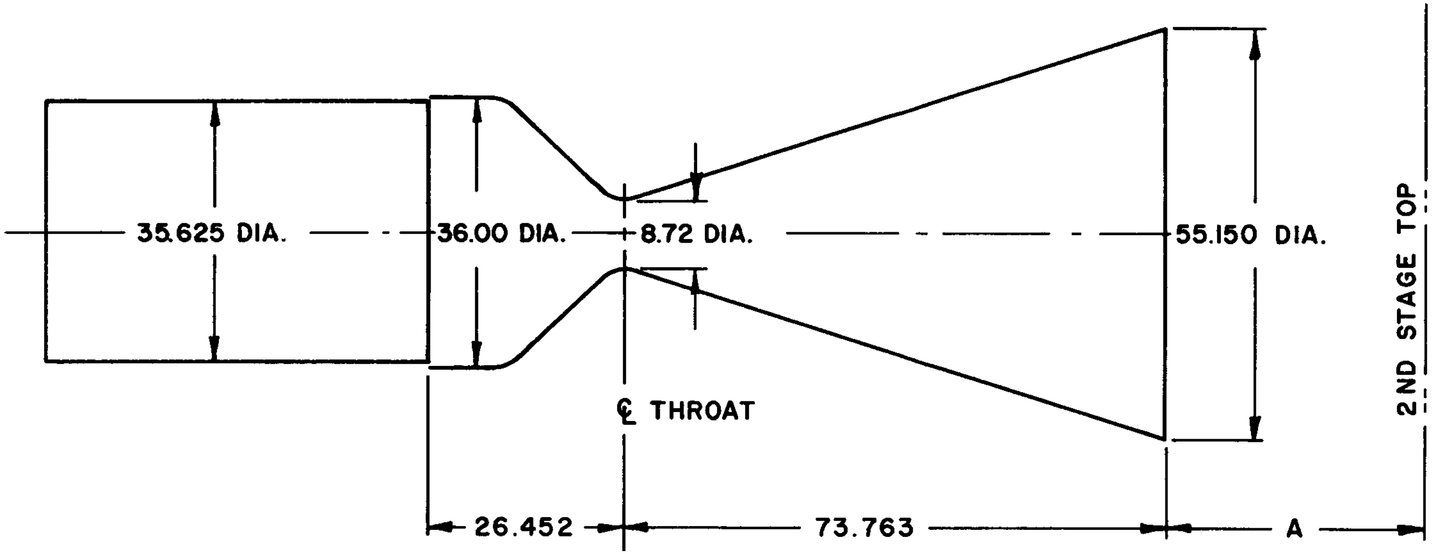

ACTUATORS	DIM A
SINGLE STAGE	47.00
DOUBLE STAGE	25.75
MULTIPLE STAGE	10.50

FIGURE 3.5 CORE-NOZZLE ORIENTATION CORE POISON SYSTEM

IV. MECHANICAL DEVELOPMENT OF THE POISON WIRES

It was recognized early in the development of a core poison system that two major problems existed. First, the erosion effects of the poison wire being drawn the length of a fuel channel and support block and secondly, the determination of forces required to pull a group of wires, recognizing possible geometrical bundling effects in the nozzle throat. Two simple test rigs were built to explore these effects. The first simulated a plane section through the axial center line of the core. It used several simulated full length fuel elements fastened to a board in varying radial positions. Wires were pulled through the elements and a simulated nozzle, and pull forces measured on individual wires and groups. From these simple tests, we learned the following:

1. A soft wire, used in a channel, tends to straighten out between the exit hole and the nozzle, breaking the inboard lip.
2. A springy wire, used in the outer channels, will maintain a reverse curve, showing tangency at the channel exit and nozzle. The problem with a springy wire, however, is the whipping that accompanies channel exit, tending to break off the outboard lip.
3. The whipping effect of the spring wire could be relieved by pre-shaping a wire to a form approximating the nozzle curvature.
4. The whipping effect could also be alleviated by placing a teflon sleeve or ball over the end of the wire, allowing it to rotate freely out of the hole on exit.
5. Rough estimates of individual wire pull forces were made. Addition of a teflon coating to the wire reduced the force by three to four.

A major unknown in the behavior of a many-wire bundle was the interaction of wires in the throat section, with possible twisting, kinking, etc., which may result in very high withdrawal forces. A simple three dimension rig shown in Figure 4.1, was built to investigate the geometric problems. It was confirmed that a limited bundle could be pulled with a minimum of wire interaction, and that whipping could be alleviated, it not eliminated by pre-shaping.

Figure 4.2 shows the front face of the assembly which is a barrel simulation of the core. Full length fuel clusters may be placed in any of 43 positions, including a center cluster, 6 at 4" radius, 12 at 8", 12 at 12", and 12 at 16-1/4". At the front end of the mockup, we have mounted a nozzle throat section shown in Figure 4.3. A pneumatic cylinder, Figure 4.4, is mounted in line with the nozzle throat and a pull head attached to the ram. It is possible to vary pull velocity by controlling air flow through the cylinder. A strain gauge load cell measures the pull force. The fuel clusters used are a true simulation of NERVA fuel, complete with support block. There are 1,650 fuel elements in the NRX-A core, 6 of which are associated with each of 275 fuel clusters. Each cluster contains a central unfueled element through which a supporting tie-rod passes. Each fueled element has 19 coolant-channels which are 0.098 in diameter.

The back face of the test rig, Figure 4.5, shows the retention keepers which enable the clusters to be locked in place axially and radially. Measurements were made of pull forces for combinations of cluster wires, the fuel elements and support blocks were examined for any signs of damage after each trial pull. Pull velocities were varied up to 1/2 fps. to deterimine if there is a velocity threshold for channel damage. No channel damage, either from erosion or chipping, was found when teflon coated wires were used. Figure 4.6 shows a plot of the pull force per wire versus radial position of the wire in the core for a pull velocity of 1/4 fps. Both the critical and end loads are shown. The initial load is that required to overcome static friction whereas the end load arises from the increased moment exerted by the wire on the channel as it clears the hole.

FIGURE 4.1 THREE DIMENSIONAL RIG TO INVESTIGATE WIRE INTERACTION UPON WITHDRAWAL

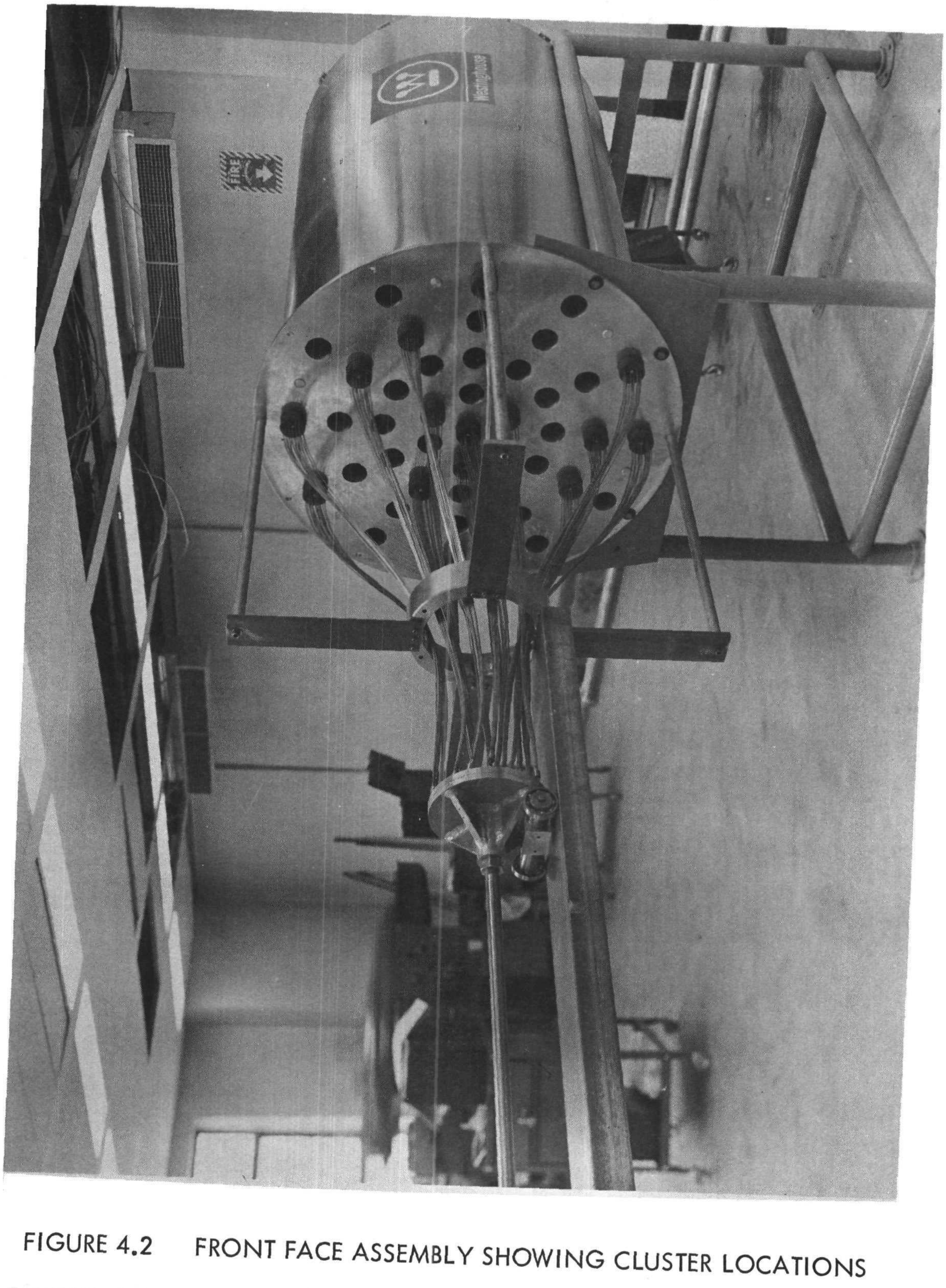

FIGURE 4.2 FRONT FACE ASSEMBLY SHOWING CLUSTER LOCATIONS

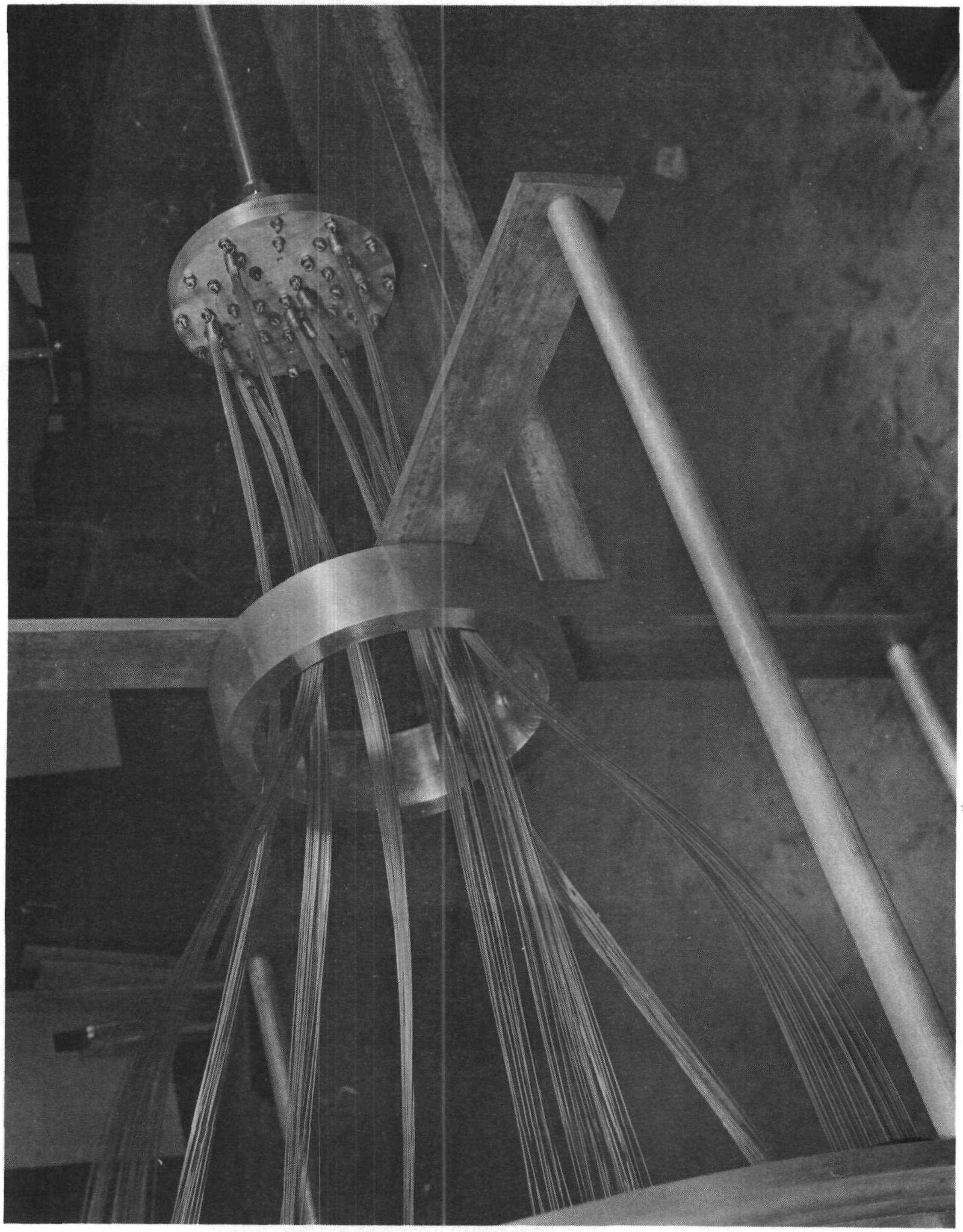

FIGURE 4.3 NOZZLE THROAT SECTION

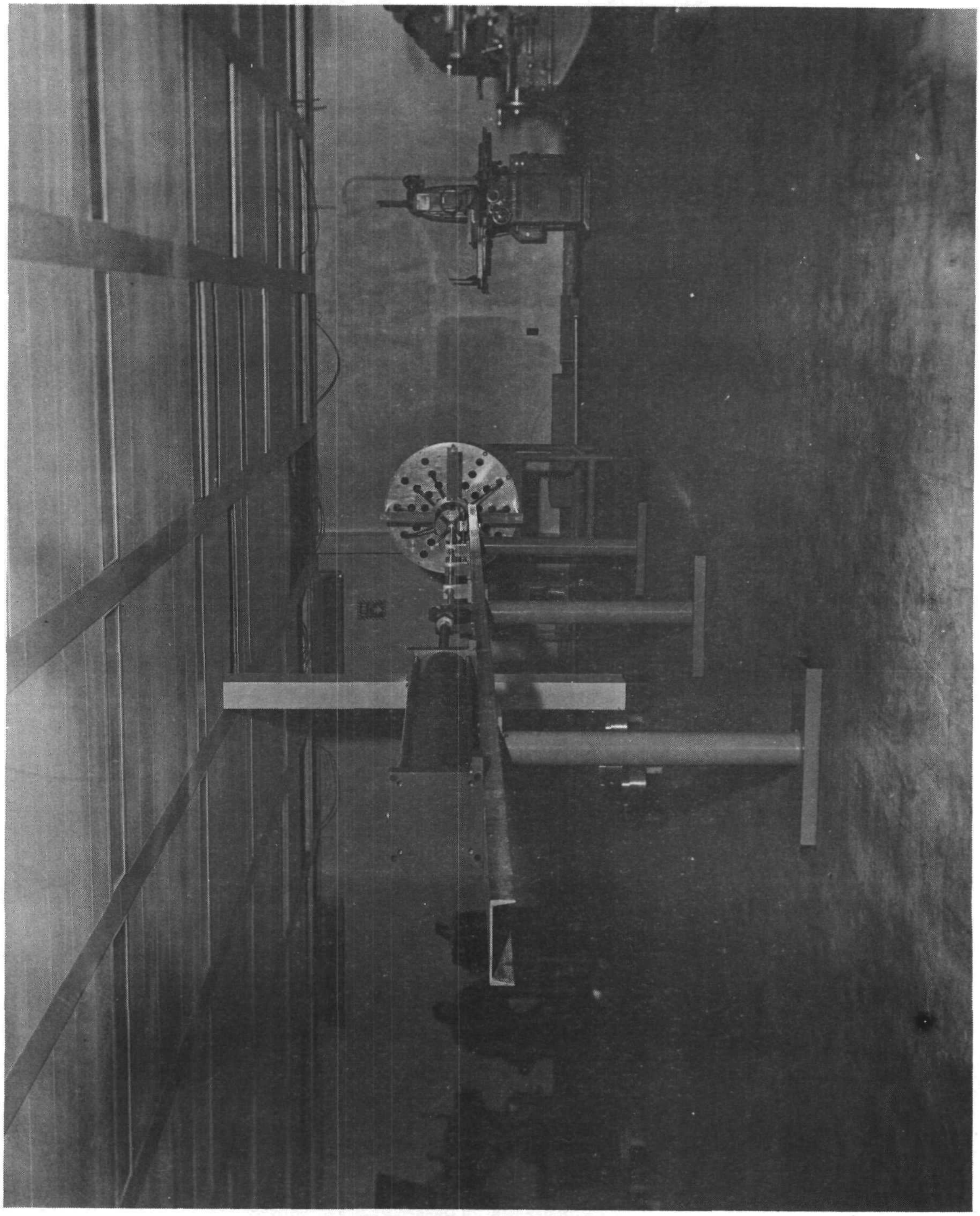

FIGURE 4.4 PNEUMATIC CYLINDER AND PULL HEAD

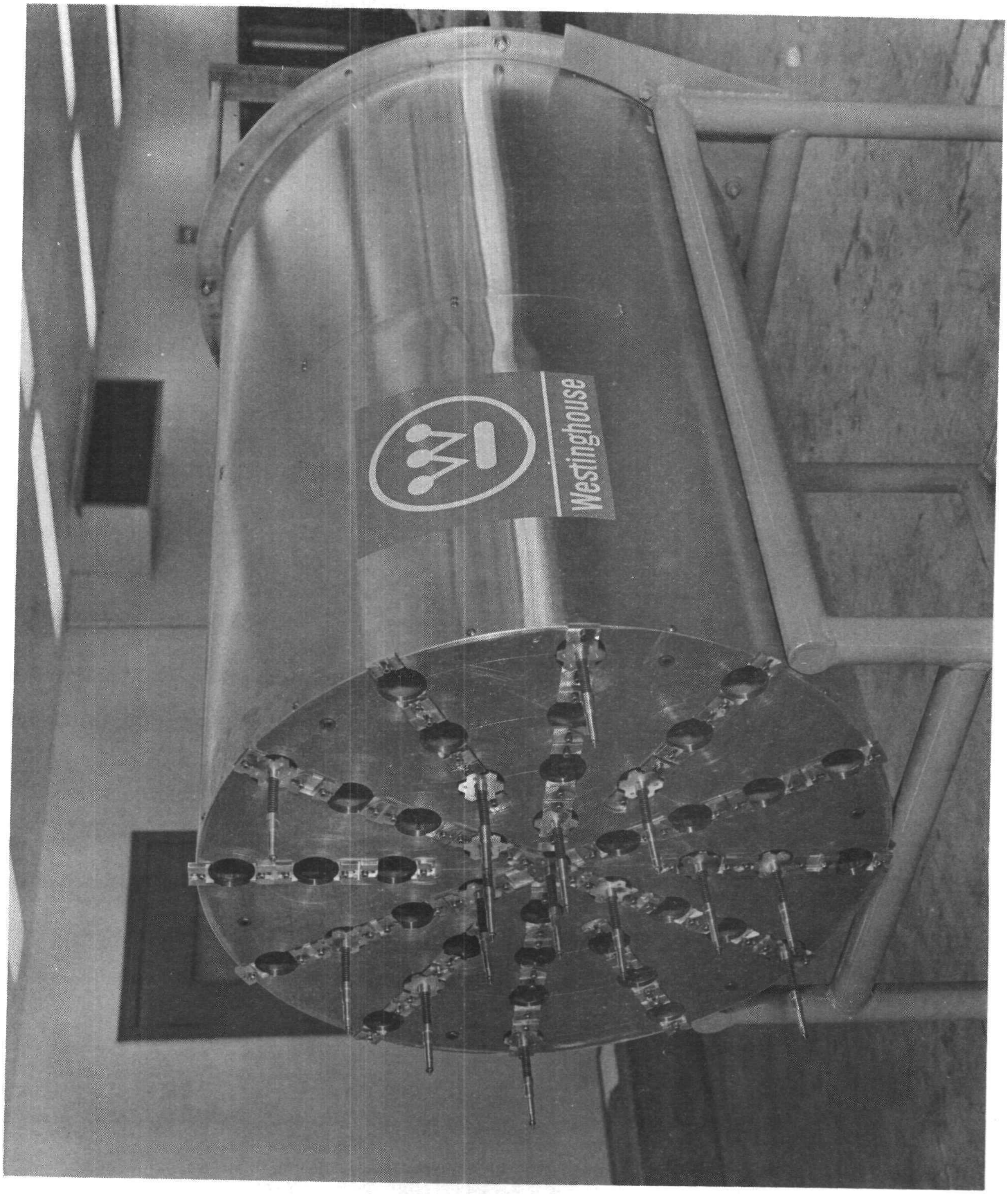

FIGURE 4.5 BACK FACE OF TEST RIG

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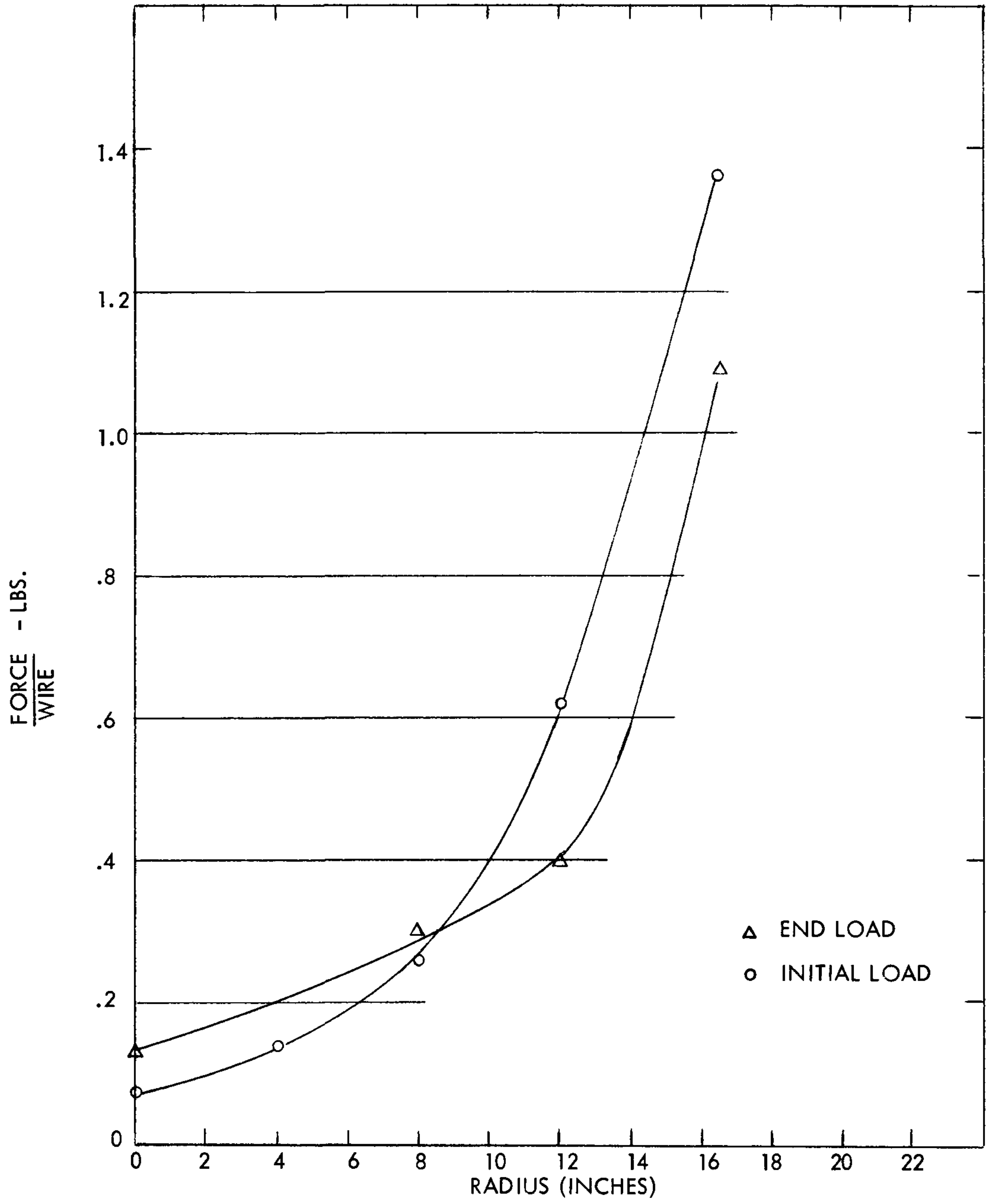

FIGURE 4.6 POISON WIRE PULL FORCE VS RADIAL POSITION

[redacted]

Both loads increase rapidly with larger radii with the end load being dominant and reaching a maximum of 1.36 lbs. per wire at the outer-most cluster radius. The data for this curve was generated by pulling wires from each radius independently. Additional data indicates that the forces required for simultaneously pulling wires from different radii are additive which implies that no interaction exist. For example, one test run consisted of pulling 15 wires from each of the 43 clusters simultaneously, and resulted in a total load of 410 lbs. Figure 4.6 would predict a load of 417 lbs. for this distribution. Other data obtained indicates that the loads corresponding to a pull rate of 1/2 fps would be a factor of 7/5 higher than those at 1/4 fps.

The nuclear calculations described in Section 5 indicate that a uniform distribtuion of about 2,000 wires would represent the optimum arrangement (least number of wires) for a 5% shutdown of the fully-immersed core. Based on Figure 4.6 such a system would require a pull force of 1540 lbs. for removal. Scaled for a pull rate of 1/2 fps, the pull force is 2150 lbs.

V. NUCLEAR POISON REQUIREMENTS

The experimental program develops the information on desired wire bundle radius and the pull force for an arbitrary number and distribution of wires. Obviously, the smallest diameter bundle and the least number of wires to be pulled are desired from both the standpoint of the forces required and potential damage to the core coolant channels. The minimum bundle diameter is determined by the maximum thickness of the annular unpoisoned region between the reflector and the central poisoned region which can be tolerated.

All eigenvalue calculations presented here are based on 4-group, 1-dimensional, diffusion theory using the "AIM-5" computer program. The input constants were obtained from the "MUFT" (3 fast groups) and the "TNS" (thermal group) codes. The groups are distinguished by the following energy breakpoints: 0.821 mev, 5.53 kev, 1.86 ev.

This analysis deals solely with pure B-10 metal. Although an exhaustive study has not been made, no materials problems are apparent which would invalidate its use as the poison material. Other materials, such as boral and boron carbide using natural boron have been investigated by WANL and found to be appreciably less effective. For example, with a uniform poison distribution, about 2.5 times as many wires of B_4C would be required as of pure B-10 to achieve 10% shutdown. Although 100% pure B-10 metal was assumed, a proposed A.E.C. specification obtained recently indicates that the enrichment of B-10 maybe as low as 92%. This degradation of B-10 has not be included in the results but direct extrapolation on the effective B-10 density should be conservative.

The poison wire consists of a 50 mil diameter B-10 metal clad with stainless steel which is 0.0075 inch thick. This in turn is sheathed with 0.0055 inch thickness of polyethylene.

A major effort in the analysis was to obtain flux depression or self-shielding factors for the pure B-10. These factors must be introduced so that the total absorption reaction rate in the poison will remain the same when the wires are homogenized throughout the core.

For this purpose, the WANL Advanced Reactor Design Group calculated the 4-group fluxes throughout a cell consisting of one wire surrounded by an essentially infinite fuel region. These calculations utilized a 4-group, 1-dimensional, transport code "DSN" with the S4 approximation. The depression factor (i.e. the ratio of the average flux within the wire to the average flux throughout the cell) was found to be 0.036 for the thermal group and 0.426 for the third ($1.86 < E < 5530$ ev) fast group. The first two fast groups were not significantly depressed in the wire. As more wires are placed within the core the effective cell size associated with each wire decreases. This "mutual shadowing" decreases the average cell fluxes and, therefore, increases the depression factors. Figures 5.1 and 5.2 show the variation of the depression factors in the thermal and third fast groups respectively with with wire concentration per fuel element assuming a uniform distribution of wires within the fuel element. Another important effect, particularly in the thermal group, is the spectral and consequently the B-10 micro-absorption cross section variation with poison concentration. For example, this cross section is 1380 barns for the unpoisoned flooed core and reduces to 770 barns for a concentration of 15 wires per fuel element. Figure 5.1 shows the thermal flux depression factor variation due to spectral change and mutual shadowing combined.

Figure 5.3 shows the variation of K_{eff} with the concentration of pure B-10 poison wires per fuel element uniformly dispersed throughout the completely immersed NRX-A core. The unpoisoned immersed core is 53.4% supercritical. It is seen that a total of 1.1 wires/element x 1650 elements = 1815 wires would render the immersed core 5% subcritical.

Figure 5.4 shows the effect of leaving an outer radial region of the core unpoisoned while uniformly poisoning the remainder with various concentrations of pure B-10 wires. The bundle radius necessary for the 5% shutdown is shown in Figure 5.5 versus the total number of wires employed. The bundle radius can be reduced to about 35 cm without appreciably increasing the total number of wires required, but any further reduction could be made only at the expense of using considerably more wires. This is because, with

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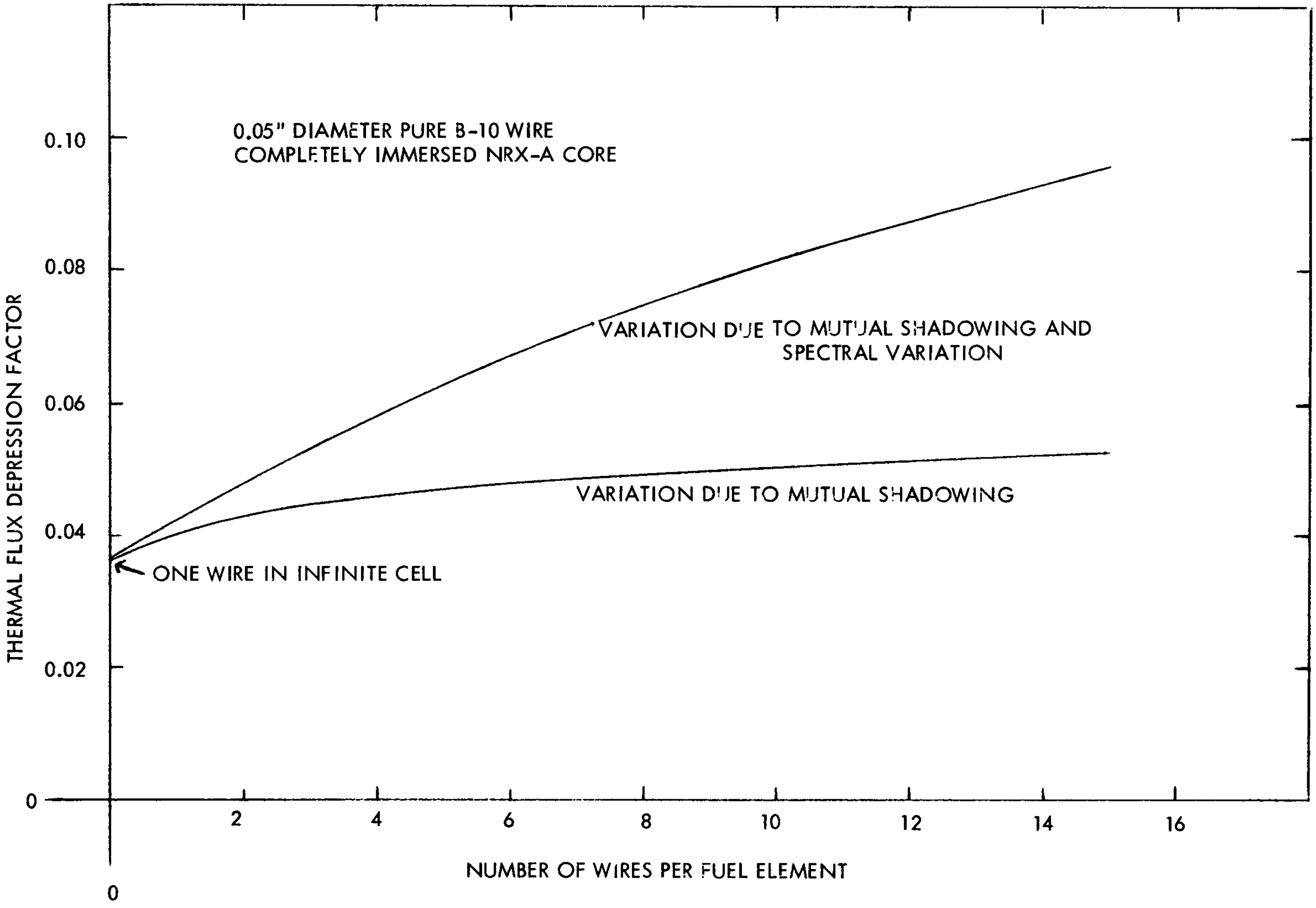

FIGURE 5.1 VARIATION OF THERMAL FLUX DEPRESSION FACTOR WITH POISON WIRE CONCENTRATION PER FUEL ELEMENT

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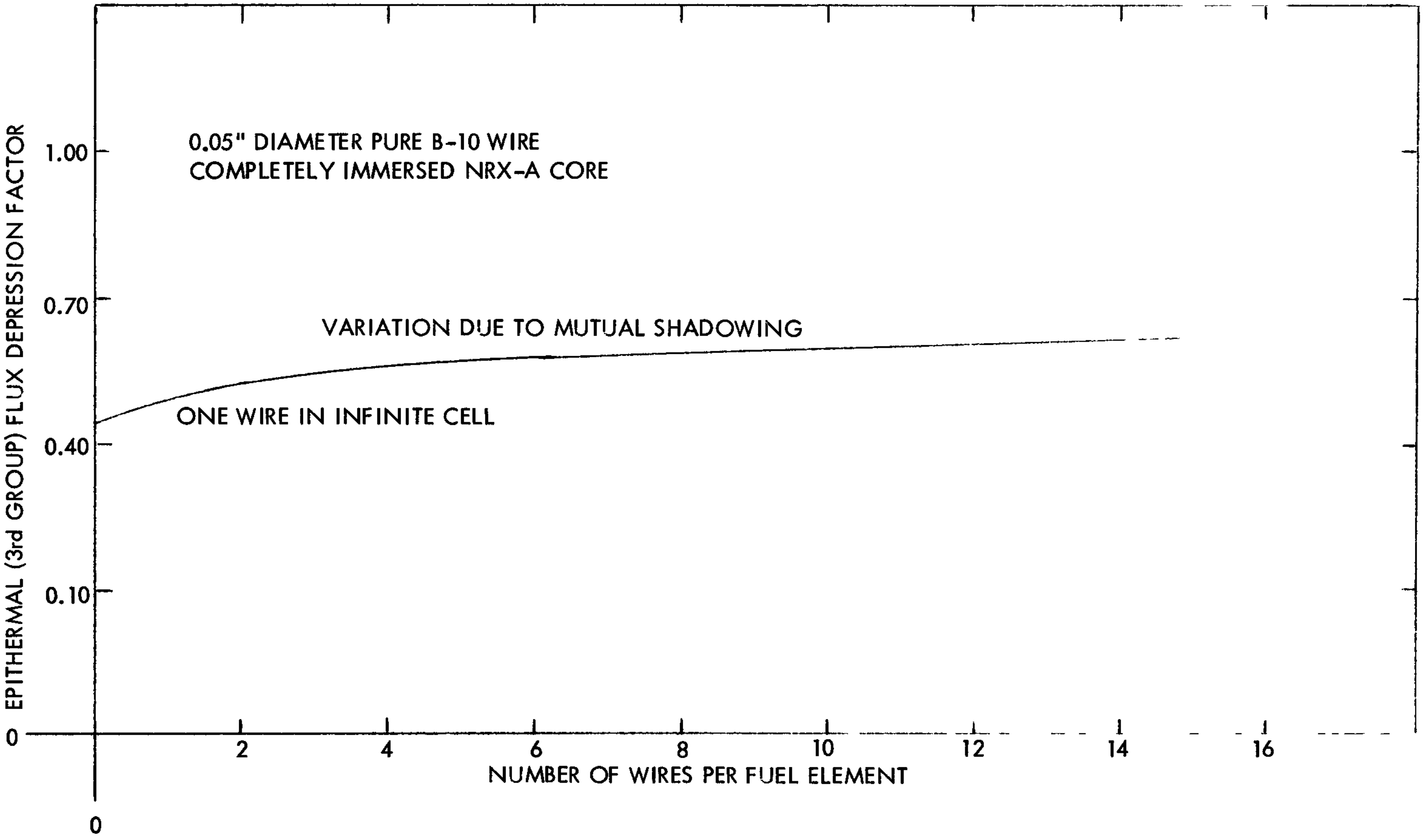

FIGURE 5.2 VARIATION OF EPITHERMAL (3RD GROUP) FLUX DEPRESSION FACTOR WITH POISON WIRE CONCENTRATION PER FUEL ELEMENT

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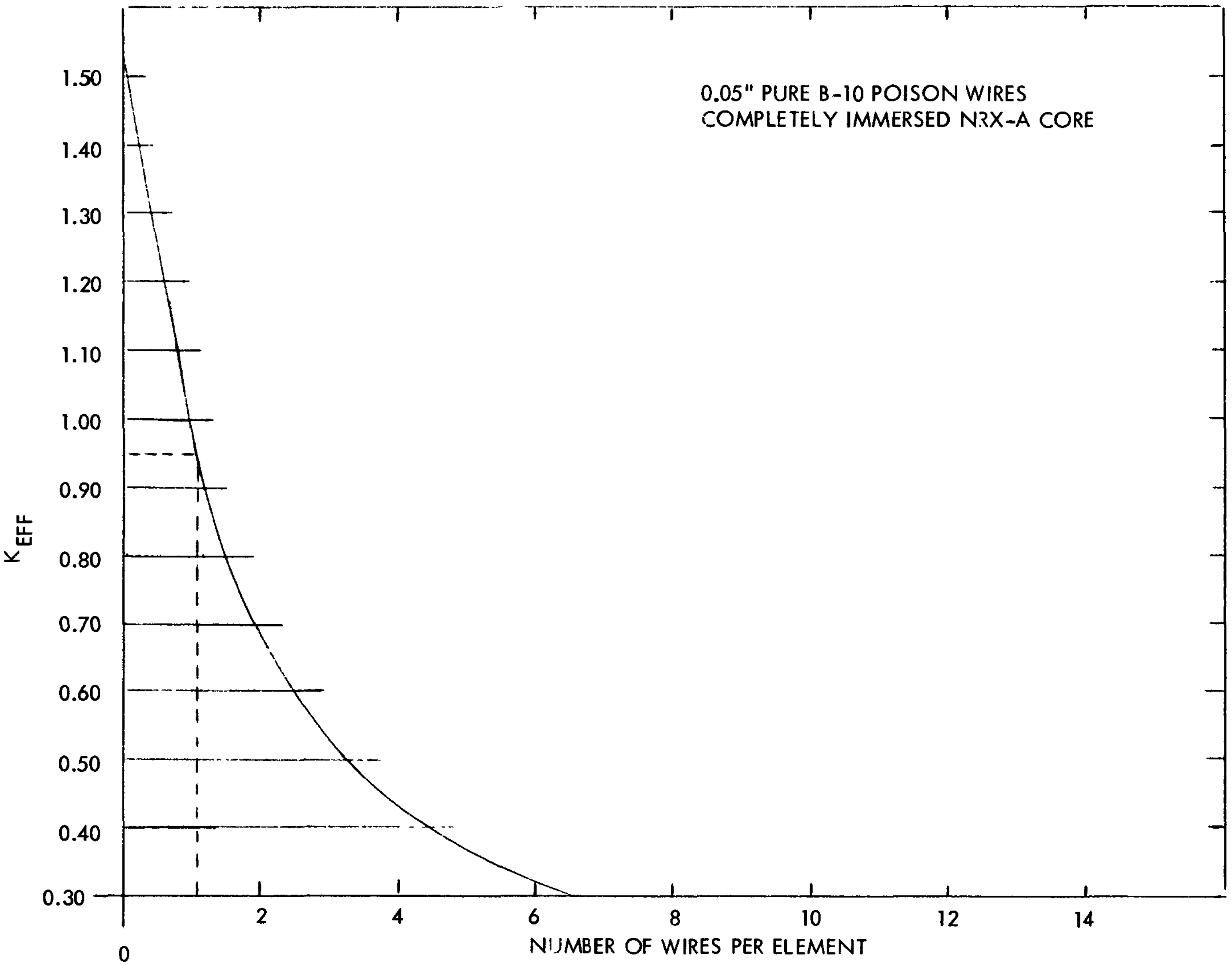

FIGURE 5.3 EIGENVALUE VARIATION WITH POISON WIRE CONCENTRATION PER FUEL ELEMENT UNIFORMLY DISPERSED THROUGHOUT THE CORE

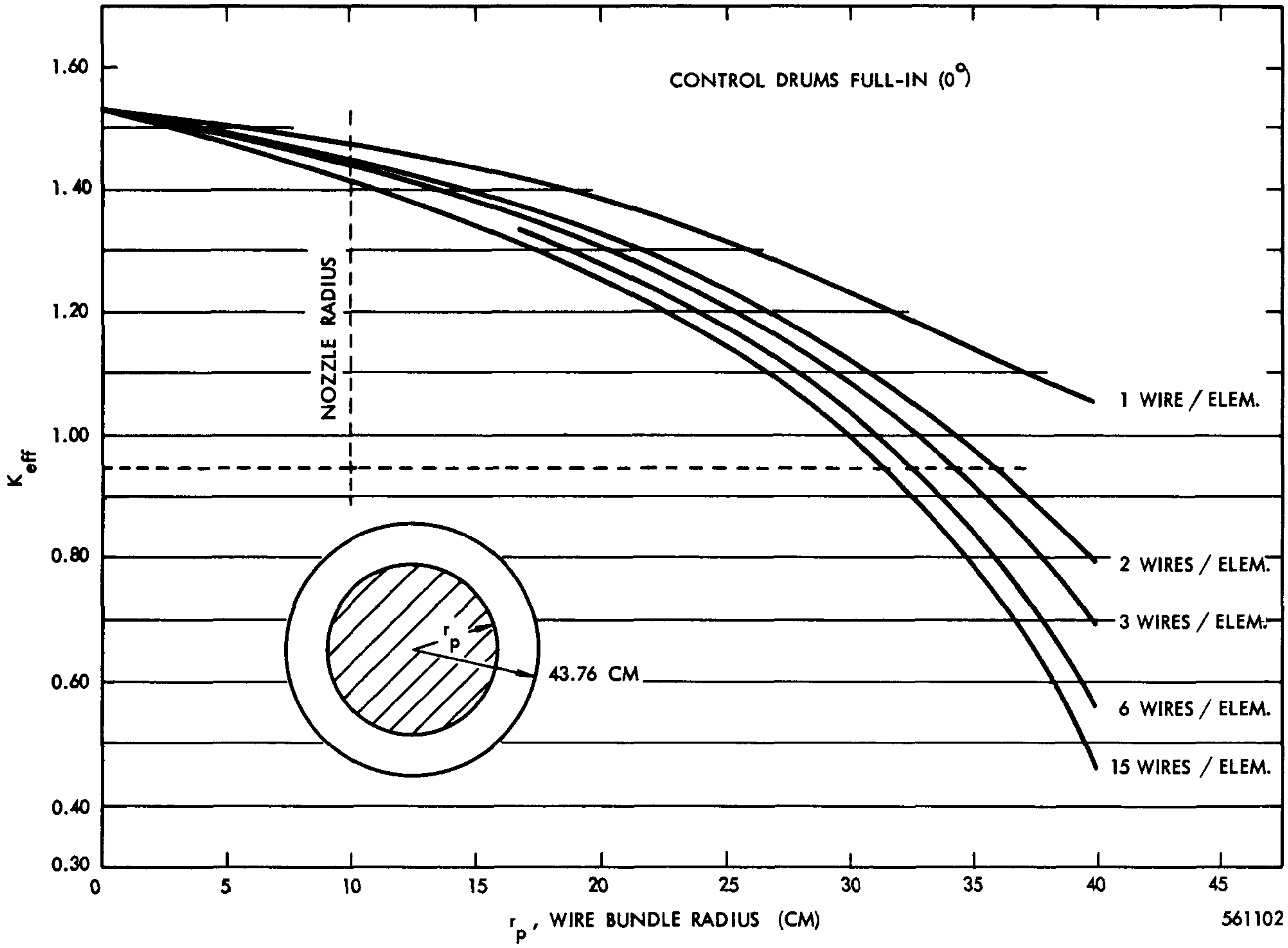

FIGURE 5.4 EIGENVALUE VARIATION WITH UNIFORMLY POISONED BUNDLE RADIUS AND VARIOUS POISON WIRE CONCENTRATIONS PER FUEL ELEMENT

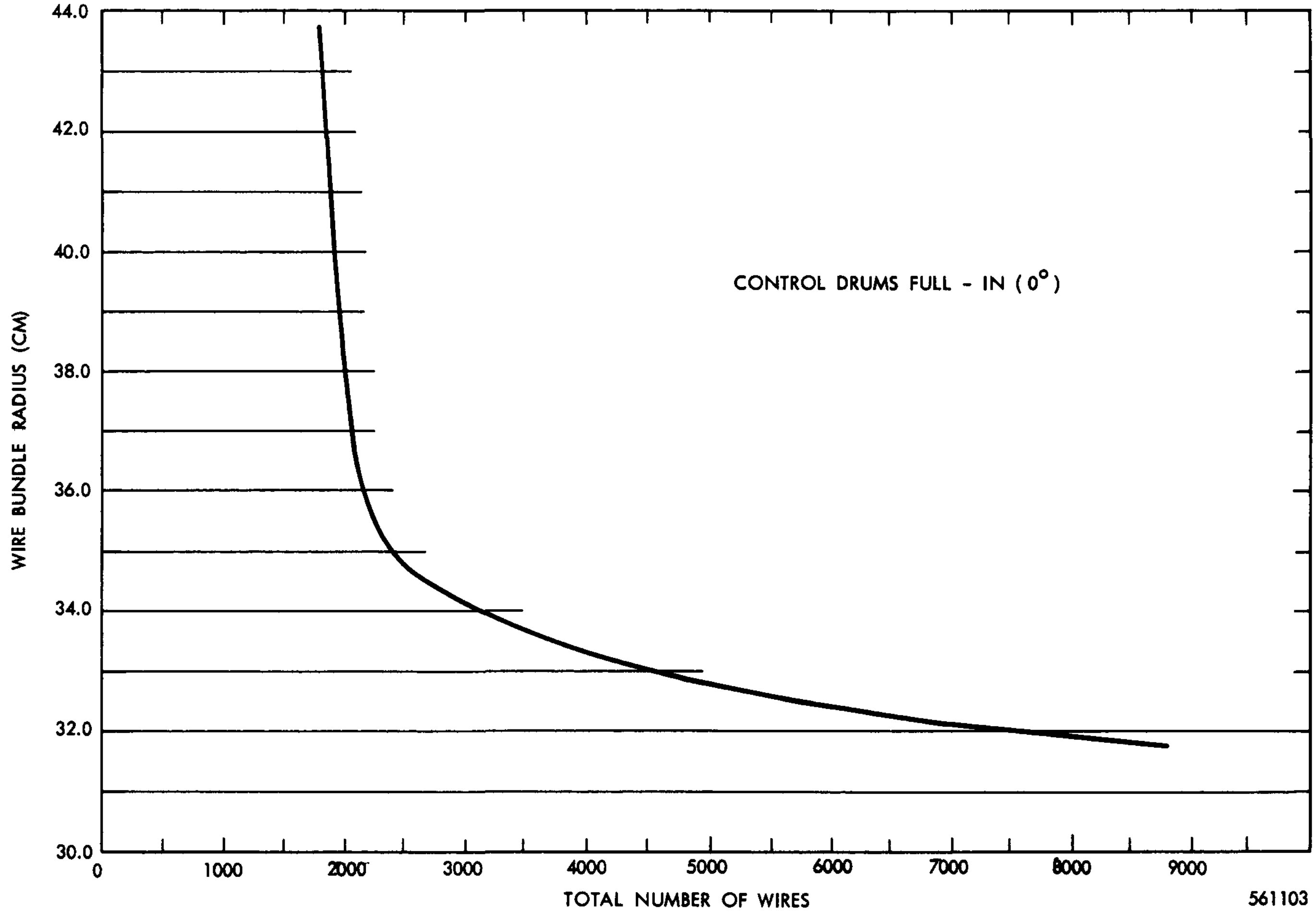

FIGURE 5.5 UNIFORMLY POISONED BUNDLE RADIUS REQUIRED VERSUS TOTAL NUMBER OF WIRES EMPLOYED FOR 5% SHUTDOWN

decreasing bundle radius, the outer unpoisoned region appr'paches the thickness at which it is critical without coupling with the rest of the core.

Finally, the possibility of reducing the number of wires required by isolating two unpoisoned core regions with a heavily poisoned annular ring was investigated. For this purpose, a central poison region of 9.5 cm radius and 3 wires per element concentration was employed. These wires are readily accessible for removal and, without adding appreciably to the total number of wires, aid considerably in isolating the unpoisoned core regions. Figure 5.6 shows the number of wires necessary for the 5% shutdown versus the outer annular radius for various inner annular radii in the region of interest. Included in this figure are the uniform poison bundle results. It is seen that the annulus approach has significant merit only if the desired outer poison radius is quite small (i.e.$<$ 34 cm). For an outer radius of about 35 cm, where the optimum trade-off between number of wires and outer radius occurs, the uniform bundle and the annulus approach with a small inner annular radius are competitive.

To conclude, the minimum number of pure B-10 poison wires required for a 5% shutdown occurs when the wires are distributed uniformly throughout the core. Such a distribution would require 1815 wires or slightly more than one per fuel element. An outer radial core region of about 8 cm thickness may be left unpoisoned without requiring appreciably more wires, but larger thicknesses can be realized only with prohibitively large numbers of wires. For example, a uniformly poisoned bundle of 35 cm radius would require 2400 wires whereas a 33 cm radius would require 4550 wires. The annulus approach does not effectively isolate the unpoisoned core regions due to the annulus's relatively large transparency to fast neutrons. This approach has some merit in removing wires from the core region immediately adjacent to the fully accessible region (in line with the nozzle throat area) by increasing the number of accessible wires in the centrally poisoned region, but the savings is not significant.

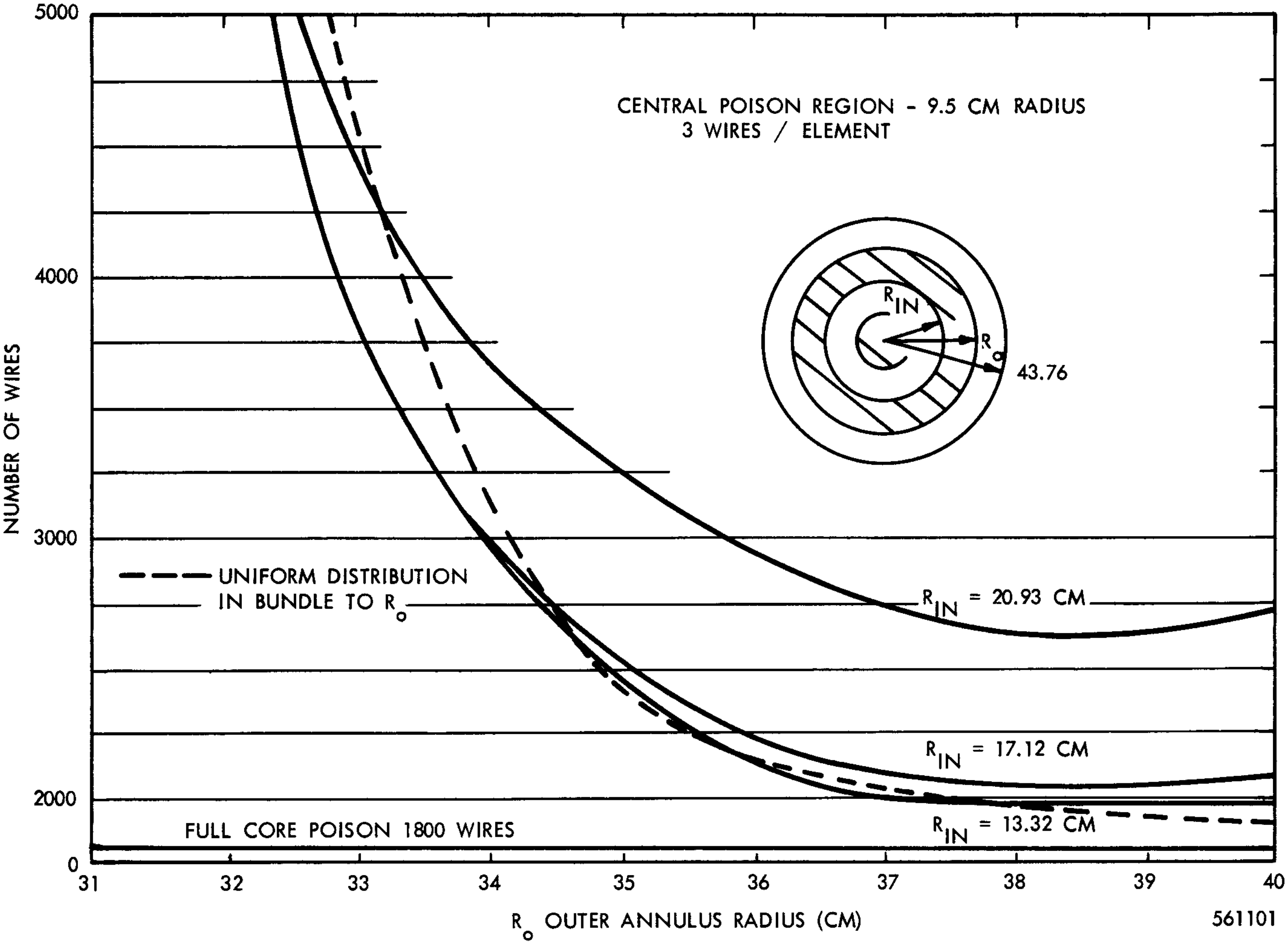

FIGURE 5.6 TOTAL NUMBER OF POISON WIRES REQUIRED FOR 5% SHUTDOWN USING VARIOUS ANNULAR POISON REGION GEOMETRIES