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By

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ABSTRACT

SNAP 8 is a nuclear powerplant intended to produce approximately 30 kw of electric power output for use in spacecraft. The system, which is being developed jointly by NASA and AEC, employs a nuclear reactor (being developed by Atomics International under contract to AEC) as the heat source for a mercury Rankine cycle power conversion system (being developed by Aerojet General Corporation under contract to NASA).

The purpose of this paper is to provide information on the design of the SNAP 8 reactor and shield which may be of use to spacecraft designers considering applications for SNAP 8. The performance requirements, design, weight, and operating characteristics of the SNAP 8 reactor are summarized and a typical shield is discussed. The effects of spacecraft configuration and payload dose tolerance on shield weight for unmanned spacecraft are discussed. Approximate relationships are presented to facilitate rough estimates of shield weights for preliminary design studies of unmanned spacecraft employing the SNAP 8 reactor.

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INTRODUCTION

This paper summarizes the SNAP 8 reactor design and shielding requirements. It is hoped that the information will be useful for preliminary design studies of spacecraft employing SNAP 8.

SNAP 8 is a 30-kilowatt electrical power supply for use on spacecraft. It employs a nuclear reactor heat source to drive a mercury Rankine cycle turboalternator. The system is being developed jointly by the Atomic Energy Commission and the National Aeronautics and Space Administration. The power conversion system is being developed by the Aerojet General Corporation under contract to NASA. The reactor is being developed by Atomics International under contract to AEC. The system has been under development for approximately three years.

The major performance objectives of the SNAP 8 reactor are: 600 kilowatts of thermal power, 1300°F NaK outlet temperature, 10,000 hours endurance, orbital startup and automatic control, high reliability, and low weight.

The SNAP 8 reactor core vessel is approximately 9.4 inches OD by 22.4 inches long and contains 211 fuel elements of 0.56 inch OD. The fuel moderator material is uranium-zirconium alloy containing 10 weight percent fully enriched uranium-235 and hydrided to a hydrogen density of 6×10^{22} hydrogen atoms per cubic centimeter of fuel-moderator material. Outside the core vessel is a beryllium neutron reflector nominally three inches thick. The reactor is controlled by rotating six reflector control drums. An automatic controller senses the reactor coolant outlet temperature and adjusts the position of the control drums to maintain the proper outlet temperature. After startup, the reactor operates at essentially constant power.

Use of a reactor imposes some severe restrictions on the spacecraft design. It is shown that shield weight can vary from a few hundred pounds to several thousand pounds depending on the payload dose tolerance and the spacecraft configuration. Approximate relationships are presented to facilitate shield weight estimates for preliminary design studies of unmanned spacecraft utilizing the SNAP 8 reactor.

PERFORMANCE OBJECTIVES

THERMAL POWER

The SNAP 8 reactor is designed to transfer 600 thermal kilowatts to the NaK coolant. The reactor may be operated at any constant power level desired from approximately 1 to 100% of rated power.

TEMPERATURE

The reactor is designed for a NaK coolant outlet temperature of 1300°F with a control deadband of ±30°F. The coolant inlet temperature is nominally 1100°F.

ENDURANCE

The reactor and its associated controls and shield are designed for 10,000 hours endurance.

STARTUP

SNAP 8 is designed to start in orbit upon ground command. During reactor startup, at least 10% of rated NaK flow must be maintained in the primary NaK loop. Orbital restart is not required.

CONTROL

The reactor control system is designed to maintain the NaK outlet temperature in the range 1300 ± 30°F while the reactor operates at essentially constant power. A rapidly acting, load-following, control system is not required because both the reactor and the power conversion system operate at essentially constant power after startup.

SHIELDING

It is anticipated that the several shield designs may be required for various spacecraft configurations, payloads, and missions. One such set of shield criteria requires that the shield reduce the direct neutron and gamma dose emanating from the reactor during 10,000 hours of operation at 600 kwt to 5×10^{12} fast nvt and 9×10^{6} rads (C) of gammas, respectively, over most of the surface of an 8-ft diameter payload assumed to be 15 ft from the reactor. A relatively small portion of the payload may receive more than 10^{13} fast nvt due to neutron scattering from the NaK pipes and wire harness where they pass around the outside of the shield. It is assumed that the spacecraft will be designed to limit scattering from the power conversion components, radiator, spacecraft structure, etc., to 5×10^{12} fast nvt in 10,000 hours so that the total payload dose due to direct plus scattered neutrons will be $\sim 10^{13}$ fast nvt. Similarly, the total gamma dose to the payload (due to activated coolant outside the reactor as well as to direct and scattered photons) is assumed to be $\sim 10^{7}$ rads.

CONFIGURATION

The reactor and shield are designed to be launched with the reactor above the shield.

RELIABILITY

A tentative reliability goal of 93% has been set for the reactor and its associated shield and controls to survive launch, achieve automatic startup, and operate for 10,000 hours. This figure includes failures due to meteorite puncture.

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REACTOR DESIGN

The performance objectives above have led to the reactor and shield design illustrated in Figures 1 and 2. Reactor and shield design data, operating parameters, and weights are listed in Tables I and II. The overall size and configuration of the SNAP 8 reactor is illustrated by the wooden model of the reactor shown in Figure 3 and by the SNAP 8 Experimental Reactor shown in Figures 4, 5, and 6.

CORE

A layout drawing of the reactor is shown in Figure 1. The stainless steel core vessel is 9.214-inches ID by 22.4 inches long. The complete core assembly including the vessel, fuel elements, other internal components, and the NaK coolant weighs approximately 300 lb. The core contains 211 fuel elements, 0.56-inch OD and approximately 17 inches long. Each fuel element contains a fuel-moderator rod composed of a zirconium - 10 weight percent uranium alloy hydrided to a hydrogen concentration of 6×10^{22} hydrogen atoms per cm^3 (i.e., near the hydrogen concentration in cold water). The fuel elements are clad in Hastelloy-N and a hydrogen permeation barrier is applied to the inside of the cladding tube to limit hydrogen loss to an acceptable value during reactor operation.

The space between the hexagonal array of fuel elements and the cylindrical core vessel is filled with internal reflector elements as illustrated in Figure 7. These internal reflector elements are composed of beryllium oxide clad in stainless steel.

REFLECTOR

Reflector Control System

The core vessel is surrounded by an annulus of beryllium approximately 3 inches thick and approximately 17 inches long. This neutron reflector contains six movable semicylindrical sections or drums as shown in Figure 1.

Reactor control is accomplished by rotation of the drums toward or away from the core to increase or decrease the fraction of leakage neutrons reflected back to the core. The reactor control system is designed to maintain the NaK outlet temperature within the range between 1270 and 1330°F. If the coolant outlet temperature wanders out of this range, the controller signals one of the long-term actuators to rotate one of the control drums in or out approximately 0.5 degree.

Startup

Reactor startup is initiated by a signal to the startup programmer located in the payload compartment of the spacecraft. The startup programmer automatically sequences the disarming of the reactor launch safety systems and energizes the control drum motors to drive the control drums in at a preset rate to take the reactor to critical and to rated operating temperature. NaK coolant flow (at least 10% of rated flow) must be maintained through the reactor during startup. The startup sequence, illustrated schematically in Figure 8, proceeds as follows: The reactor destruct charge (described later) is ejected overboard. The six control-drum lockout pins are released. The startup programmer energizes all six control drum actuators. Three "startup drums" are driven in at constant speed and lock full-in in approximately 5.8 minutes after startup is initiated. Simultaneously, the other three "long-term control drums" are stepped inward fairly rapidly until the reactor is approximately $0.50 subcritical. At this point, the stepping rate is slowed down by a signal to the programmer from a preset position-sensing switch on one control drum shaft. The control drums continue in until the NaK temperature reaches 1270°F, approximately 3 hours after initiation of startup. The closing of the low-temperature limit switch deactivates the startup programmer and the control system is switched to the automatic temperature control mode.

During temperature control, for the 10,000-hour life of the system, if the low or high temperature (1270 and 1330°F) switches are closed, the control drums are stepped one-half degree every 4 minutes until the NaK temperature is within the control band.

Safety

During ground checkout and assembly of the spacecraft, the reactor control drums are locked in the least reactive position by both drum lockout pins and by a mechanical lock on each drum which requires a key for removal. The keylocks are utilized during checkout and would be removed prior to launch through small access holes (about 6 inches in diameter) in the vehicle skin. This leaves the drums pinned out during launch. The drums are unpinned during the orbital startup sequence by explosive pinpullers.

If the proper orbit is not reached, the reactor can be destroyed on ground command by the destruct charge located around the inlet plenum of the core vessel. This shaped charge is designed to rupture the core and disperse the fuel elements sufficiently to prevent accidental criticality. The destruct charge is ejected during the orbital startup sequence.

Irreversible shutdown of the reactor is accomplished by spring ejection of the entire beryllium reflector from the core.

The reflector is divided axially into two halves which are held together by a steel band around the top of the reactor. This band can be broken by

1) A ground command release actuator,

2) A coolant temperature sensing actuator to shut down the reactor when the coolant temperature drops significantly at the end of reactor or PCS life, or

3) The heat of reentry into the earth's atmosphere.

SHIELDING REQUIREMENTS

Nuclear radiation is obviously a significant factor in the design of a spacecraft which employs a reactor. Maximum permissible radiation levels are always included in the design criteria. The design dose for an unmanned spacecraft is generally defined by the radiation damage tolerance for the payload equipment. This dose may be met through the combination of good shield design and good system design.

The radiation levels outside a SNAP 8 reactor are presented in Figure 9. The doses correspond to a 10,000-hour exposure to an unshielded reactor operating at a nominal power level of 600 kw (thermal). The angular distribution of the radiation leakage is approximately isotropic.

Fast neutron radiation dominates shield design for unmanned SNAP 8 systems. This is a result of the relative composition of the radiation environment external to the unshielded SNAP 8 reactor. For typical payload components, the ratio of unshielded neutron dose to design neutron dose is several orders of magnitude higher than the gamma dose ratio. For this reason, the SNAP 8 shield is primarily designed on the basis of adequate neutron attenuation. The neutron shield material used is lithium hydride. This material has a very high value of neutron removal cross section per unit weight, and, in addition, it has good thermal and radiation stability.

Figure 10 presents the variation of lithium hydride shield weight with three spacecraft design criteria. These parameters are (1) the separation distance between the payload and the center of the reactor core, (2) the permissible fast neutron dose at the payload, and (3) the payload diameter. It should be noted that these weights do not include allowances

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for shield casing and structural support. The relative importance of these weights may be inferred from Table 3, in which the shield weight breakdown for an actual SNAP 8 shield design is tabulated.

The radial wall thickness of the shield containment vessel is determined by micrometeorite protection considerations. This sort of protection is required since a rupture of the containment vessel results in a loss of hydrogen from the lithium hydride shield and a consequent increase in radiation damage to the payload. Figure 11 presents the most recent data on zero-penetration probability versus required armor thickness.

The neutron radiation levels quoted in Figure 10 refer only to the direct dose — that due to neutrons which come directly from the reactor. Another extremely important source is that due to neutrons which scatter from the vehicle structure and radiators of the spacecraft. Figure 12 presents estimates of the scattered neutron dose at the payload, which is about 15 feet from the center of the core. Each isodose line represents the payload dose due to neutrons which scatter from 1 square foot of surface area centered at any point along the isodose line. The scattering surface to which the figure applies is the representative radiator section illustrated in Figure 13.

The scattered radiation characteristics of several possible SNAP 8 radiator configurations have been analyzed. Table III presents the results of one such study. In general, the fast neutron dose from unshielded radiators exceeds 10^{13} nvt for reactor-to-payload distances of less than about 40 feet.

One way to reduce the fast neutron dose scattered from the radiator to the payload is to shield the radiator. For most radiator configurations except a conical radiator, however, shielding the radiator requires increasing the solid angle shadowed by the shadow shield, thus increasing the weight of

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the shield. It should be noted that, in general, the portion of shield which shadows the radiator must be nearly as thick as the payload shadow shield. Otherwise the neutrons emerging from the surface of the thinner shield constitute a more powerful surface source than the outer surface of the payload shadow shield. Thus, a shield which reduces the radiation incident upon the radiator can be prohibitively heavy if the radiator extends out like wings, for example.

On this basis, it is strongly recommended that the conical radiator concept be given serious consideration for the SNAP 8 spacecraft. This concept has the inherent disadvantage that the radiating area is restricted to the external surface only, but retains the extremely desirable characteristic that all spacecraft components and structures can be located behind a relatively small shadow shield.

TABLE I

SNAP 8 REACTOR AND SHIELD DESIGN DATA

Rated Operating Conditions	
Reactor thermal power, kwt	600
Operating life, hr	10,000
NaK outlet temperature, °F	1300
NaK inlet temperature, °F	1100
NaK operating pressure, psia	40
NaK flowrate, lb/sec	13.3
Average thermal flux, $n/cm^2/sec$	5×10^{12}
Medium fission energy, ev	0.2
Reactor Design	
Fuel elements	
Number	211
Fuel element OD, in.	0.560
Degree of hydriding, N_H, atoms/cc	6.0×10^{22}
Internal reflectors	
Composition	BeO
Cladding material	Stainless steel
Core vessel	
Inside diameter, in.	9.214
Length, in.	22.4
Thickness, in.	0.105
Material	Stainless steel
Reflector	
Composition	Beryllium
Thickness, in.	3 ± 1
Number of control drums	6
Shield	
Composition	LiH
Vessel material	Stainless steel
Vessel thickness, in.	0.109
Vessel OD at large end of cone, in.	40.4
Vessel OD at small end of cone, in.	31.9
Direct neutron dose at payload 15 ft from reactor, fast nvt	0.5×10^{13}
Direct gamma dose at payload 15 ft from reactor, rad (C)	0.9×10^{7}
Electric power requirements	
3500 watt-seconds dc pulse to fire explosive pin-pullers to initiate startup	
300 watts, 28 volt dc for 6 hours during startup	
100 watts, 28 volt dc for 10,000 hours after startup	

TABLE II

REACTOR AND SHIELD WEIGHT SUMMARY
(lb)

Core Assembly		
Fuel elements	202	
Core vessel	40	
Grid plates, flow baffle plate, and structural components	18	
Internal reflectors	10	
NaK in core vessel	14	
NaK pipes and NaK in pipes	14	
Temperature sensor switches	2	
		300
Reflector Assembly		
Beryllium reflector	155	
Control drum actuators	25	
Drive mechanisms and structure	35	
Shutdown and safety devices	15	
		230
Shield Assembly		
Lithium hydride	680	
Shield vessel and structure	310	
Gamma shield	34	
Cable harness	15	
Destruct charge	11	
		1,050
Programmer and Controller (located in instrument compartment of spacecraft)		20
Total Reactor and Shield Weight		1,600

TABLE III

RADIATION SCATTERING ANALYSIS OF SEVERAL RADIATOR CONFIGURATIONS*

Radiator Type†	Radiator Dimension§			Payload Diameter (in.)	Reactor-Payload Distance (in.)	Scattered Fast Neutron Dose at Payload (nvt)**
	Width (in.)	Length (in.)	Radius (in.)			
Folding (L), Flat-Plate	120	150	-	114	200	1.8×10^{14}
Folding (L), Flat-Plate	160	112	-	114	162	1.8×10^{14}
Folding (L), Flat-Plate	150	120	-	148	171	1.3×10^{14}
Folding (L), Flat-Plate	150	120	-	214	188	4.8×10^{13}
Folding (T), Cylindrical	151	119	-	114	201	7.7×10^{14}
Folding (T), Cylindrical	155	116	-	148	206	4.9×10^{14}
Folding (T), Flat-Plate	120	150	-	214	188	1.9×10^{14}
Fixed, Flat-Plate	27	667	-	114	718	2.1×10^{12}
Fixed, Flat-Plate	44	409	-	148	460	1.0×10^{13}
Fixed, Flat-Plate	77	234	-	214	288	2.6×10^{13}
Fixed, Flat-Plate	57	335	-	114	386	6.0×10^{12}
Fixed, Flat-Plate	74	258	-	148	309	1.6×10^{13}
Fixed, Flat-Plate	107	178	-	214	229	7.4×10^{13}
Conical	-	255	22.5-74	148	286	$< 4 \times 10^{5}$
Conical	-	180	66 -107	214	210	$< 4 \times 10^{5}$
Cylindrical	-	201	57	114	252	2.6×10^{15}
Cylindrical	-	155	74	148	206	6.7×10^{14}
Cylindrical	-	107	107	214	176	8.9×10^{14}

*Illustrated in Figure 14.

†The folding, flat-plate radiators have longitudinal (L) or transverse (T) hinges. Sketches of the radiator types are shown in Figure 14.

§"Width" of radiators refers to radial span, "length" to axial span. All radiators have 500 square feet of radiating surface area.

**10,000 hours of reactor operation at 300 kw (thermal).

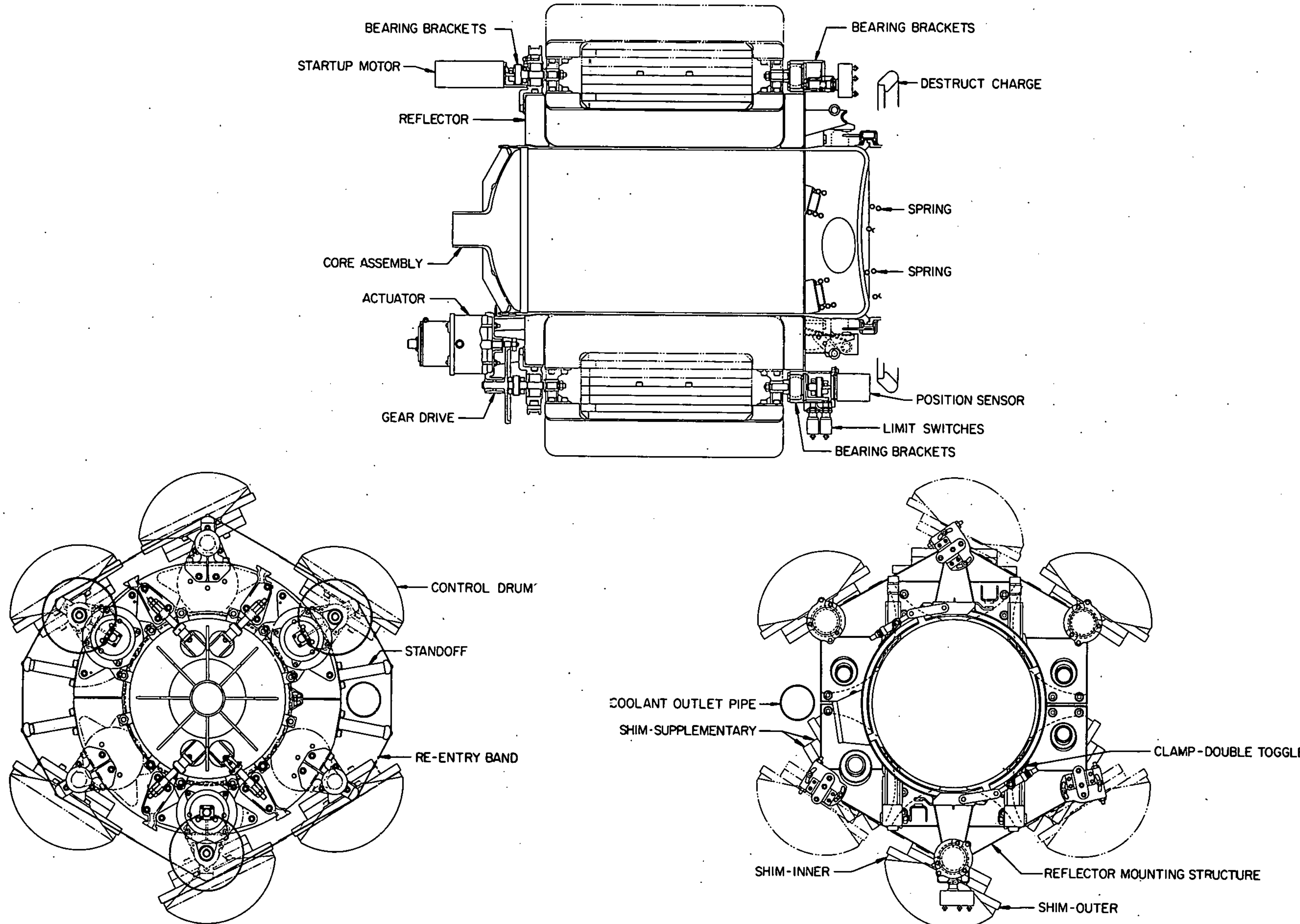

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Figure 1. SNAP 8 Reactor Layout

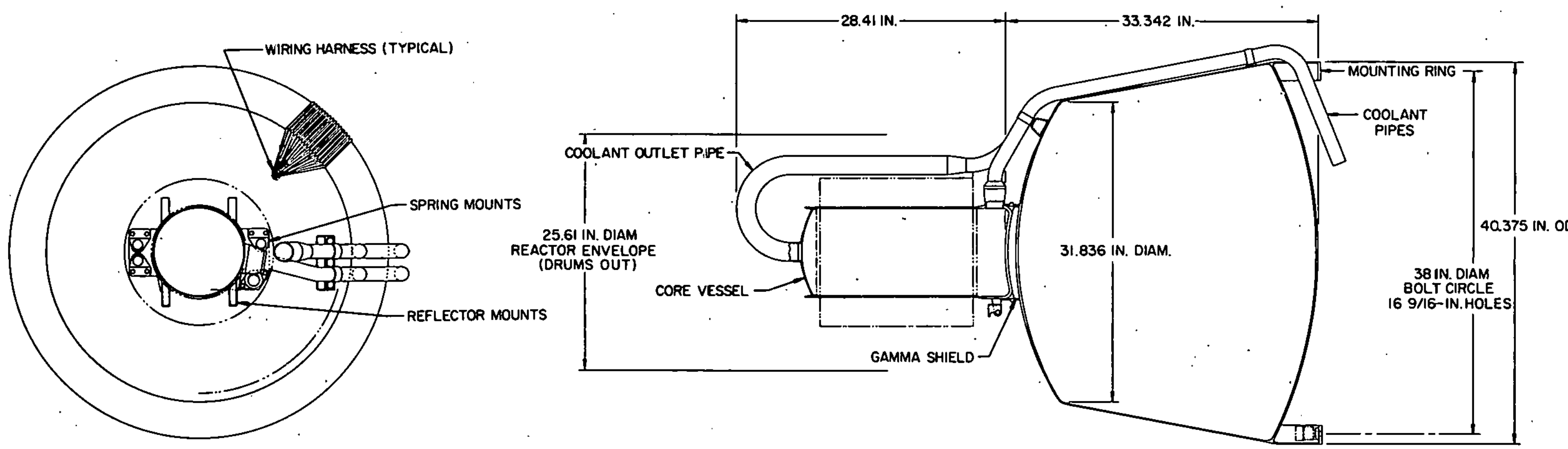

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Figure 2. SNAP 8 Reactor Envelope and Typical Shield

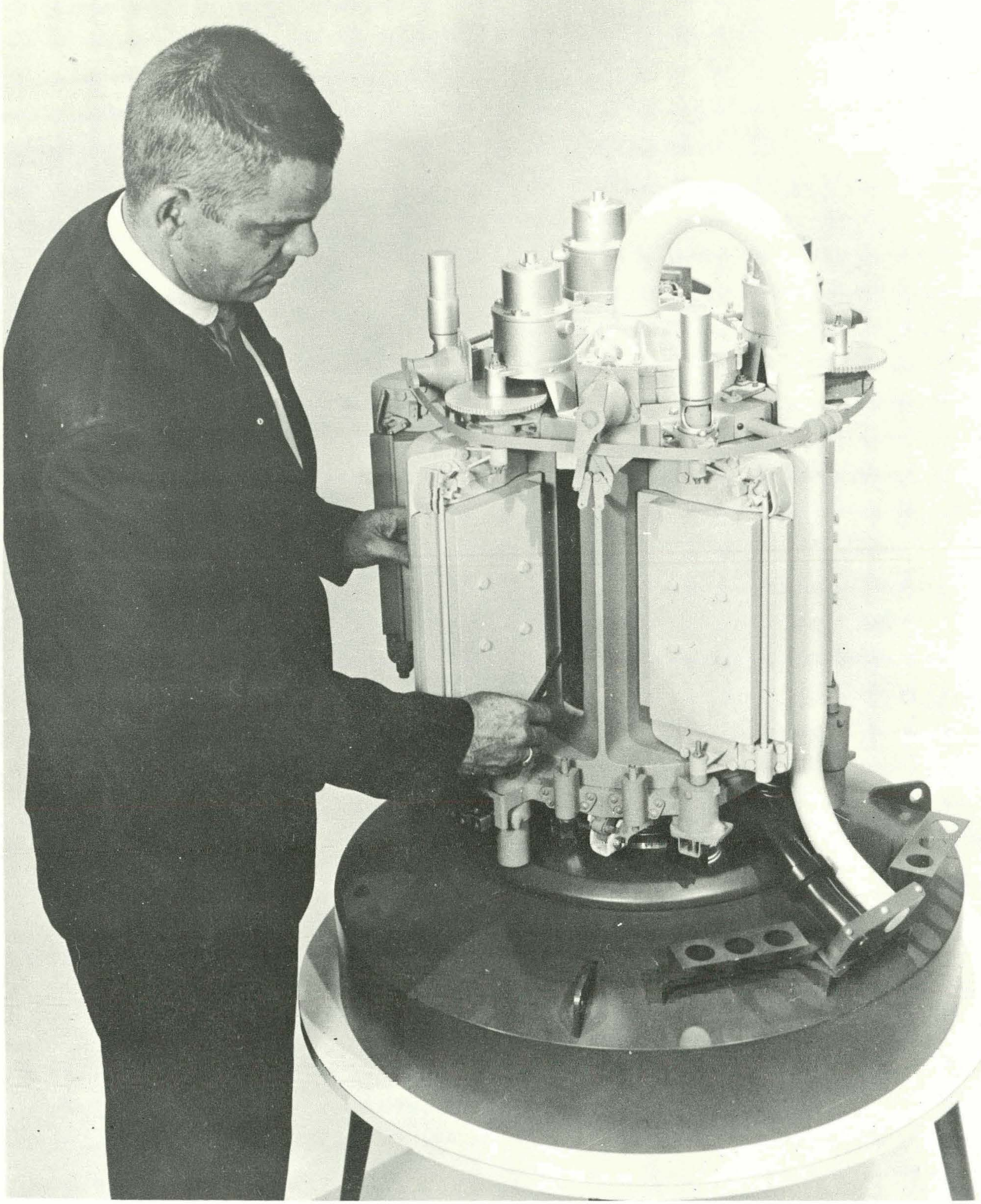

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Figure 3. Model of SNAP 8 Reactor

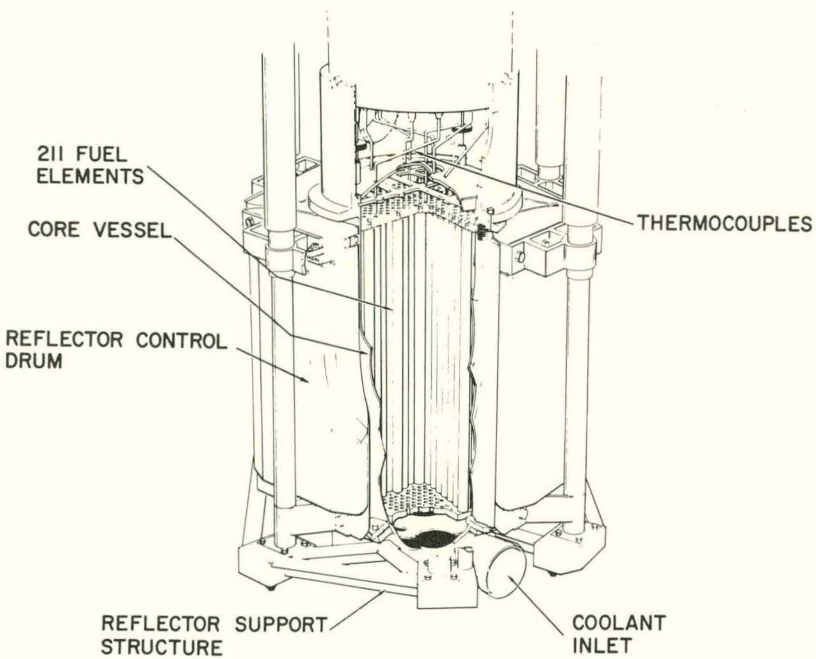

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Figure 4. SNAP 8 Experimental Reactor

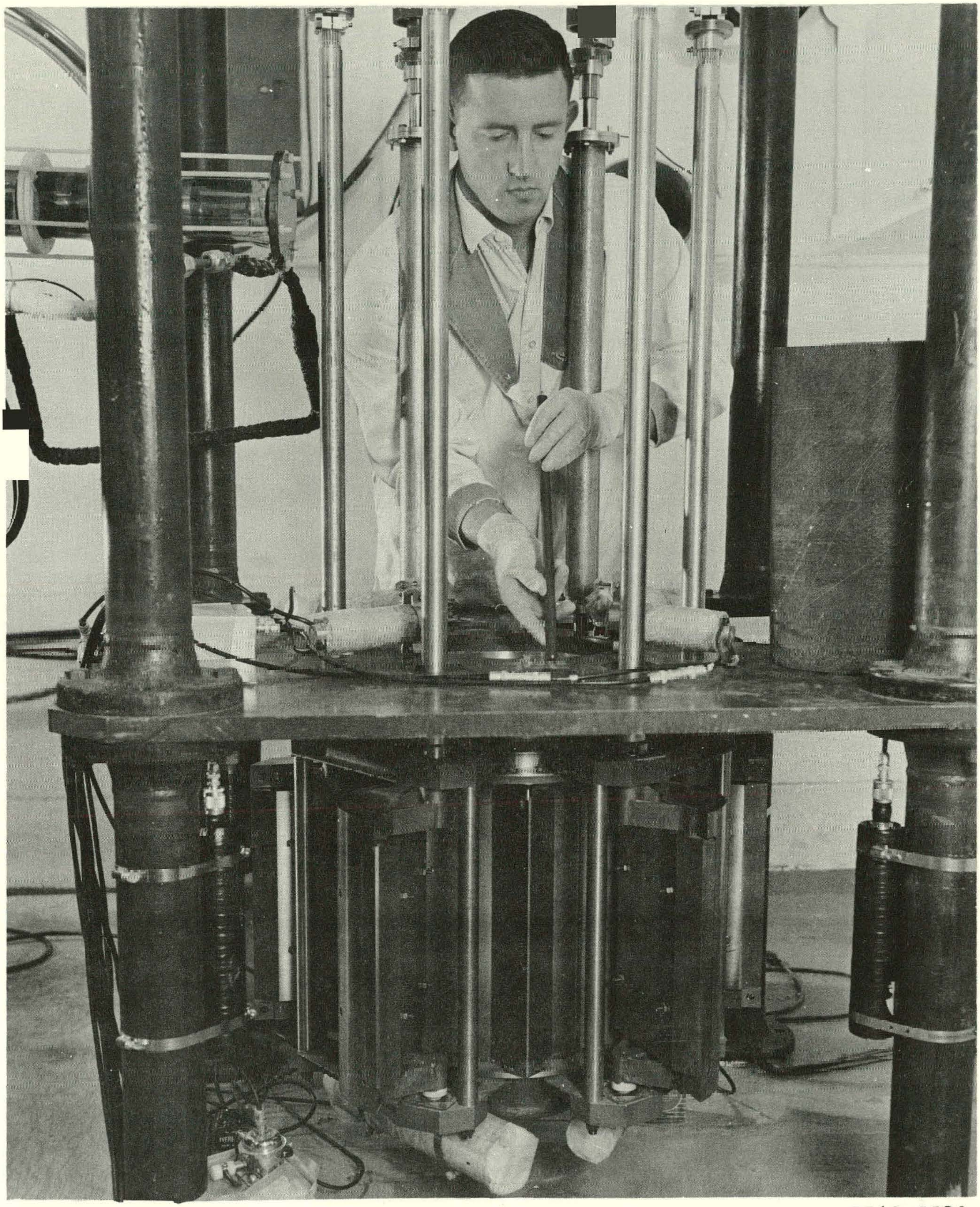

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Figure 5. S8ER Dry Critical Fuel Loading. The reactor is attached to the bottom of a table.

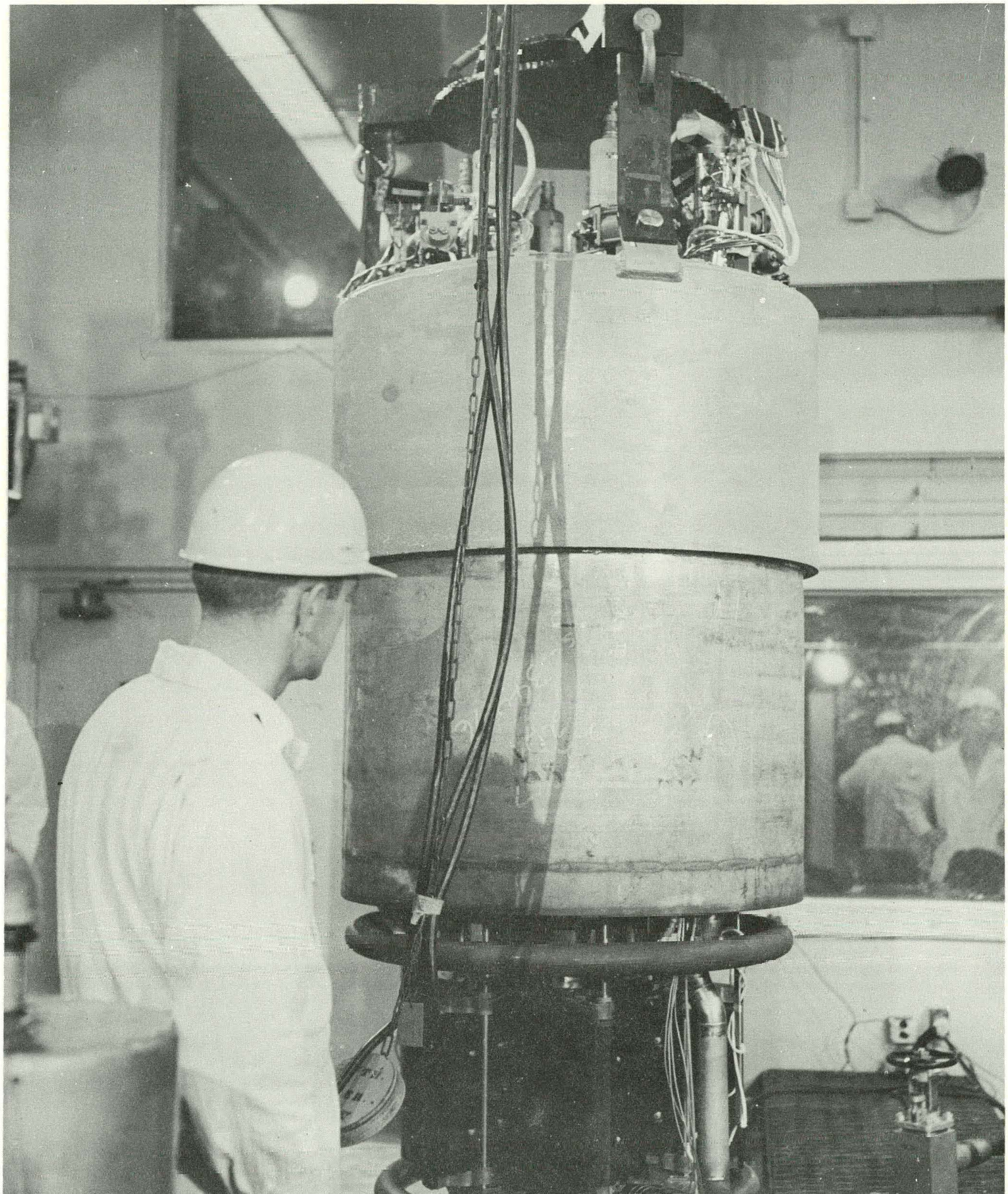

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Figure 6. Installation of S8ER for Power Operation. Note: The reactor is attached to the bottom of a concrete shutdown shield. The control drum actuators and drives are attached to the top of the shutdown shield.

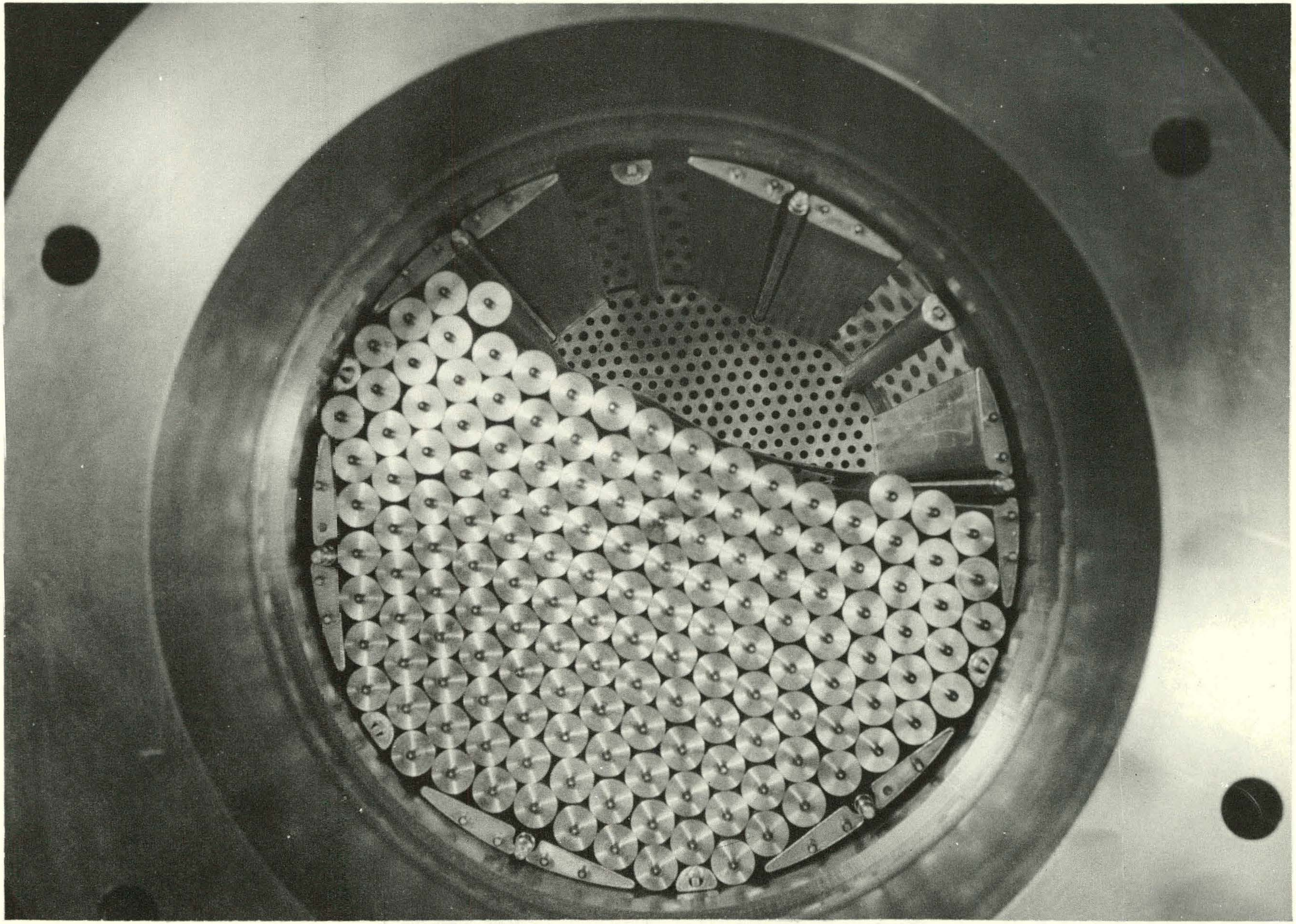

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Figure 7. SNAP 8 Reactor Core Partially Filled With Fuel Elements

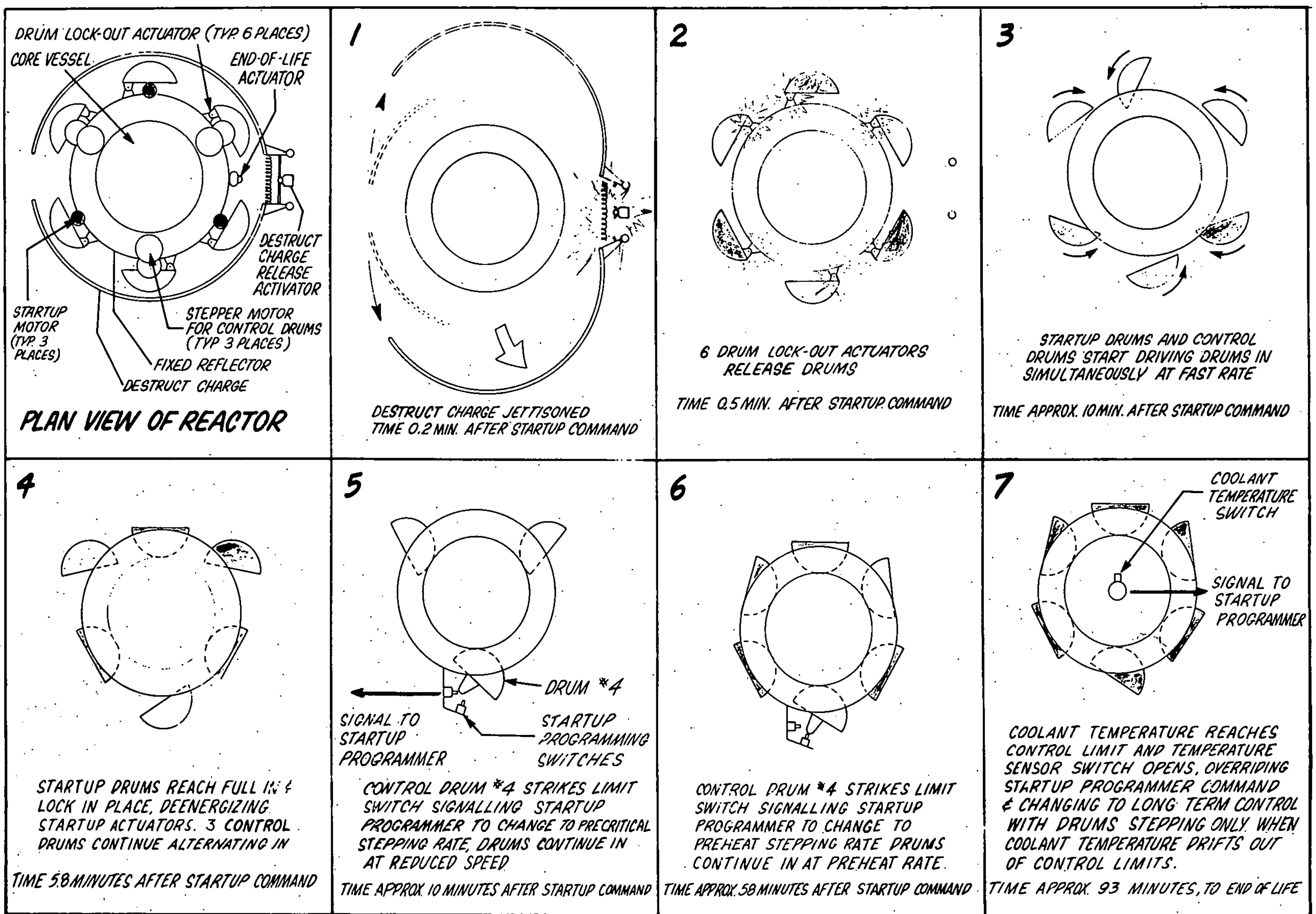

Figure 8. Reactor Startup Sequence

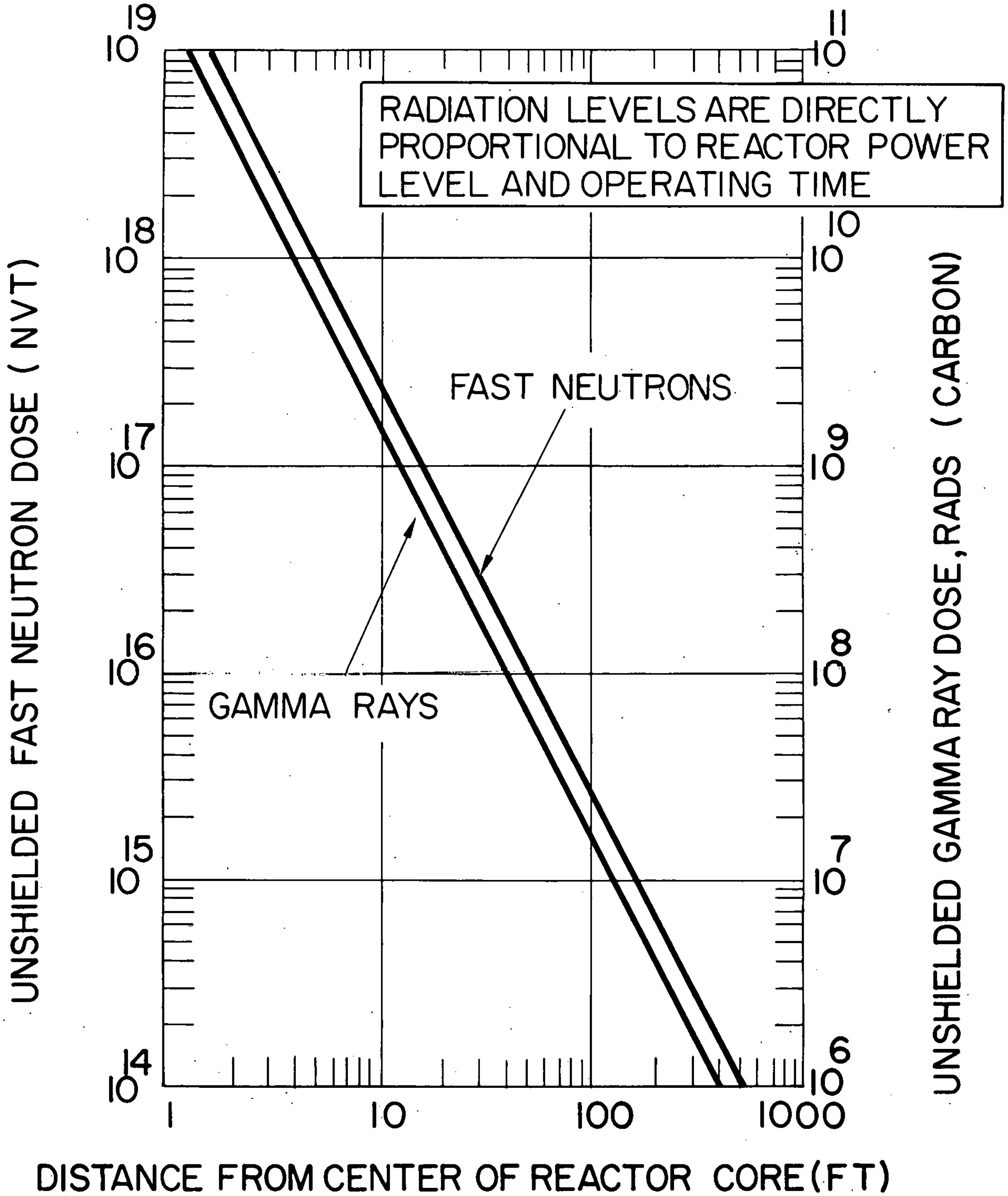

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Figure 9. Nuclear Radiation Levels Outside an Unshielded SNAP 8 Reactor Following 10,000 Hours of Operation at 600 Kilowatts, Thermal

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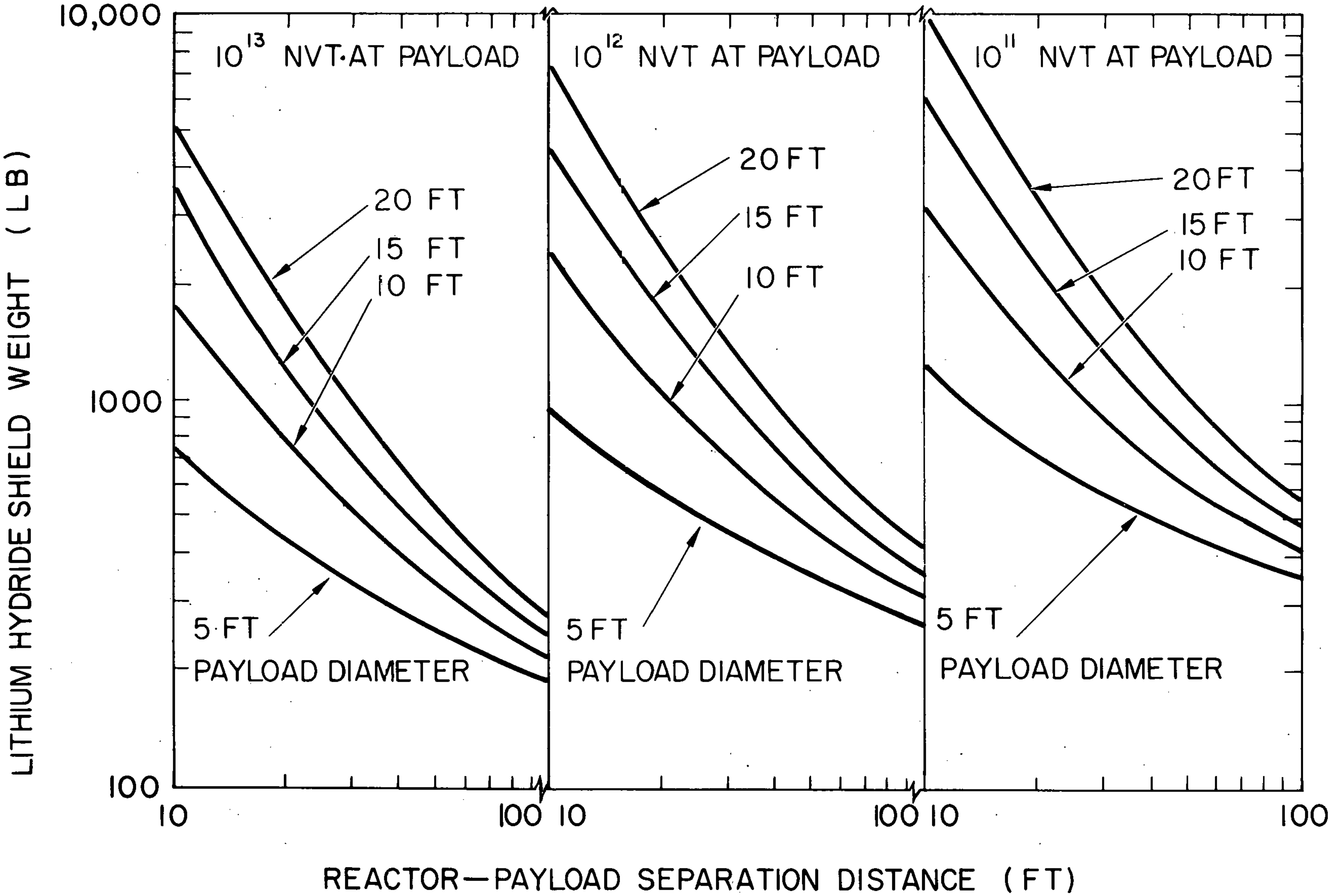

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Figure 10. Weight of Lithium Hydride Required for Shadow Shields for Various Shield Criteria

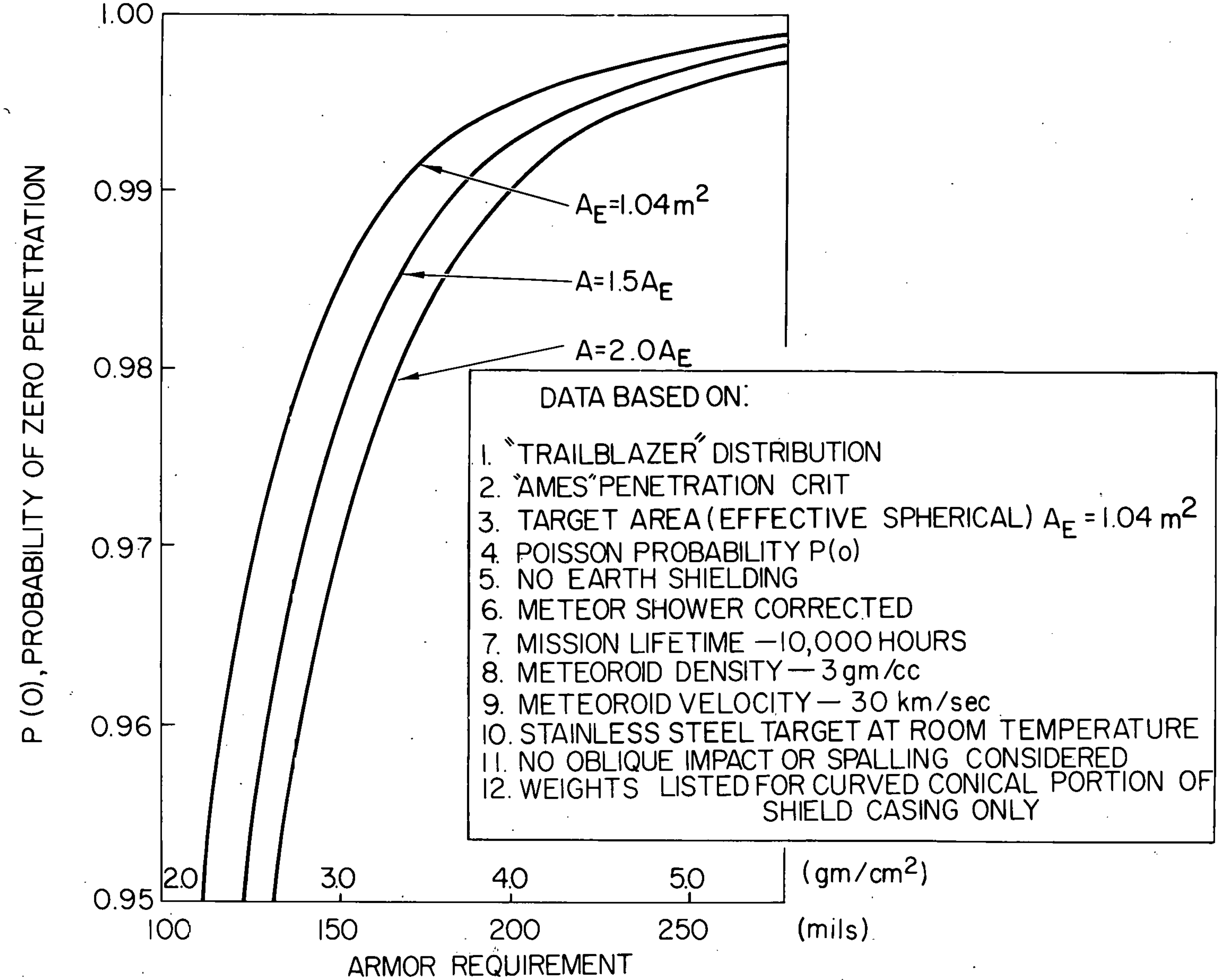

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Figure 11. Shield Vessel Thickness Required for Protection Against Micrometeorite Puncture

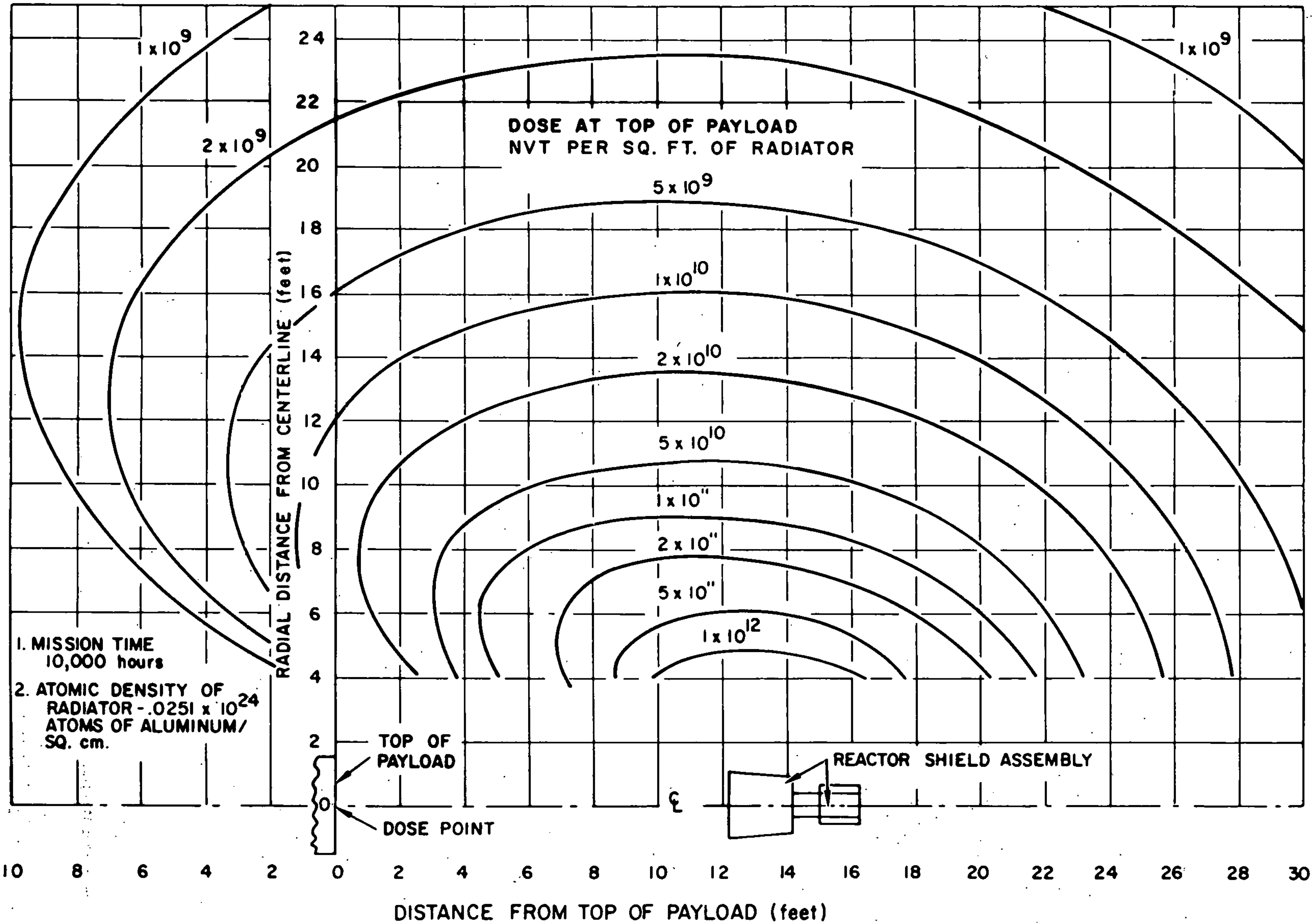

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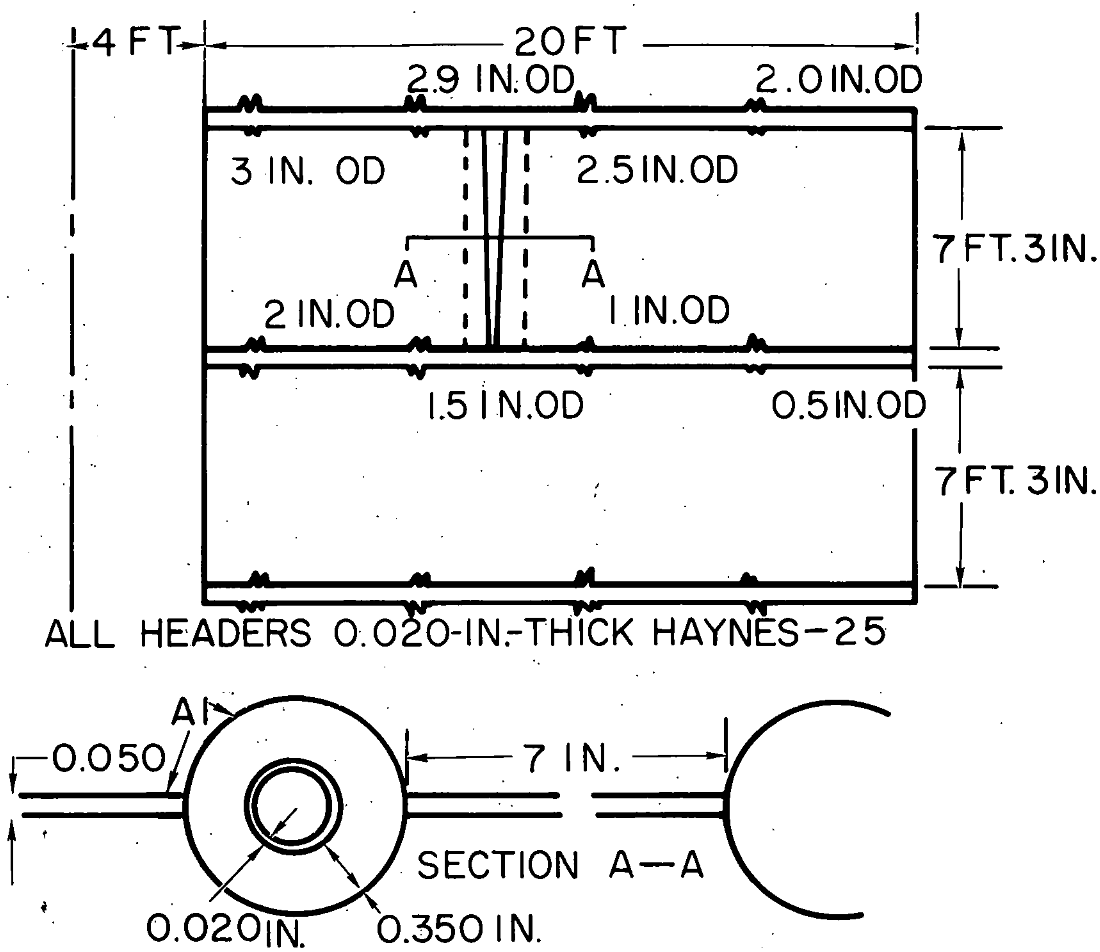
Figure 12. Neutron Dose Scattered to a Payload 15 Feet from the Reactor per Square Foot of Flat-Plate Radiator of the Type Illustrated in Figure 13



COMPONENT WEIGHTS

TUBES	HAYNES-25	ALUMINUM
INLET VAPOR HEADER	27.7	479.7
RETURN LIQUID HEADER	19.2	114.9
INLET HEADER BELLOWS	3.8	24.4
RETURN HEADER BELLOWS	17.2	17.0
	3.1	3.9
	71.0 LB	639.9 LB

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Figure 13. Flate-Plate Radiator Configuration Assumed for the Neutron Scattering Calculations Illustrated in Figure 12

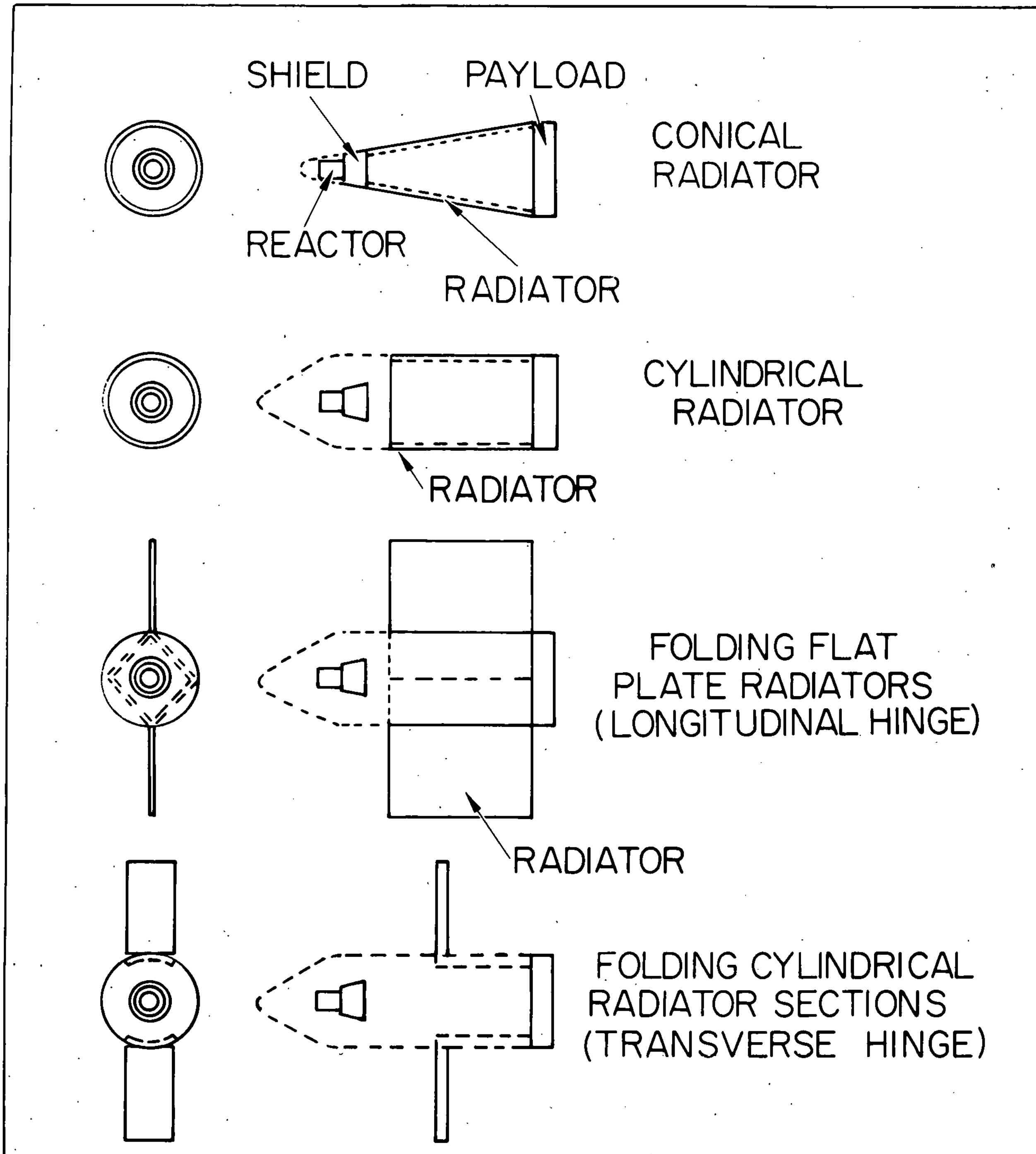

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Figure 14. Radiator Configurations Assumed for the Neutron Scattering Calculations Summarized in Table III

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