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APPLICATION OF SNAP REACTOR POWER SYSTEMS TO MANNED SPACE STATIONS

AEC Research and Development Report

ATOMICS INTERNATIONAL
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A DIVISION OF NORTH AMERICAN AVIATION, INC.
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CONTENTS

TABLES

Page

FIGURES

FIGURES

Page

ABSTRACT

Manned space laboratories and stations are an integral part of the National Space Program and are currently in the planning phases within both NASA and the USAF. These laboratories and stations will require sizeable amounts of on-board electric power to perform their life-support, guidance and control, communications, and operational functions. Nuclear power systems currently under development in the USAEC's SNAP Program offer many advantages as prime power sources for these laboratories and stations, i.e., a high power-to-weight ratio, low radiator areas and therefore low drag and minimum propellent inventory for station keeping in low earth orbit (150 to 350 n-mi), no effect on power production during the sun-shade orbital transient, no complex sun orientation required during the sun portion of the orbit, etc.

The SNAP nuclear power system which appears to offer the most potential for these applications in the 5 kw to few hundred kw power range with lifetimes greater than several weeks, is the zirconium-hydride-uranium thermal reactor coupled through a NaK loop to a Mercury-Rankine Power Conversion System. This system is currently under development by the USAEC and could be qualified and ready for use during the 1970 to 1980 time period. Preliminary designs of this system at 5, 10, 15, and 20 kwe power levels give unshielded system weights (including one redundant power conversion system) of 1850, 2530, 3230, and 3940 lb, respectively. Shielding for 90-day on-orbit stay time in a 10-ft-diameter space station results in total plant weight for these power levels of 4310, 5040, 5760, and 6470 lb.

I. INTRODUCTION

Earth orbiting research laboratories and stations occupy a major role in the National Space Program and are currently in the final planning stages in NASA and the USAF. NASA is initiating development work on extended Apollo, a 45- to 120-day orbiting version of the Lunar Apollo System. This development is expected to lead to the Apollo Orbiting Research Laboratory (AORL) with orbital life times of 1 yr or more. Other NASA study programs include the Manned Orbiting Research Laboratory (MORL), a 6-man, 1- to 5-year lifetime system, and the Large Orbiting Research Laboratory (LORL), a 30- to 40-man system.

The USAF has initiated development on the Manned Orbiting Laboratory (MOL), a 2-man, 30-day cylindrical laboratory which is being developed to determine the military role of man in space.

Each of the foregoing laboratories and stations requires significant amounts (3 to 50 kwe) of reliable, long duration electrical power for life support, environmental control, communications, station control, and operational functions. As mission lifetimes exceed several weeks in duration, nuclear power systems become advantageous as prime power sources. This report discusses in detail the significant design and operational features of an attractive nuclear system in the 5 to several hundred kwe range, the zirconium hydride reactor — Mercury Rankine Power Conversion System. This system is designated in this report as Nuclear Power Plant — Mercury Rankine (NPP-MR).

Major emphasis is placed on plants in the 5- to 20-kwe range, but some attention is devoted to systems capable of higher power levels. Main elements of the overall system are: (1) reactor subsystem and biological shielding; (2) primary subsystem coolant (NaK) loop; (3) power conversion subsystem (PCS); (4) radiator/condenser (RC), which also acts as the main structural member of the plant; and (5) electrical and control equipment. An artist's concept of an NPP-MR powered station in space flight is shown in Figure 1. The general process is schematically pictured in Figure 2 with only a single module in the PCS shown. A building block approach is adopted for the power conversion subsystems based on using an assembly of 3- to 5-kwe modules to furnish the total power level.

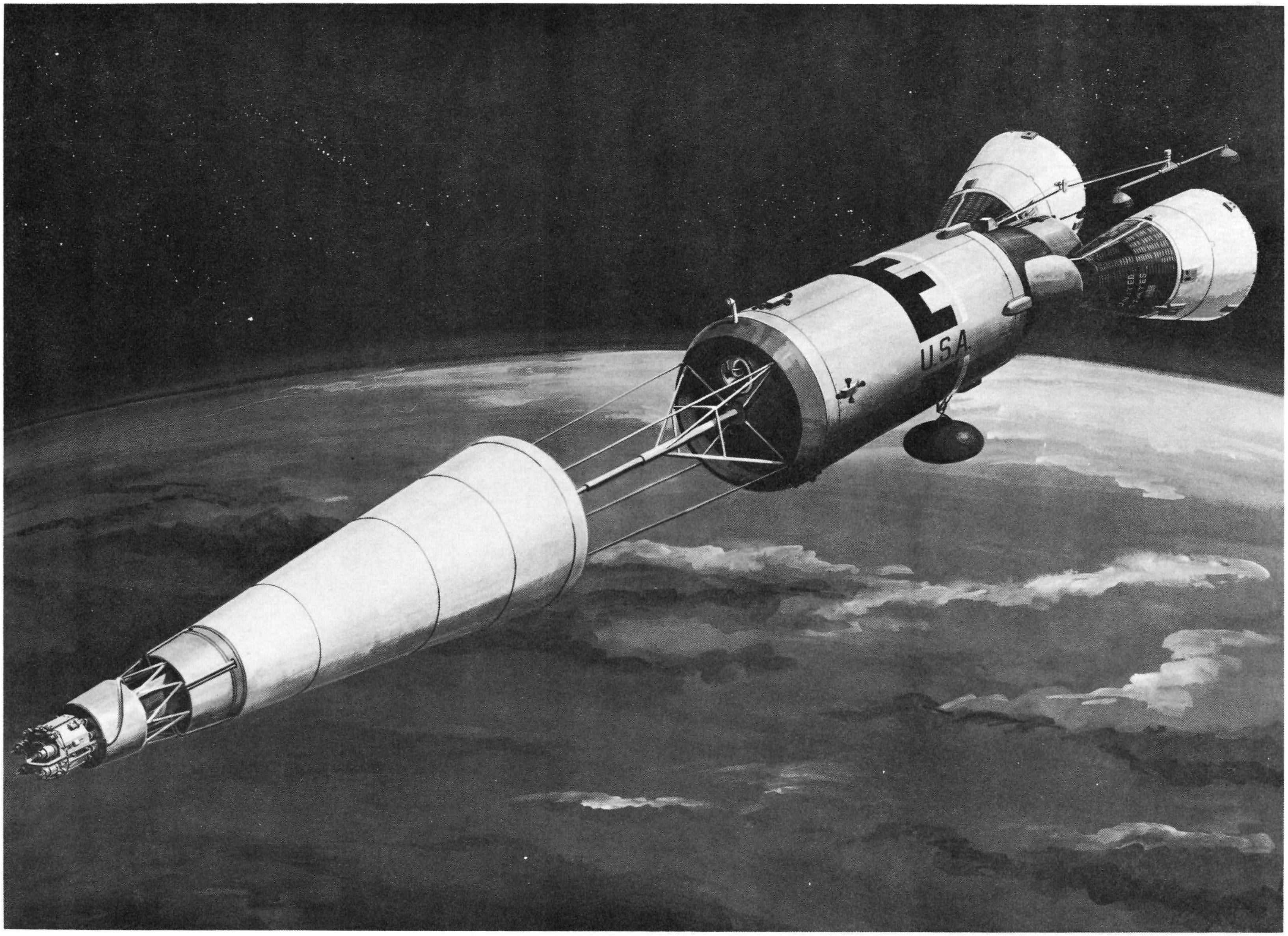

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Figure 1. Orbiting Space Station — NPP-MR Assembly

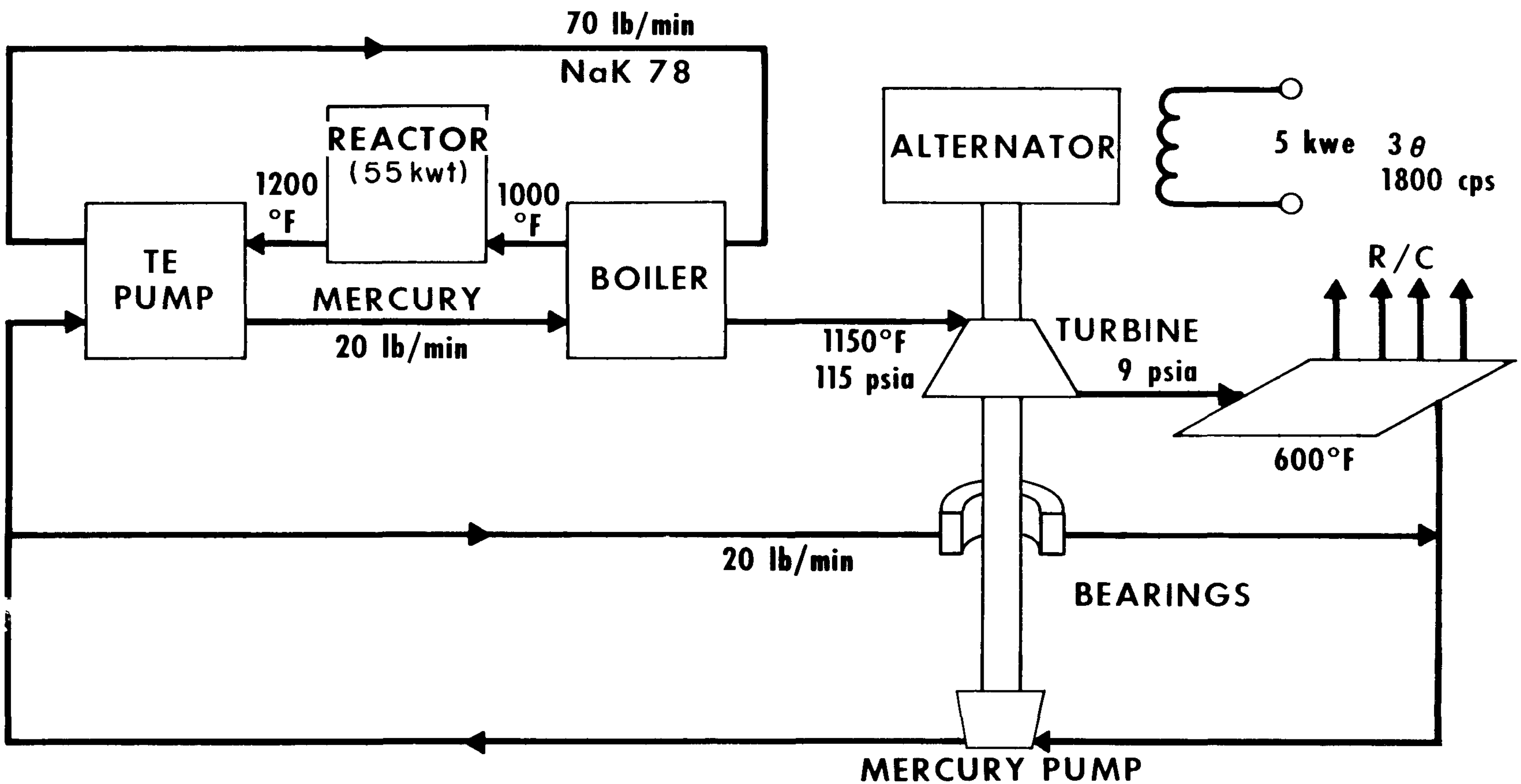

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Figure 2. Process Flow Schematic

The technology for these 3-kwe modules is in a state of advanced development as a result of extensive engineering, design, and test activities conducted during the past 7 yr on the AEC SNAP 2 program.* The necessary performance characteristics of all basic components have been demonstrated, and each unit has either completed, or is at some advanced stage of endurance testing. Startup and reliable long-term operation of the reactor and the 3-kwe rotating machinery has been achieved. Tests, including simulated orbital startups, of integrated (single module) systems are well underway and verify performance predictions. Along with the benefits of early availability, the modular approach offers reliability (achieved in part from the use of spare or standby modules), relative economy, and flexibility which extends the permissible lead time in a particular space station program before final electrical requirements must be fixed.

While the need for such operations is not anticipated, NPP-MR systems are designed to be capable of being shut down and then restarted a number of times in orbit. Also, the engineering and testing carried out in support of a planned flight with an Atlas-Agena booster has demonstrated the ability to meet structural space vehicle interface requirements.

The material discussed in subsequent sections is listed in the order of its treatment in the text. The material is intended to:

1) Summarize the general considerations pertinent to all design aspects of NPP-MR systems for space station applications;

2) Provide extensive parametric information which may be used by designers in developing realistic preliminary estimates of NPP-MR characteristics for space stations of various sizes and configurations, with emphasis on the 5- to 20-kwe range;

3) Provide in some detail preliminary designs of 5-, 10-, 15-, and 20-kwe plants for use with a 10-ft diameter cylindrical space station;

4) Present briefly the characteristics estimated for NPP-MR systems of sizes up to 300 kwe;

5) Review in some detail the current advanced state of technology of such systems.

*SNAP 2 was the designation of the flight test program for the reactor powered 3-kwe system with mercury Rankine power conversion. The current technology program has been renamed the Mercury Rankine Program.

II. GENERAL CHARACTERISTICS OF NUCLEAR–MERCURY RANKINE SYSTEMS

This section contains brief discussions of general design and operational characteristics of reactor-mercury Rankine power systems for space application. Special attention is given to power plant-payload interface characteristics. In Part IV, the features of a particular system design are deal with in detail.

A. GENERAL DESCRIPTION

The primary element of the power plant is the reactor. Nuclear and materials considerations indicate that the most suitable reactors for the energy levels of interest, i.e., 5 kwe to several hundred kwe, should operate in the thermal-epithermal neutron energy spectrum and should be hydride moderated. The resulting reactor is of small size and light weight SNAP 2/10A and 8 reactors are in this category and are very similar in design.[1,2] The reactor core consists of a number of homogeneous uranium-zirconium-hydride fuel-moderator rods. The high content of hydrogen in the fuel results in a small, compact core. The SNAP 2/10A reactor envelope is about 20.8 in.* in diameter by 15.5 in. high; SNAP 8 is slightly larger. Heat removed from the core by low pressure (15 psi) NaK coolant is used (in Rankine systems) in vaporizing Hg in the boiler. The small size and resultant high-neutron leakage of the reactor core permits effective reactor control by means of movable drums in the beryllium reflector. This external reflector control feature preserves the compactness of the reactor and results in a mechanically simple and reliable control system.

A number of interdependent factors play roles in determining the specific power capabilities of SNAP type reactors. Reactor stability, operating temperatures, fuel life, and available reactivity control are but a few. The S2/10A and S8 reactors are capable of meeting the power demands which are expected to develop for space stations in the near future.

The Hg Rankine power cycle offers the advantage of high thermodynamic efficiency and exhibits the smallest area requirements per unit power output of

*With control drums full out the envelope diameter is 23.1 in.

any conventional power plant thermodynamic cycle. It is for these reasons that Rankine cycles have historically been chosen for high performance nuclear and solar power systems. The essential items of equipment for such a system are the boiler, radiator-condenser (RC), turbine, alternator, and mercury pump, as indicated in Figure 2. Liquid mercury is supplied by the pump to the boiler where it is vaporized. Additional heat is added to superheat the vapor thereby minimizing the possibility of turbine blade erosion due to liquid carryover. The superheated vapor expands adiabatically through the turbine to a low pressure, with that turbine extracting energy from the flowing vapor stream. The energy is then converted to electrical power by means of an alternator. Mercury exhausting from the turbine is condensed and subcooled in the RC after which it flows to the pump suction, thus completing the cycle. In the NPP-MR system the turbine, pump, and alternator constitute a single unit called the Combined Rotating Unit (CRU.) The present CRU is suitable for 3 kwe service, and has been operated as high as 5 kwe.

B. PLANT RELIABILITY AND LIFE

For manned space stations, reliability is a prime consideration. There are well accepted methods for prediction of power system reliability based on the individual reliabilities of the system elements. Human presence in the space craft will effectively increase system reliability, since to some degree testing, maintenance, repair, and replacement of certain parts (particularly electrical and control components) will be possible. Design objectives and component allocations for reliability of a nuclear space power plant are predicted on achieving an overall system reliability of 0.95 - 0.99, which seems to be in the range of manned space station requirements. The demonstration of reliabilities in this range at a reasonable confidence level for a particular system, however, is very expensive since numerous replications are required. This is illustrated in Figure 3 for the case of a 15-kwe system consisting of three 5-kwe modules and one standby unit.

In order to achieve high reliability at an early date, it is desirable to adopt a modular approach to build up high powered systems using SNAP components already developed. Also, greater reliability can be achieved early through the use of increased design margins, quality control, maintainability, and increased redundancy in system components. An example of improving reliability through using large design margins is the provision of a

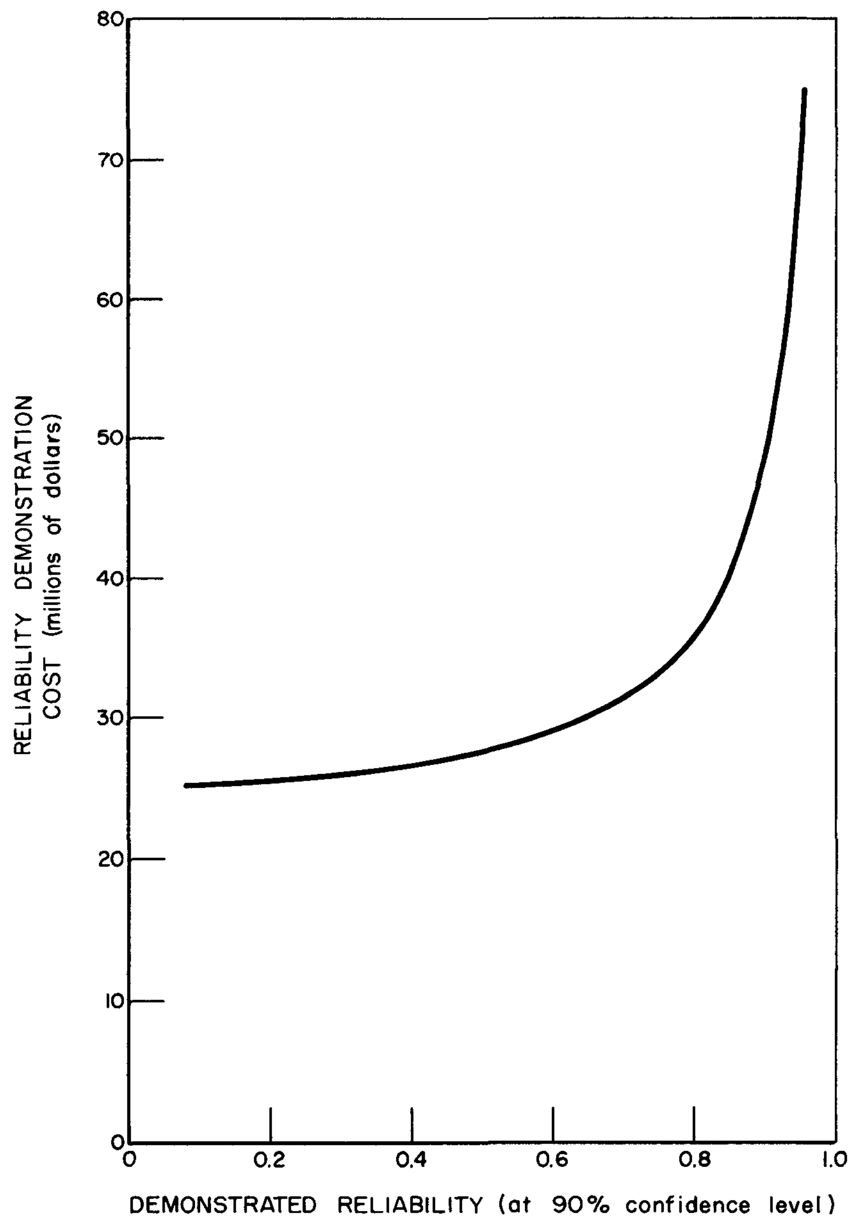


Figure 3. Reliability Demonstration Cost

4 σ stress margin against structural failure due to all critical loads and operating conditions. Another illustration is the practice, in sizing R/C area, of providing a 3 σ overall heat transfer margin based on specified tolerances in flow regulation, material properties, etc.

Use of multiple PCS modules provides redundancy which will allow continued operation at less than rated power in the event of failure in a module. The use of one or more standby units in excess of those needed for the design power level can considerably increase the reliability of providing full power during the mission, while increasing total plant weight by a small percentage. These and other design characteristics of multiple systems are discussed in more detail in Part IV.

The effectiveness of the redundant loop approach in increasing system reliabilities is illustrated in Figure 4a. The curves are based on 5-kwe module power rating and tentative NPP-MR potential reliability objectives shown in Table 1. Information relative to the development of these curves is given in Appendix B. For a given reliability of each 5-kwe PCS module, the reliability required of the reactor and primary loop to achieve overall reliability of 0.98 is shown in Figure 4b, assuming one redundant PCU in each system and the NPP-MR reliability objectives. The minimum design objectives for major parts of the system are summarized in Table 1. These values represent reasonable goals which probably can be realized during the normal course of development activities.

An important factor in power plant reliability is the reactor. The tentative SNAP 2 reactor-control near term design reliability objective is 0.977. Significant strides have been made toward demonstrating the reliability of the reactor and its control system, as discussed in VI. Programs are underway to further increase SNAP 2/10A and 8 reactor reliabilities by providing generally greater design margins and total or partial redundancies in items such as startup programmer, startup and control drum release and drives, temperature sensor-switches, controller, and safety circuits. Excess reactivity available over the reactor design life provides, in effect, a redundancy or surplus of fuel elements in that some may fail without resulting in unacceptable loss of reactivity. A similar reliability picture exists for the control drum system. Manual override and switching provisions add further reliability. Still further increases in

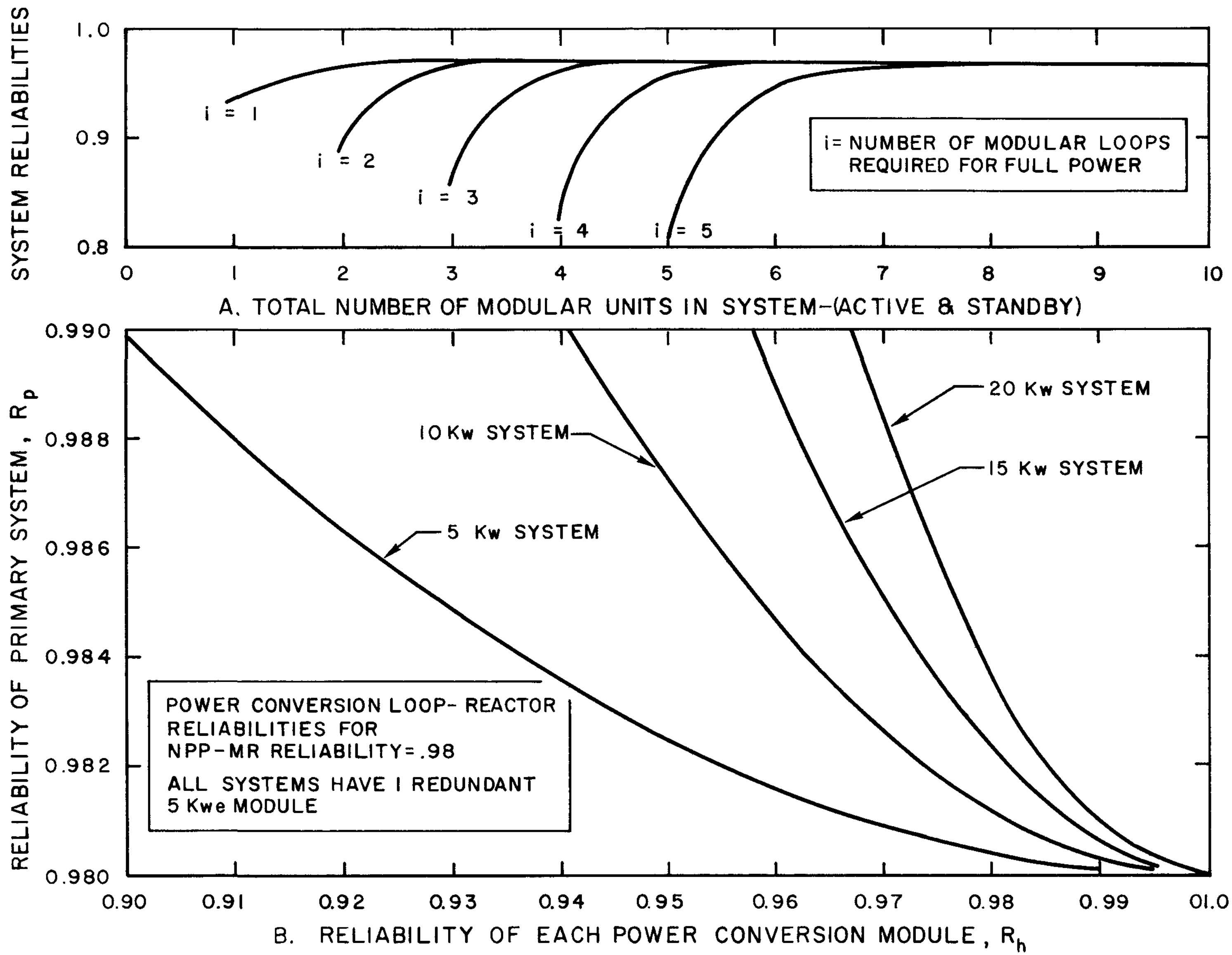


Figure 4. Reliability of Modular Systems

design reliability may be obtained using redundant reactors. Design layouts of dual SNAP 8 units have been made, and the weight penalty was found to be about 2,000 lb. Finally, the use of passive reactor control for long-term operation will further improve reliability.

TABLE 1

NPP-MR RELIABILITY OBJECTIVES

	Early Program Objective			Estimated Potential Reliability		
	Startup	90-Day Endurance	1-Year Endurance	Startup	90-Day Endurance	1-Year Endurance
Reactor-shield and primary subsystem	0.9901	0.9936	0.9744	0.9999	0.9992	0.9966
Power conversion system	0.9748	0.9819	0.9789	0.9995	0.9965	0.9858
Structure radiator condenser assembly	0.9968	0.9982	0.9928	0.9999	0.9996	0.9983
Startup control	0.9789			0.9995		
Steady-state control		0.9894	0.9579		0.9931	0.9724
Total system	0.943	0.964	0.861	0.9989	0.9984	0.9536
Total system with redundant startup and steady-state controls				0.9994	0.9952	0.9799

Recent studies indicate this control mode is effective and does not cause excessive swings in operating temperatures and other characteristics.

The factor that controls power plant life is the reactor, assuming that adequate shielding against meteoroid puncture is provided. (There is some weight penalty involved in establishing very high probability that meteoroid puncture failure will not occur). Useful reactor life depends on a number of features including reactivity characteristics, fuel temperature, fuel rod integrity, and power level. With the present SNAP 2/10A design, the life limitation is due to reactivity. Considerable extension of reactor longevity could be derived from changes in such variables as the control scheme (prepoisoning distribution) and fuel rod size. However, with the present reactor, a one to two year design life is reasonable for all power levels of interest for both SNAP 2/10A and SNAP 8 cores. Some power plant concepts suitable for long missions (> one year) incorporate reusable radiation shields. Eliminating the need to replace the comparatively heavy shield each time the power plant is replaced can allow a worthwhile reduction in logistics support costs. (Reusable shields will however incur an initial launch weight penalty.) For the power plants discussed in this report, shield lives in the range 5 to 10 years may be expected.

C. SAFETY

The nuclear safety aspects may be divided into several chronological phases: (1) transportation, ground handling, and launch; (2) reactor startup; (3) steady-state operations; (4) reactor shutdown; and (5) disposal. These phases are discussed in order below.

Nuclear safety problems during transportation, ground handling, and launch will be minimal. The requirement limiting nuclear operation (at very low power) prior to shipment results in an almost insignificant fission product inventory and associated radiation levels. During transportation and ground handling, mechanical control drum interlocks coupled with specially designed reactivity protective devices and shipping containers will prevent the occurrence of accidental reactor criticality. During final countdown and preorbital flight, precautions ordinarily taken for range and flight safety will be adequate for public protection and (along with design safeguards) for operations personnel. Tests have shown that reactor criticality due to forced drum insertion from land impact (launch pad accident) of the unit is not credible. However, if the package impacted in water or other hydrogeneous fluids during a launch abort, and was immersed sufficiently, the reactor would most likely undergo a self-terminating power excursion. The maximum energy release from such an excursion would be ~70 Mws. Direct, prompt, radiation exposure of personnel from such an incident would be negligible because of the normal exclusion distance required. The closest possible operations personnel would be a distance of approximately 1400 ft from the launch pad. They would normally be housed in an operations building with a self-contained ventilation system and walls 1 ft thick or more. If these personnel were outside the building and directly downwind of the reactor, they could receive a maximum of 2 rem from external cloud dose, and the total potential thyroid exposure due to inhalation would be 19 rem. These doses are not excessive. The corresponding unattenuated external and inhalation doses at a range of 10,000 ft are 0.2 and 0.9 rem, respectively. Launch aborts leading to downrange ocean impacts could also result in similar nuclear excursions, but the general absence of population would preclude significant hazards.

Both mechanical and electrical interlocks will restrict control drum rotation during launch until orbit attainment, at which time the normal reactor startup would be initiated under the cognizance of the station operator. Control drum lockout pins will be explosively removed as part of the startup sequence. Startup of the reactor will be done with all drums actuated simultaneously. This serves to minimize shielding requirements and provides redundance. The system is designed to allow manual override of the control drums at any time. The electrical controller gear will desirably be located in the manned compartment, so that it may be easily replaced and maintained without system shutdown.

Redundant temperature instruments and controls are provided for reactor control (see Section IV-B). Either of these instruments may be selected by the station operator to provide the drum "in" or "out" signals sent to the independently powered controllers. The high level of redundancy in this control system should prevent any power or temperature overshoot. If such an unlikely event should occur, the information and alternatives provided the operator via a single control console, combined with the relatively long time (several minutes) available for corrective action to be initiated, would prevent the occurrence of any mission damaging reactor excursion.

Radiation shielding must be provided for protection of the astronauts during the mission. No permissable radiation dose for manned space flight has been formally established by any government agency; however, biological tolerance limits to radiation exposure have been fairly well defined. Whether or not a space station employs a nuclear power plant, a radiation problem exists because of the environmental radiation belts present in the space environment. It is expected that for space stations with NPP-MR, optimum (with regard to weight) shielding against space and reactor radiation will result in the astronauts receiving a much higher radiation dose from the environment than from the reactor. Discussions of the biological effects of radiation and the space environment are presented in Appendix C. The actual design of radiation shielding is discussed in Section III of this report.

After the useful life of the nuclear plant is over, the power package could be separated from the manned space craft by cold gas jets and disposed of by injecting into a much longer life orbit. A new power system would then be installed in its place. Ultimate reactor shutdown can be assured by manually controlled reflector ejection. Disposal and subsequent decay of the spent power plant poses the greatest potential safety problem. It is possible to transfer the spent plant to a long-lived orbit to allow radioactive decay of fission products.

The plant might reenter the atmosphere after a shorter time either due to malfunction or as part of the disposal plan. With employment of one or more of several possible positive means of core disassembly-fuel element release, fuel element burnup is fairly certain. Even without assured burnup, the hazard is not significant as indicated in Figure 5. These curves are based on the very conservative assumption that the reactor is disassembled but not burned up during reentry, and that the dose is due to the exposure of a man to a whole fuel element at a distance of 1 ft for one hour. The ultimate reactor shutdown and disposal method will await more detailed Aerospace nuclear safety studies evaluation of specific space station operations.

D. MECHANICAL CHARACTERISTICS

The power plant package must be designed to withstand a variety of load conditions and fall within certain structural and stability constraints when integrated with the vehicle. The reactor is normally positioned in the system in such a fashion that radiation will not be scattered from other parts back into the space station. This normally places the reactor at the far end of the power package from the station (see Figure 1). Contiguous to the reactor is the shield, and the remainder of the system then lies between the shield and the manned craft. SNAP 2 flight system engineering experience indicates NPP-MR's are capable of meeting all expected mechanical interface requirements and structural and stability constraints.

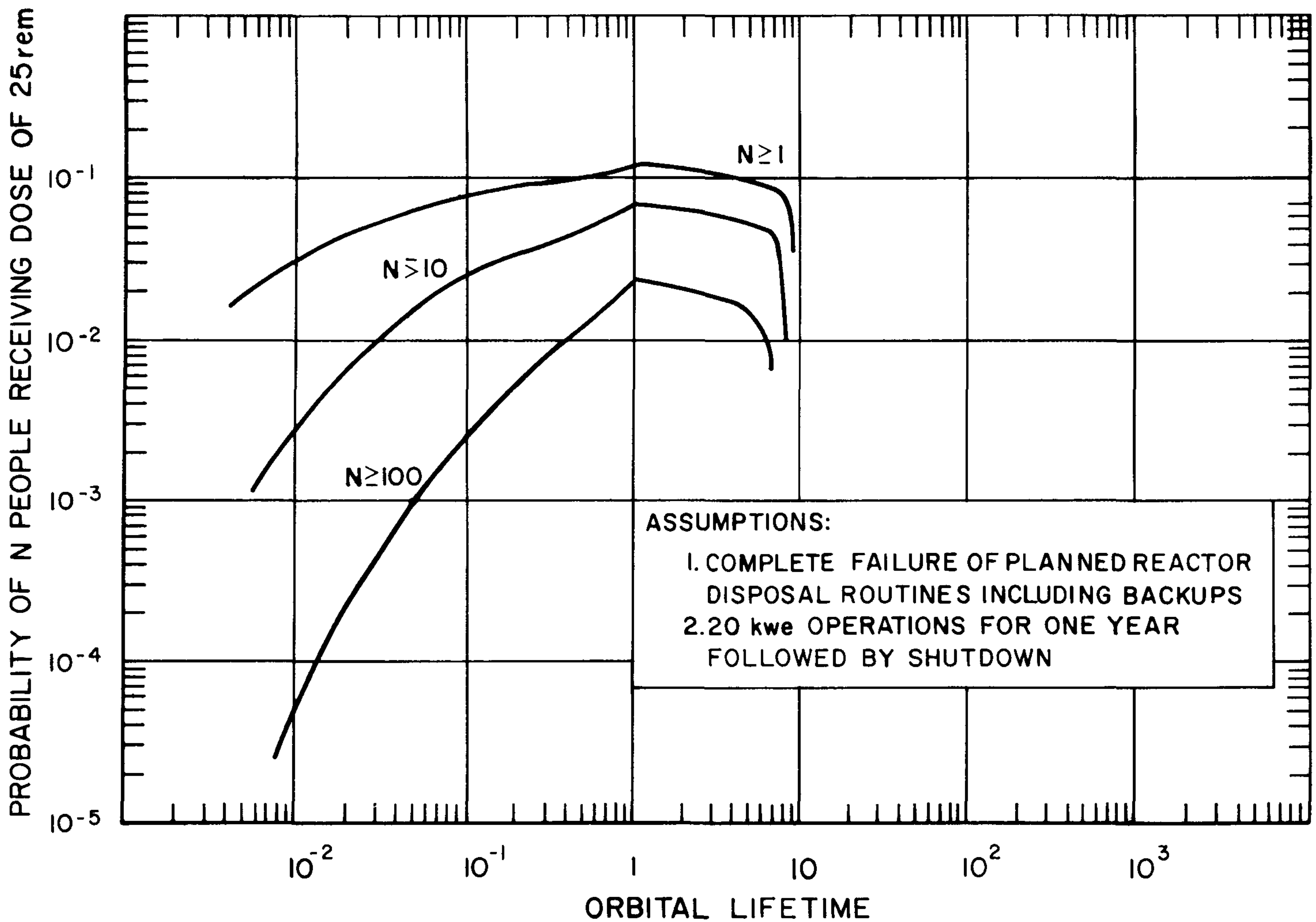


Figure 5. Improbability of Reactor Disposal Hazards

The sequence of events from launching through long-term operation in orbit results in a variety of design environments for the power plant. The structural loads encountered during the early phase of flight include lift off shock, vibration, and acoustical noise. In the next flight phase wind loadings occur, giving rise to an angle of attack combined with high dynamic pressure — these result in comparatively high bending loads in the power plant structure. After completion of this flight phase, maximum acceleration is reached and temperatures of the structure rise due to aerodynamic heating. In studies of SNAP 2 launching of Atlas-Agena vehicle, it was found that maximum temperatures reach about 810°F for the case of an aluminum steel RC, and 680°F for a honeycomb RC. Radial differences in temperatures across the RC structure reach a maximum of about 300°F and 260°F for the honeycomb and aluminum steel units, respectively.

The structural integrity of the SNAP 2 flight system has been shown by component and system tests covering the envelope of environmental conditions represented by the combinations of loads previously mentioned. As discussed in subsequent sections of this report, the power package heights and diameters for manned stations will exceed those of the flight system. However, studies have indicated that the external loading and heating conditions outlined in the preceding text should be less severe with a Titan III vehicle than with the Atlas-Agena, and all present components and the overall system are capable of withstanding this environment.

After orbit has been established, system startup will begin and the relatively slow rates of temperature increase in different parts of the system will preclude adverse thermal stresses. During steady-state operations, some components will experience cyclic temperature swings of as much as 50 to 60°F if the station is traveling in a sun-shade orbit. It is easy to design these components with a safe margin against thermal fatigue. Also, there will be small vibration-induced loads due to expected CRU rotor imbalances (approximately 600 cps). However, these induced loads are small and may be isolated to avoid design problems.

The influence of powerplant angular momenta and torques on overall space station stability should be very small. The spinning axis angular momentum of any spinning stations will be so large that any effects due to the powerplant on station stability will be negligible. For any inertially oriented space station, the penalty in stabilization system weight necessary to compensate for power plant effects would not exceed 100 lb, assuming the design of station and plant was done in parallel. Even comparatively small, zero-g, earth-centered stations should present no significant problem. NPP-MR torques and angular momenta may be constrained within allowable values by steps such as balancing multiple CRU's against one another, designing fluid flow paths in such a way as to have cancellation of angular momentum, and balancing magnetic torques of thermoelectric pump magnets against one another. These design techniques have been explored and found feasible.

As representative values, the principal steady-state angular momenta and torque for the SNAP 2 flight system (one CRU) are listed in Table 2.

TABLE 2

FLIGHT SYSTEM ANGULAR MOMENTA AND TORQUES

	Axis		
	Yaw*(X)	Pitch**(Y)	Roll(Z)
Angular momentum on 3 axes due to CRU and Hg and NaK flow (ft-lb-sec)	0.02	0.07	0.01
Maximum (periodic) torques due to system magnetic materials in earth field (600 n.mi. polar orbit) (ft-lb)	40×10^{-4}	2×10^{-4}	80×10^{-4}
Torques from CRU and fluid systems startup (ft-lb)	1×10^{-4}	0.4	2×10^{-4}

*Longitudinal, vehicle centerline axis.
**CRU axis.

Impulse torques from slight acceleration and deceleration of the CRU with load changes give ~ 0.02 ft/lb-sec x kwe (step load change). The worst case for the flight system was a 3 kwe step load change giving ~ 0.06 ft/lb-sec. For purposes of estimating the magnetic torque for conditions other than those in the table, the flight system could be regarded as being made up of two dipole moments. The first (permanent magnet) having a moment of 1100 ampere meters^2 along the lateral axis of the unit, and the second (permeable material) given by $M \sim 60 \times 10^4 B$ (ampere meters^2) where B is the external field along the longitudinal axis. The resulting net torque (T) would be given by:

$$\vec{T} = \vec{M} \times \vec{B} \quad . \qquad \ldots(1)$$

E. THERMAL CHARACTERISTICS

Thermal considerations play a major role in setting nuclear power plant design for space applications. The waste heat in the power cycle must be rejected by radiation to space. This process must occur at relatively high temperatures in order to have reasonable radiator areas and weights. From this requirement for a high temperature rejection of heat follows the need for comparatively high temperatures of reactor operation. Materials and reliability considerations indicate the maximum (NaK) coolant temperature should fall in the range 1200 to 1300°F, with the lower value preferred. In earth orbit, the plant receives direct radiation from the sun, reflected solar radiation from the earth, and thermal radiation from the earth. The effective equilibrium radiation-sink temperature depends upon the orbital path and the properties of the radiating surface; it generally falls in the range -200 to 0°F. The NPP-MR is designed to operate with a wide range of sink temperatures and with no preferential orientation.

An area related to thermal performance is the influence of rotating station "g" effects on system characteristics. These effects are discussed briefly in Appendix D. Although the presence of a "g" field is not required for NPP-MR operation, when it exists it can be used to advantage.

Because of the high temperature of the RC shell internal volume (i.e., the PCS region), special measures are required to reduce the flow of heat to the payload. Under the SNAP 2 flight program, a thermal barrier was developed which segregated the instrument compartment (at the base of the plant) from the balance of the system. The barrier allowed only 100 watts to be transferred into the compartment at design conditions.

F. ELECTRICAL CHARACTERISTICS

The basic output of the developed CRU's, which have permanent magnet rotor alternators, is 1800 cps, ac. This power can be used directly for lighting and heating needs since frequency is not critical for these applications. Studies indicate that a significant fraction of the electrical load could be rotating equipment for which 400 cps is preferred. Some of this is vital equipment which must be maintained even during shutdown periods, such as during reactor replacement operations. Studies also indicate requirements for a 28 vdc supply; thus the ac supply could be obtained from a 28 vdc inverter. Vital dc loads would be fed directly from a 28 vdc bus supplied by a bank of batteries which are recharged by a rectifier running directly from the CRU output. The inverter supplying vital ac loads would of course be one of the vital dc loads. A typical electrical diagram is presented in Section IV-B, Nonvital 400 cps loads could be supplied by a 1800/400 ac inverter tied directly to the alternator output.

The alternators would be connected three-phase, four-wire with isolated neutral. When multiple CRU's are to be used, all ac buses may be completely separate and redundant with load banks desirably split and run from the separate CRU's. During normal operation, this precludes the necessity for paralleling alternators and enhances power system reliability by the use of multiple buses. The separate distribution systems can be routed through a central switching arrangement with provision for load interchange. In the event of CRU failure, all vital equipment which was supplied from the CRU would continue to run from the storage batteries until the redundant CRU could be started and made to supply that bus (actuation of several minutes). All switching actions could be automatic with provision for manual override.

The anticipated range of possible power factors is 0.8 to unity lagging and the PCS can operate satisfactorily under these conditions. For reasonably constant loads and power factor, a capacitive reactance may be selected which will make possible voltage regulation within about ±5% with the present CRU. In order to prevent demagnetization of the permanent magnet rotor in the event of a short circuit transient, short circuit protection capacitors must be installed in series with the alternator output overload. Also, protection must be provided to rapidly remove short circuits or sustained overloads in order to prevent large speed changes of the CRU or damage resulting from thermal overload of the alternator. With the protective elements and for operating load variations between zero and full load and power factors between 0.8 and unity lagging, the worst voltage regulation in the 1800 cps bus with the present permanent magnet CRU alternator would be about 15%. Voltage regulation on the 28 vdc and 400 cps ac supplies could be about ±1%. The output frequency is maintained within ±1% of nominal by use of a parasitic load controller.

An alternate CRU approach presently being studied is a brushless electromagnetically excited machine. With such units, a PCS voltage regulation of ±1% may be achieved. While such units are not subject to demagnetization due to short circuits, like the PM machine they must be protected against sustained overcurrent resulting from overload or short circuits.

The electrical system outlined above is versatile and reliable. The load requirements for a particular station and mission may not demand such versatility, and a simpler system may be used. Sizing of the power supply is dependent uppon mission electrical load scheduling. From preliminary studies it appears to be most efficient to design for peak load requirements and to limit peak to average ratios by load programming in the station power system. However, detailed studies for a particular mission might point toward designing for average load requirements and using batteries to accommodate increased demands during peak periods. As previously discussed, batteries will be needed to supply power for vital loads when the reactor is not operating, as during power plant replacement periods. Batteries capable of furnishing unregulated dc for periods of reactor shutdown weigh approximately 90 lb/kw-hr. Secondary batteries designed for many discharge-recharge cycles at low depth of discharge weigh about 30 to 50 lb/kw-hr.

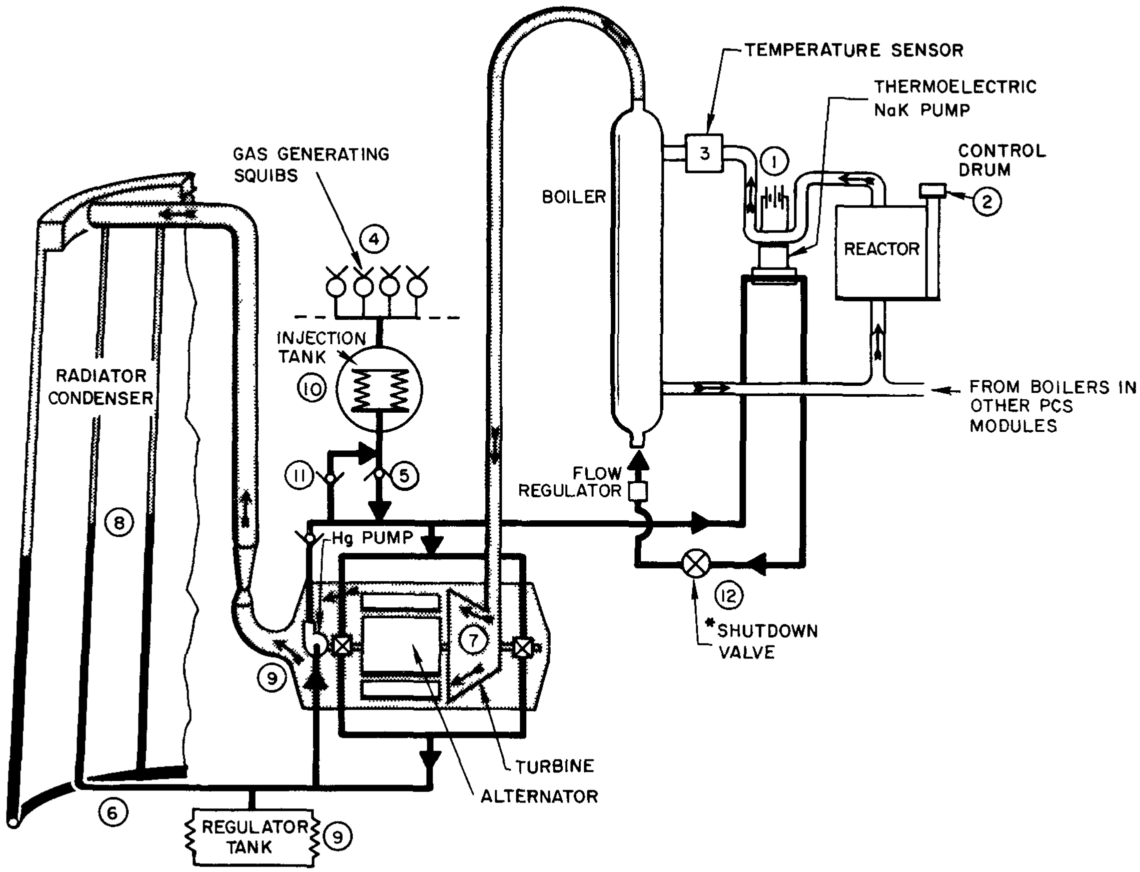
G. ORBITAL STARTUP, SHUTDOWN, AND RESTART

While it is not anticipated that system shutdowns and restarts will be required during normal operations in orbit, the NPP-MR system nevertheless has this capability. This capacity enables ground tests to be carried out using all flight system components and requires a minimum of auxiliaries. Detailed engineering analyses and component tests indicate the shutdown-restart may be carried out a number of times with high reliability. The equipment and procedures involved are discussed below.

NPP-MR startup is carried out in three phases — reactor startup, primary loop preheat, and power conversion system (PCS) startup. The overall scheme is depicted schematically in Figure 6. The reactor startup is accomplished

(1) BATTERY POWER SUPPLIED TO MAINTAIN 5 % FLOW DURING STARTUP

(2) A COMMAND STARTS CONTROL DRUMS STEPPING IN TO PREHEAT NaK LOOP



* FEATURES CONNECTED WITH GROUND TESTS OR EMERGENCY SHUTDOWN AND RESTART

(3) WHEN BOILER INLET REACHES 1160°F A SIGNAL ---

(4) FIRES A GAS GENERATOR SQUIB, PRESSURIZING THE INJECTION TANK

(5) MERCURY FLOWS THROUGH A CHECK VALVE & IS SIMULTANEOUSLY INJECTED INTO THE BEARINGS & THROUGH THE THERMOELECTRIC PUMP INTO THE BOILER, CAUSING NaK FLOW TO STEP UP

(6) MERCURY FROM THE BEARING DRAINS PASSES INTO THE BOTTOM OF THE R/C

(7) MERCURY VAPOR FROM THE BOILER SPINS UP THE CRU, & IS CONDENSED & COLLECTED IN THE R/C

(8) CONDENSING Hg PREHEATS THE R/C UNTIL THE CONDENSING PRESSURE REACHES 6 psia AT WHICH TIME,

(9) THE MERCURY PUMP PRIMES, THE INJECTION TANK IS EXHAUSTED & THE CRU PUMP SUPPLIES THE BOILER, THE Hg SUPPLY COMING FROM THE R/C. THE EXCESS FLOW COMING FROM THE R/C AS IT APPROACHES EQUILIBRIUM IS COLLECTED IN THE REGULATOR TANK

(10) AS TIME GOES ON, GAS IS BLED FROM THE INJECTION TANK THROUGH A FIXED ORIFICE

(11)* WHEN THE INJECTION TANK PRESSURE FALLS BELOW THE Hg PUMP DEVELOPED PRESSURE, A CHECK VALVE OPENS ALLOWING THE INVENTORY IN THE REGULATOR TANK TO FLOW BACK INTO THE INJECTION TANK, THUS PRIMING IT FOR A SUBSEQUENT STARTUP

(12)* SYSTEM SHUTDOWN IS ACCOMPLISHED BY SIMPLY CLOSING THE VALVE IN THE BOILER SUPPLY LINE. THE STEADY STATE Hg INVENTORY REMAINS IN THE SYSTEM DURING SHUTDOWN

7636-0059

Figure 6. Orbital Startup and Restart

by (1) an initial rapid insertion of the control drums to a position close to criticality, followed by (2) further insertion at a uniform rate until the reactor is slightly supercritical. This phase can be carried out in about 15 minutes without approaching any system limitations.

The primary loop preheat phase occurs from the time of initial generation of sensible heat by the reactor until boiler inlet design temperature conditions are attained. A small NaK flow (5%) is initially provided by the TE pump (using battery power) to assure a smooth temperature transient up to design conditions. Using the same uniform control drum insertion rate that was employed for reactor startup, preheat of the primary loop may be completed in 10 min without exceeding allowable temperature transients. With the combined rapid increase in NaK temperature and thermal lag of the "cold" elements of the T/E pump, a NaK flow of 60% of design rate develops by the end of the preheat phase. This effect considerably moderates the temperature transients resulting from mercury injection into the boiler during the final startup phase.

The final phase covers the time from the end of primary loop preheat until electrical power output is attained. In the PCS prior to startup, about 50 lb (normal steady-state inventory) of mercury is dispersed through the system and approximately 95 lb is stored in the injection tank. Upon injection, mercury flows both to the boiler and through the bearings and toward the RC. Liquid previously in the system is pushed ahead by the injected liquid or generated vapor. With plant sizes up to 15 kwe, startup of all active mercury loops commences simultaneously. In the 20 kwe case, however, it is necessary to delay startup of the fourth loop for several minutes to avoid exceeding allowable reactor temperature transients. The CRU spins up a short time (20 sec) after injection begins, but pressure in the injection tank is maintained above pump supply pressure for about two minutes so that all mercury is expelled from the tank. Vapor condensation causes preheating of the R/C, and as the saturation pressure increases the pump primes. When the mercury from the injection tank is exhausted, the mercury pump starts supplying the system flow.

As steady-state operation continues, the injection tank pressure starts to decay, and a ΔP develops across the check valves which separate the injection tank from the main system. Backflow occurs through one of the valves and mercury is slowly re-admitted to the tank, thus restoring conditions needed for startup. During periods of shutdown, the boiler inlet valve, which has been found to be the most satisfactory means for PCS shutdown, must be closed to prevent the introduction of mercury into the CRU cavity.

For each startup, one of the gas generators connected with the injection tank is actuated causing pressurization of the bellows and injection of mercury into the system. The gas generators are manifolded as shown to assure that the firing of one will not ignite others. Two small fixed orifices in the gas chamber walls will restrict gas leakage so as to maintain the needed injection pressure (600 psi) for the necessary duration (2.2 min). Subsequently, the gas will rapidly bleed to space allowing restoration of conditions for restart to begin. Weight of an injection unit equipped for 10 ground and 20 orbital starts is about 110 lb.

The soundness of this startup routine has been demonstrated in numerous tests of components and systems. CRU injection startups have been carried out in test rigs under a variety of conditions. Startup capabilities and stability of the integrated PCS have been verified in PSM-1 and -3 tests.*

A broad range of potential problem areas connected with start and restart has been investigated in depth, and the results indicate few special design measures are required to assure system restart capability. The main obstacles arise in connection with: (1) migration of liquid to the CRU cavity during periods of shutdown, and (2) mercury freezing during nonoperating periods in orbit. The first item is of concern because it was found that liquid present in the cavity at startup might cause serious consequences. On the ground, about 25 lb of mercury will be deposited in the CRU cavity before steady-state vapor flow begins. In orbit, for sufficiently long periods of shutdown, surface tension conceivably may cause some amount of liquid to migrate to the CRU. Possible trouble from these effects, however, is easily avoided. On the ground, a drain may be attached to the CRU to collect liquid entering the cavity. The liquid may be vaporized in some convenient way following injection. In orbit, time on the order of days is probably required in order for an important amount of liquid to move into the cavity. Installation of a small battery powered heating element in the cavity would elevate the vapor pressure of mercury there and prevent flow into the cavity.

The second item, mercury freezing during nonoperating periods in orbit, may or may not be a problem depending upon flight package overall configuration. If precautions are found necessary to prevent freezing prior to initial orbital start, the use of a mechanical heat shield (150 lb) or a sublimative, low ϵ coating coupled with ground preheat would appear to be satisfactory. The

*Discussed in Part VI.

weight of fixtures for electrical heatup would be prohibitively high. Aside from the period preceding initial orbital startup, no freezing problem exists unless the shutdown period (following operation) exceeds several hours. Then removable heat shield, electrical, or possibly chemical means for prevention of freezing must be considered.

H. OPERATIONAL CONSIDERATIONS

In this section are discussed briefly some aspects of operations involving the power unit. The considerations covered here fall into the areas of: (1) possible assembly or deployment of station in orbit, (2) startup and steady-state operations, (3) rendezvous maneuvers, and (4) removal and replacement of power plant.

Whether the power plant and space station can be launched into orbit as a single package depends upon factors such as pay load weight, orbital altitude, and booster capability. There have been estimates that the early "zero-g" space stations will weigh about 15,000 lb and be placed in a 300 mile orbit. It is probable that a package consisting of this size station and a 10 kwe (and perhaps larger) nuclear power plant could be put into orbit by a Titan III-C or Saturn IB-Centaur. After orbit is achieved, the power unit may be separated from the space station by a telescoping boom,* using tension cables for stability.

For large space station power plant weights or for long missions involving power plant replacement, joining of power plant to space station in orbit is required (at least until availability of Saturn V, Nova). For these cases, the vehicle carrying the powerplant aloft and joining it with the station can be either manned or unmanned. Several possible schemes for this operation are shown in Figure 7; also shown are two concepts for integrated station-powerplant launch packages. The first arrangement pictured has the advantages of: (1) unmanned launch, and (2) the propulsion system being available for disposal. However, for this case a completely new vehicle must be developed. The second and third arrangements pictured employ a Gemini vehicle. The advantage of unmanned launch is held by the second, while the presence of the

*In Part III will be discussed the considerations in determining optimum separation distance between space station and reactor for weight reduction.

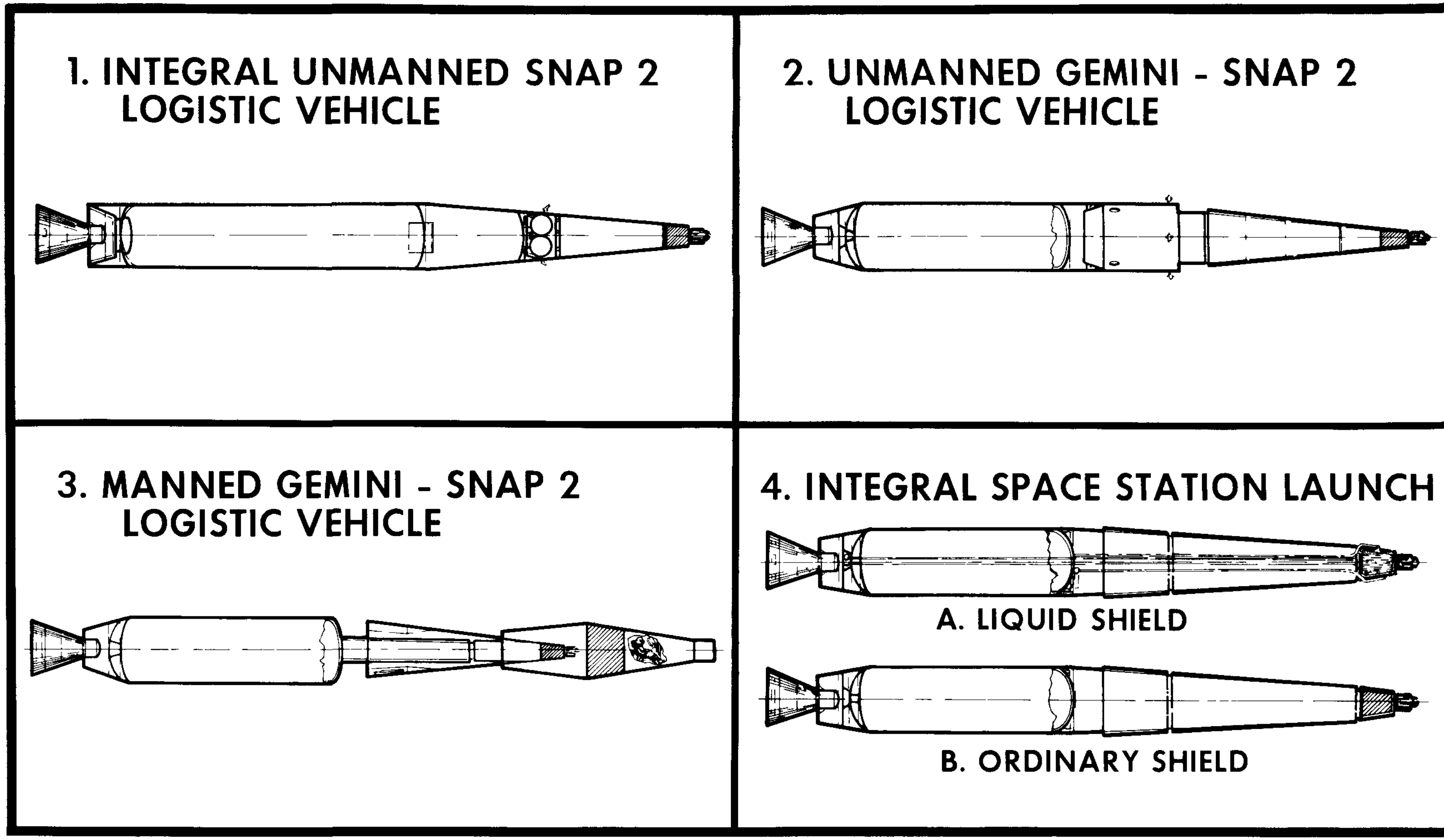


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Figure 7. Power Plant Integration With Station

astronaut in the third scheme upgrades the rendezvous and docking reliability. A structural disadvantage in either case is introduced by the logistic vehicle length. With the integral space station launch shown in the fourth frame, there is no manned launch or rendezvous requirement (for initial station assembly), but spacecraft weight and size limitations may exist, depending on station characteristics and booster capacity. An assembly operation is pictured in Figure 8 which also shows deployment of a telescoping boom arrangement. The power package is positioned on the front of the shuttle vehicle and is ready for mating as the station is approached. After mating and alignment, the structures are locked together and electrical and mechanical connections are made. Then the boom is extended to its locked position and the cables rigged to the proper tension.

To assist rendezvous and final mating of the power package to the station, special light weight tools to guide, position, index, and pin down the two bodies can be used through penetrations in the station wall facing the reactor. The astronaut may operate from a special compartment which is sealed and isolated from the rest of the station and which may be entered through an airlock. The man may also have a pressure suit, thus providing him with a doubly protective environment. The reactor control drums are locked in the out position throughout these operations. Similar operations may be carried out for other space station configurations such as spur and toroid-shaped.

The system characteristics during startup, the startup components, and the plant control system are discussed in II-G and IV-B. Completely automatic control of the reactor with manual override capability is provided for both startup and long term operation. All instrumentation control and electrical equipment except the alternator and parasitic load heaters should desirably be within the space station. They may be easily maintained and/or replaced by astronauts as required. The "shirt sleeve" environment will also enhance the reliability of this equipment. Operator and maintenance time during long-term operation will be minimal.

The information available (for example, reference 7 through 16) indicates the shuttle vehicle should have little difficulty in maneuvering to approach the station in the shadow cone of the steady-state station shield during the final phase of the rendezvous operation. The topic of rendezvous mechanics is taken up in Appendix E. A "wave off" during approach, if it occurs, will take

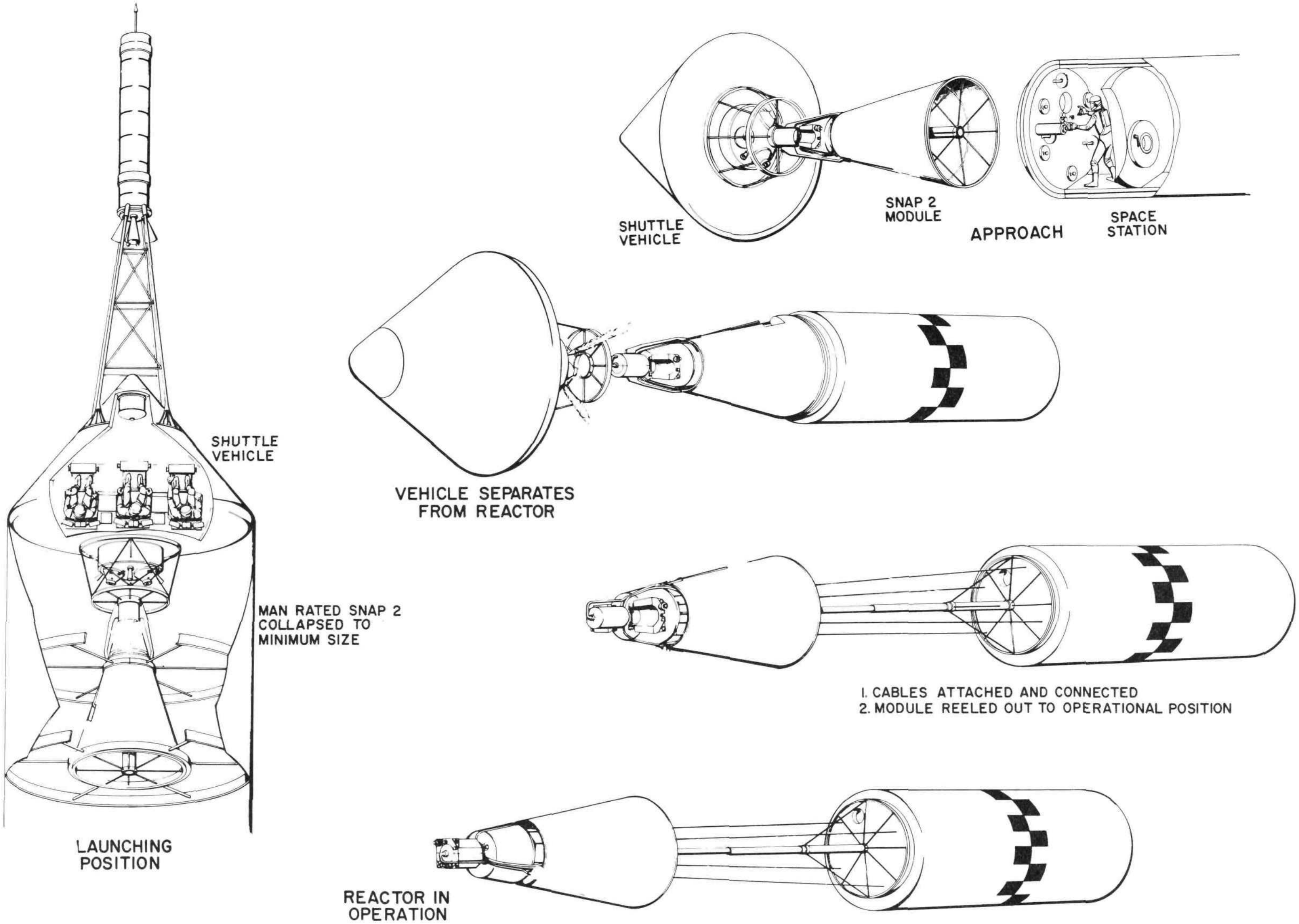

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Figure 8. Power Plant Space Station Assembly in Orbit

place early enough that any "fly by" would be at a safe range from the operating reactor. Turning to a potential hazard condition, if the space station is tumbling and the reactor is in operation, it is conceivable that astronauts leaving the station and escaping in a shuttle vehicle might receive a significant radiation dose. However, manual overrides for shutting down the reactor would minimize the radiation hazard. The condition described could well constitute a catastrophe and unless the station had redundant attitude control systems would be abandoned. Normal deorbiting of a shuttle craft might involve a velocity impulse of about 400 fps at an inclination of about 10° below horizontal. Under these conditions, astronaut exposure to radiation will be negligible.

While steady-state shielding of the operating reactor will protect the arriving personnel during normal rendezvous, additional shielding may be provided to allow for major guidance errors by astronauts and for system failures, even though it does not appear to be required. Particulars on the weight penalties associated with providing different safe regions for rendezvous maneuvers are provided in Part III. (The weight penalties may be reduced by having the reactor shutdown just before and during the docking phase. However, there accrues a reliability penalty for this reactor shutdown – restart approach. In addition, a weight penalty is incurred in the batteries required to supply power for periods when the reactor is shut down.) As will be seen in Part III, the station shield shadow regions available at fairly reasonable shield weights for a continually operating reactor will provide (for the expected velocities during docking phase) more than adequate time for astronauts to take any necessary corrective measures.

Upon termination of reactor operating life, the system is shutdown and readied for replacement. Batteries furnish the power needed while the nuclear plant is not in operation. As previously indicated, shutdown is accomplished by splitting away the reflectors from the reactor. Spring loaded fixtures would propel the reflector independently into space, thus ensuring against accidental criticality incidents. The manual override provision assures that the reactor will be successfully shut down.

For some long-term missions, economy may dictate the use of a power plant design having a reusable radiation shield. In such cases, steps would be taken, as necessary, to store the reusable shield temporarily before integration with the new power plant. Some conceptual designs which have been made for plants incorporating a reusable shield would require no special measures as the shield would be permanently attached to the supporting structure or station. After the final mechanical and electrical connections between power plant package and station are broken, the two bodies would be separated using cold gas jets. The new power plant package would then be joined to the station in a manner such as that previously described.

III. GENERAL SHIELDING DESIGN INFORMATION

A major fraction of total power plant weight is due to the shield. Shield weight is a strong function of many design considerations; among the more significant ones are: (1) space station configuration and plant integration, (2) allowable cumulative dose during mission, (3) reactor thermal power level, and (4) rendezvous maneuver. The parametric information furnished in the following sections will allow preliminary shielding estimates to be made for a broad variety of space stations, missions, and rendezvous requirements. These data, when coupled with the information of Parts II, IV, and V, will make it possible to compose realistic estimates of preliminary power plant designs for given space station applications.

A. INTRODUCTION

As discussed in Appendix C, protection against fast neutron and gamma radiation from the reactor must be provided. Several heavy metals suitable for gamma ray attenuation have satisfactory structural and thermal characteristics (viz., depleted uranium-alloyed with molybdenum, tungsten). Lithium hydride has proven to be a very satisfactory neutron shielding material, combining light weight with ability to moderate (by hydrogen atoms) high energy neutrons to thermal energies where they are captured by lithium, which has a high absorption cross section for low energy neutrons.

The discussion of shield design is facilitated by reference to the nomenclature indicated in Figure 9. Each of the two sections of the station shield consists of a layer of depleted uranium for attenuation of core gamma rays and a layer of lithium hydride for removal of neutrons. These shields must not only protect station personnel from radiation emanating from the core, they must also mitigate to tolerable levels the gamma radiation caused by: (1) the capture by uranium of neutrons at resonance energy levels, (2) the capture of neutrons by hydrogen in the LiH complex, (3) the NaK in the gallery region (boiler and TE pump), which is activated by neutrons during its passage through the core, and (4) the capture of neutrons by cobalt in the boiler structural material (Haynes 25). Furthermore, attenuation by the upper neutron shield must prevent the neutron activation of mercury in the boiler. If the mercury becomes radioactive, it would constitute a personnel hazard since it flows below the protective shielding.

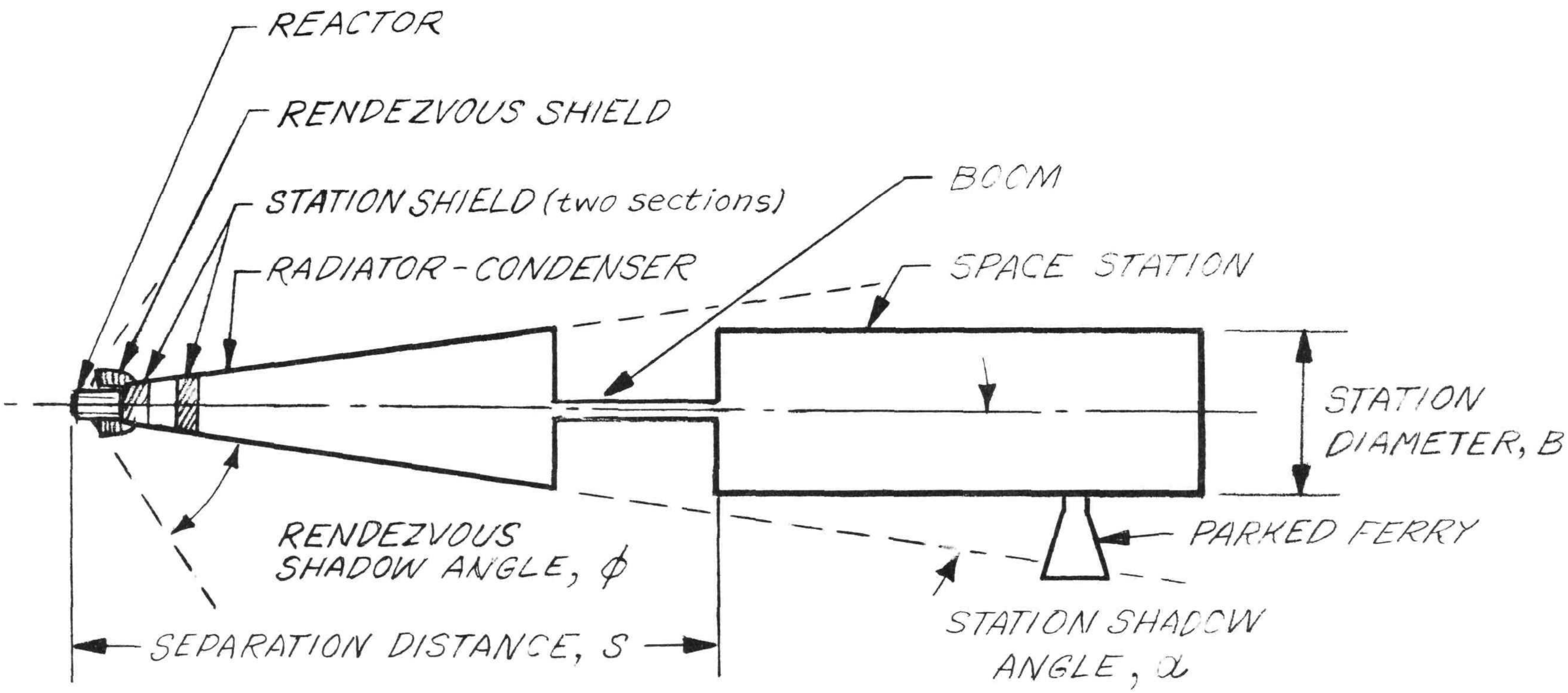

Figure 9. Shielding Nomenclature

To minimize weight, it is desirable that the diameter of each shield be as small as possible. Thus, the gallery should be of minimum height and the core section of LiH be of minimum thickness so that the lower section of the station shield will be as near the reactor as possible. The uranium of the core shield should be sufficiently thick to reduce core gammas to the desired level, but not so thick that the gamma source generated by neutron capture in the shield becomes of excessive strength. The optimum thickness of this uranium is about 3 in. The LiH in the core section of the station shield should filter neutrons to the point that the capture of neutrons by hydrogen in the lower shield and the activated mercury do not constitute important sources. The problem of neutron capture gammas from cobalt and mercury in the boiler may be eliminated by the use of borated 316 stainless steel for the thin structural canning material of the LiH in the core section of the station shield. As a conservative approximation, a thickness of 18 in. may be used for LiH in the core section for all power levels.

In the lower portion of the station shield, the thickness of uranium directly beneath the boilers must be selected (using curves presented in Section III-D) to attenuate: (1) core radiation not removed by the core shield, (2) NaK activation radiation, and (3) hydrogen capture radiation from the upper shield.* The remainder or "skirt" portion of the uranium layer is of different thickness, and it needs only to shield against the hydrogen capture gammas. The LiH in the lower shield supplements that in the upper shield to reduce the neutron flux to an acceptable dose level.

The envelope of the primary radiation source (reactor) which must be shielded is different for the SNAP 2/10A and 8 reactors. For the former, the core diameter — for which both neutron and gamma shielding must be provided — is 9 in. in diameter. With control drums — for which only neutron shielding is needed — the total reactor envelope diameter varies from 19.0 in for 5 kwe to 20.8 in for 20 kwe. Height of the 2/10A unit is 15.5 in. For the SNAP 8 unit the height and overall envelope diameter are approximately 22 and 26.6 in.

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*For preliminary purposes, the credit for gamma attenuation by LiH may be neglected

It is necessary for safety reasons that a shuttle craft or some sort of escape capsule be docked at all times, even when another vehicle is docking. This requirement imposes a shield weight penalty on small stations when the vehicle is docked at the side and protrudes from the station shield shadow as shown in Figure 9. As flux from the reactor impinges on the craft, scatter back into the space station occurs at an intensity of about 1% that of the flux incident on the vehicle. In cases where this scatter contribution is of significance, the direct radiation to the vehicle must be reduced by a "parking" shield. Also, additional shielding may be provided as insurance to protect the astronauts' support vehicles in the remote event that they should deviate from the station shield shadow during rendezvous. This topic is discussed in III-C.

Radiation flux levels in the space station depend not only on shield thickness, but also on power level (P), of course, and are inversely proportional to the square of the distance (S^2) separating the station from the reactor, i.e.,

$$D \alpha \frac{P}{S^2} , \qquad \ldots (2)$$

where D is the dose rate in mr/hr or r/hr. With the use of this proportionality, the application of shielding curves to be presented later is considerably extended. Thus, for a given allowable dose rate in the space station, the shield weight may be reduced by increasing the boom length to gain S^2 attenuation and reduce shield lateral dimensions. However, this adds structural and electrical cable weight.

B. BOOM OR EXTENDED STRUCTURE

As indicated by Equation 2, radiation intensity is degraded according to the inverse square of the distance from the source. Thus, the weight of normal shielding required to give a certain radiation level in the space station is lowered if the reactor separation distance from the plant-station mating plane is increased by means of a boom or extended structure. The reduction in shield cone angle with increased separation distance also lowers the shield weight. However, the added weight of boom or extended structure tends to compensate for shield weight reduction. Additional consequences of the increased separation distance are increased weight of electrical distribution cable and possibly decreased voltage regulation and transmission efficiency, depending on cable design.

A small reliability penalty is incurred with use of a boom. The boom must be able to telescope, being in the collapsed condition during launch and being extended for normal operation in orbit. For extension lengths under about 20 ft, the weight of a boom about equals that of a false structure. For extension lengths greater than 20 ft, false structure is lighter but results in a greater launch package height. A boom and cable array is schematically illustrated in Figure 10. The cables provide tension and shear stabilization for the connecting structure. The structural design of the boom is based on disturbing loads, due to docking, of 1/4 g in the lateral direction and 1 g along the longitudinal axis. During launch, the boom is collapsed and carries no load. The separation distance for optimum weight compromise between boom and shield is illustrated in Figure 28 (Section III-D).

C. RENDEZVOUS SHIELDING

In Appendix E the general aspects of the rendezvous maneuver are discussed. It is shown that the information available indicates the shuttle craft should have no difficulty remaining in the shadow of the station shield. The docking phase begins with the commuter in a position relative to the station such as that indicated in Figure 11, point 0. Despite the expected high reliabilities and accuracy for propulsion, navigation, guidance, and control, it still may be deemed desirable by the user to provide radiation protection against the possibility of major error by astronaut or system failure. The information provided in this report will make possible the estimation of shielding requirements for any degree of vehicle protection during any assumed rendezvous "error maneuver." The particular and conservative "error maneuver" assumed for this report is described next. It is postulated that the vehicle: (1) departs from the shadow cone at a distance d off of the cone axis because of a propulsion system failure; and (2) travels parallel to the axis (broken line in Figure 11) at constant velocity v until, (3) reaching plane A. By this time the astronaut has taken corrective action and the vehicle rapidly accelerates backwards along the path. For relative velocities used in the docking phase, this assumed error maneuver allows from one to several minutes for corrective action to be taken. With the astronauts exposed to an unshielded reactor operating at P kwt (while outside of the station shadow of cone angle α) with no rendezvous shielding, the cumulative dose in rem, M, for the rendezvous error maneuver is given approximately by:

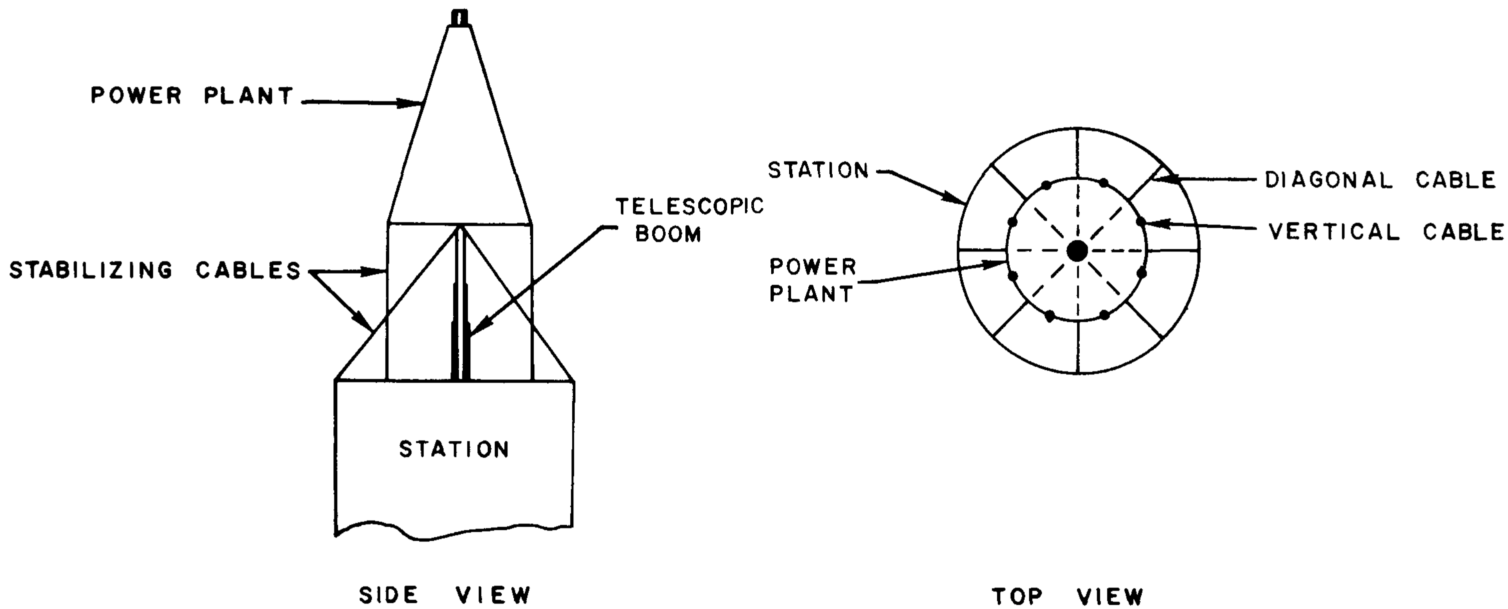

Figure 10. Extension Boom

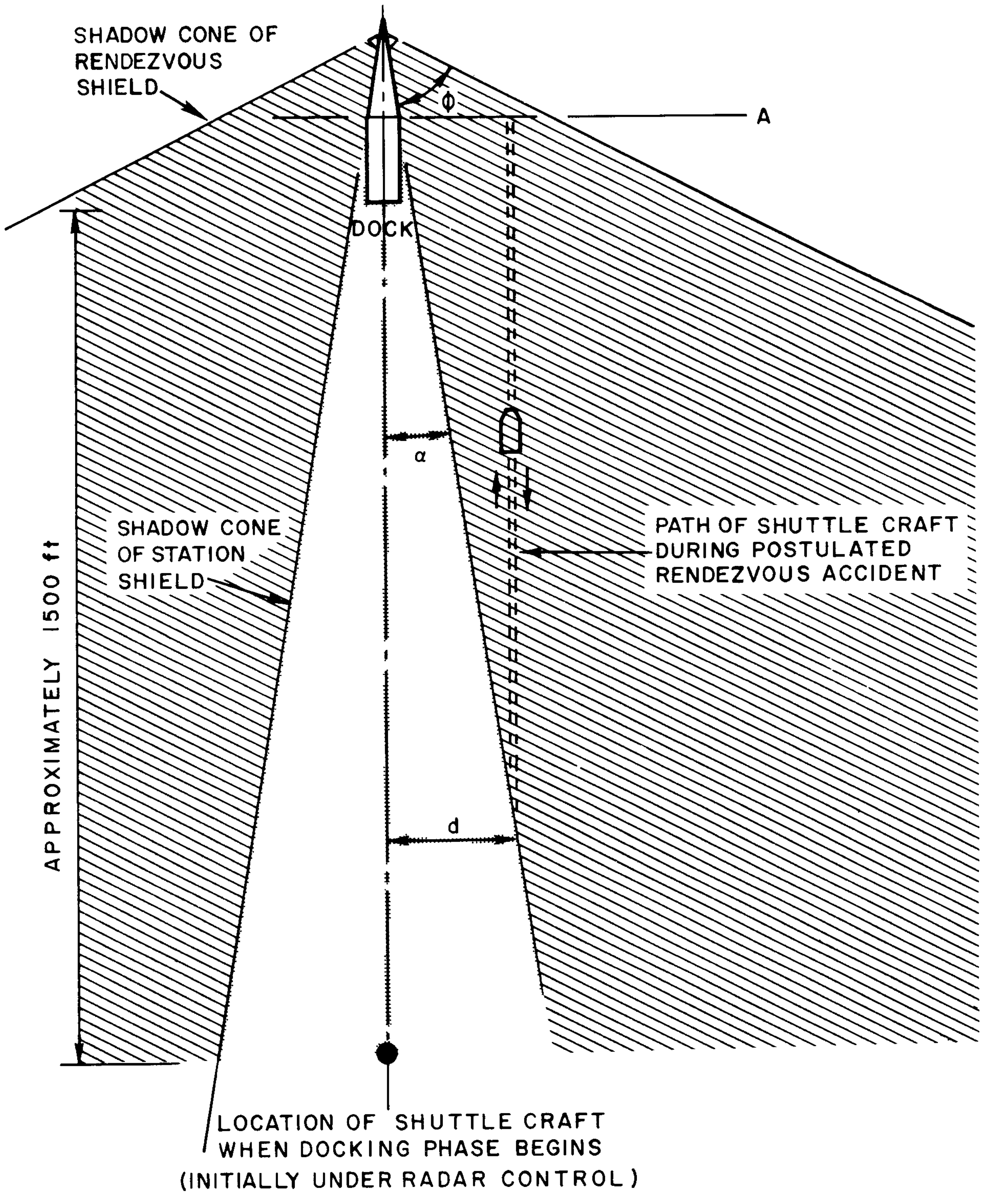

Figure 11. Rendezvous Maneuver

$$M \cong \left[\frac{178P}{vd} \quad \frac{\pi}{2} - \alpha - \tan^{-1}\left(\frac{S}{d}\right)\right] \qquad \ldots (3)$$

where S and d are in ft, and v is in fps. Solutions to Equation 3 are displayed in Figures 12a and 12b for two values of separation distance, S, between reactor and space station. Given in Figure 13 are the ranges, c, corresponding to different displacement errors, d, at which departure from the shadow cone occurs.

In Figure 14 a family of curves appear that give approximate radiation exposures occurring during a vehicle flight at velocity v which begins at distance q away from the reactor and proceeds along a radial path normal to the principal axis of station until the craft enters the steady-state shadow. "l" denotes the distance from the reactor at which the vehicle path intercepts the principal axis. Possible "terminal phase" maneuvers discussed in Appendix E could approximate such a vehicle trajectory. By adjustments of the variables v, d, q, and S, together with appropriate additions and subtractions, it is possible through the use of Figures 12 and 14 and Equation 3 to estimate the radiation dose accumulated during any arbitrary "error maneuver" for any reactor power. Knowing the exposure received from the bare reactor, it is possible from curves provided in the next section to determine the shield thickness required to reduce the total dose to the desired level. This same approach is generally applicable regardless of space station configuration or size.

For some arrangements, the station may have a "view" of the rendezvous shield and therefore be subject to radiation scattered from the shield. Gamma ray scattering will be negligible, but fast neutron scattering may be of importance. The neutron scattering may be approximately represented by a forward cosine distribution. The thickness of LiH to be placed in the line of sight between the basic rendezvous shield and the station may be selected using curves given in the next section. Where appropriate in the designs in this report, the scattered neutrons were attenuated so that their contribution to the exposed parts of the station added 10% to the normal station dose rate, i. e., 1 mr/hr.

If a rendezvous shield is used, the shield material contiguous to the reactor will produce a "vault" effect, scattering some leakage neutrons back toward the

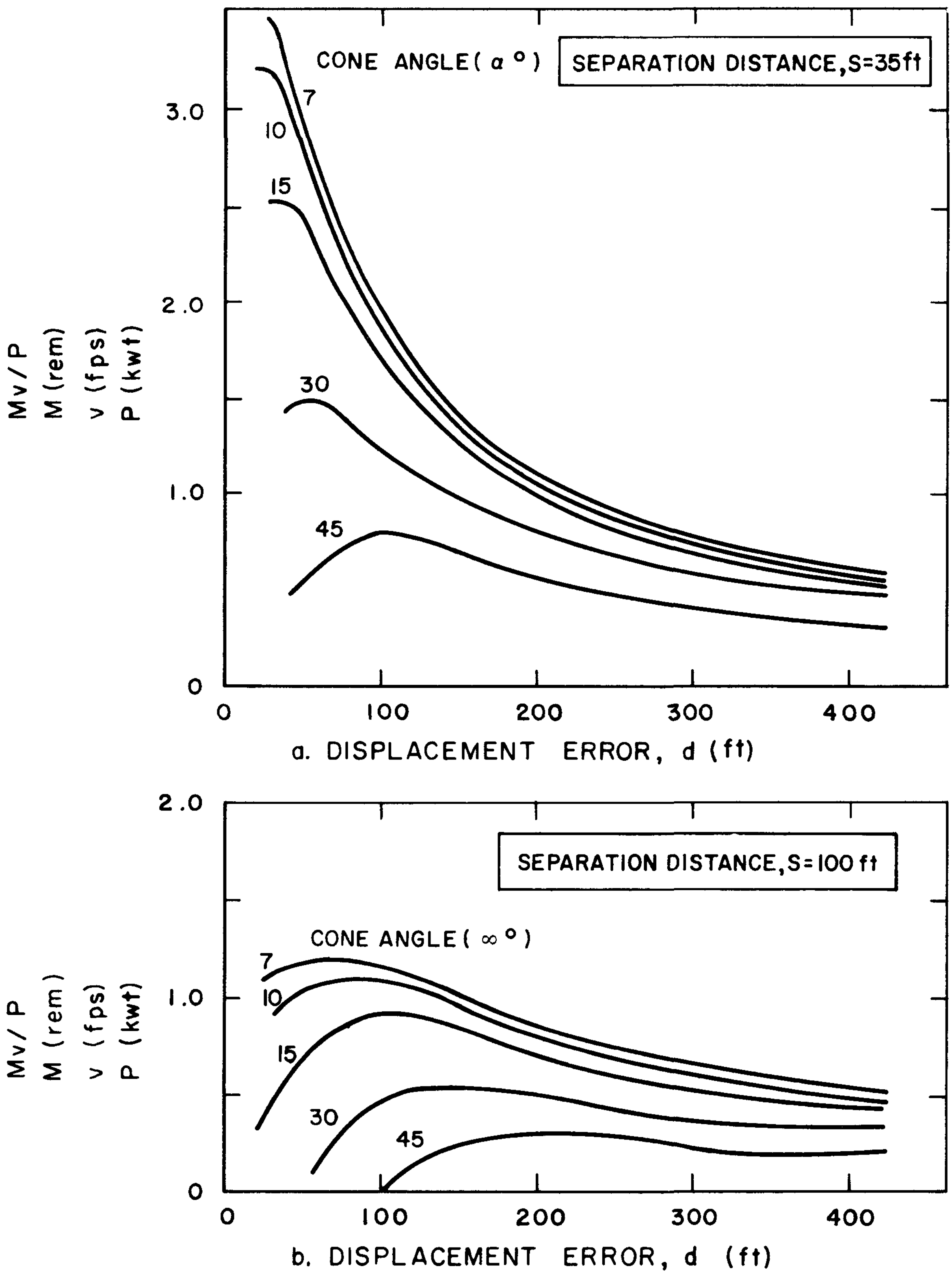

Figure 12. Exposure Due to Rendezvous Error

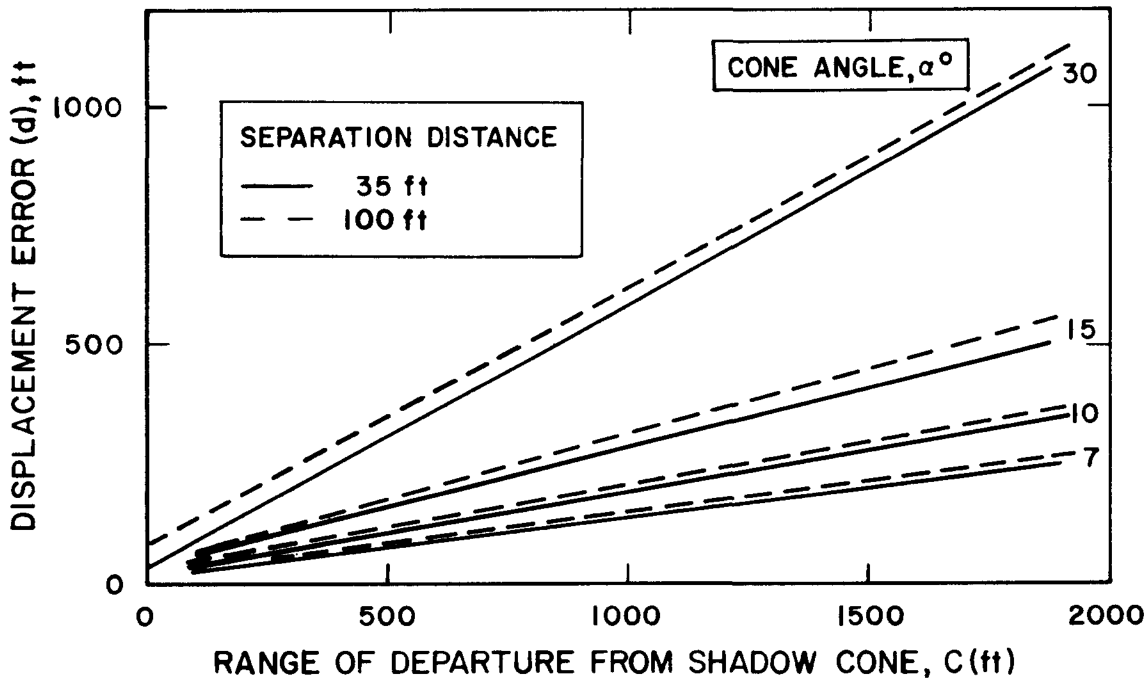

Figure 13. Range of Departure From Shadow Cone vs Displacement Error

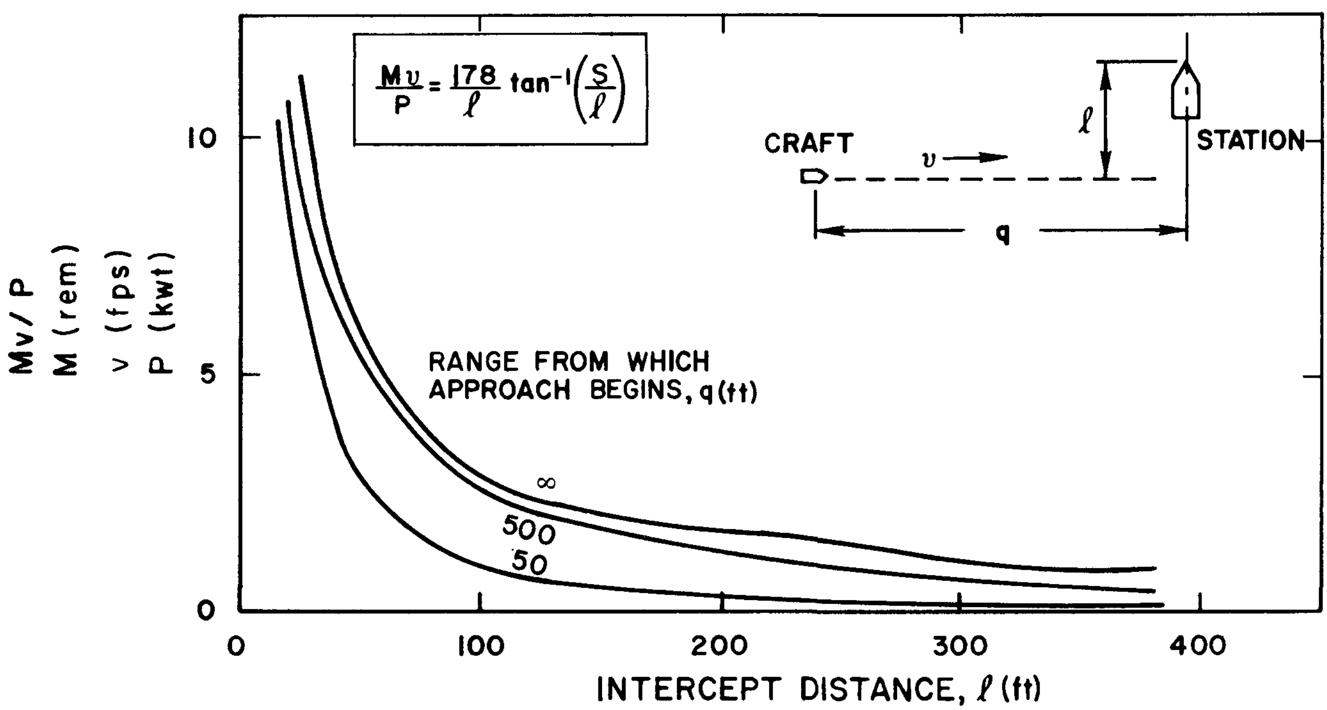

Figure 14. Exposure During Transfer to Shadow Cone

core. Calculations indicate the increased reactivity from this cause is small and will present no control or shutdown problems. Normal temperatures of components will be higher due to the rendezvous shield presence, unless special emissivity coatings are used for drums, etc. However, (90 day) component and materials compatibility tests at and above these expected higher temperatures indicate there will be no performance problems.

D. SHIELD WEIGHTS

Shown in Figure 15 are the design radiation dose rates that correspond to different mission times and cumulative steady-state exposures. The gamma and neutron station shield thicknesses required for various degrees of dose rate attenuation are shown in Figure 16. Similar curves for the rendezvous shields are given in Figure 17. The two sets of curves differ in that the thickness ration of LiH and U for minimum total weight is geometry dependent. The curves shown represent a preliminary effort at optimization.

Presented in Figures 18 and 19 are the station shield thicknesses required for different steady-state power levels. This information is predicated on the use of the split shield concept described earlier, and the total thicknesses given by the curves are divided between the upper shield and lower shield (see Figure 9) as noted on the figure. Figures 18 and 19 are based on a separation distance of 50 ft between bottom of reactor and space station mating plane. For other separation distances, an equivalent power can be calculated which will give the thickness required for a given dose. The equivalent power is given by (see Equation 2):

$$P_e = P_o \left(\frac{50}{S_o}\right)^2 , \qquad \ldots (4)$$

where P_e is the equivalent power, P_o is the operating power, and S_o is the separation distance in feet for the operating reactor. The weights of station shield and boom for different power levels and space station diameters are given as a function of S in Figures 20 and 21. The total weight of the station shields as a function of thickness is indicated in Figure 22. These values are based on gallery heights of 2 ft in all cases. The cone angle, α, is

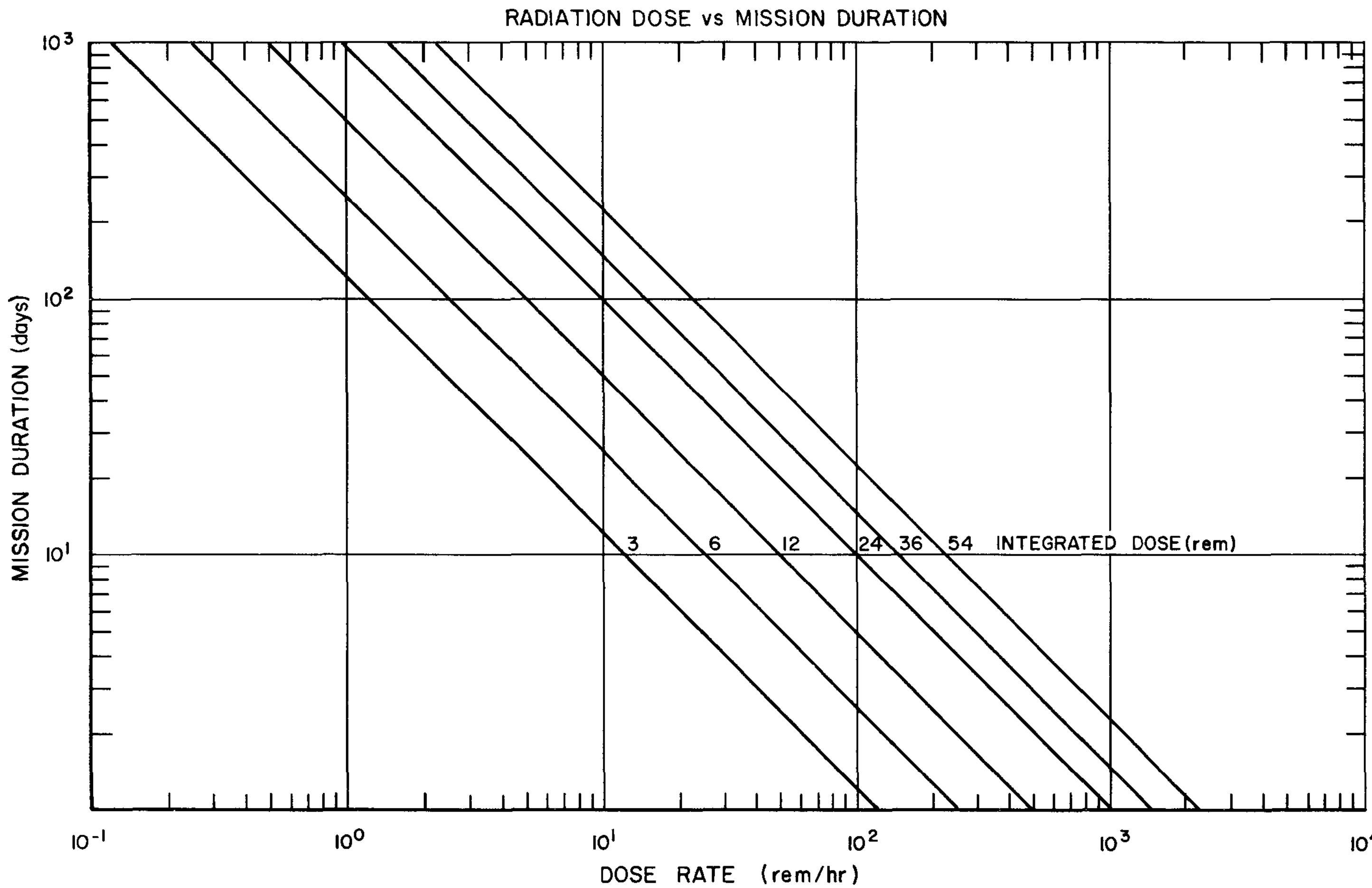

Figure 15. Cumulative Radiation Dose vs Mission Time

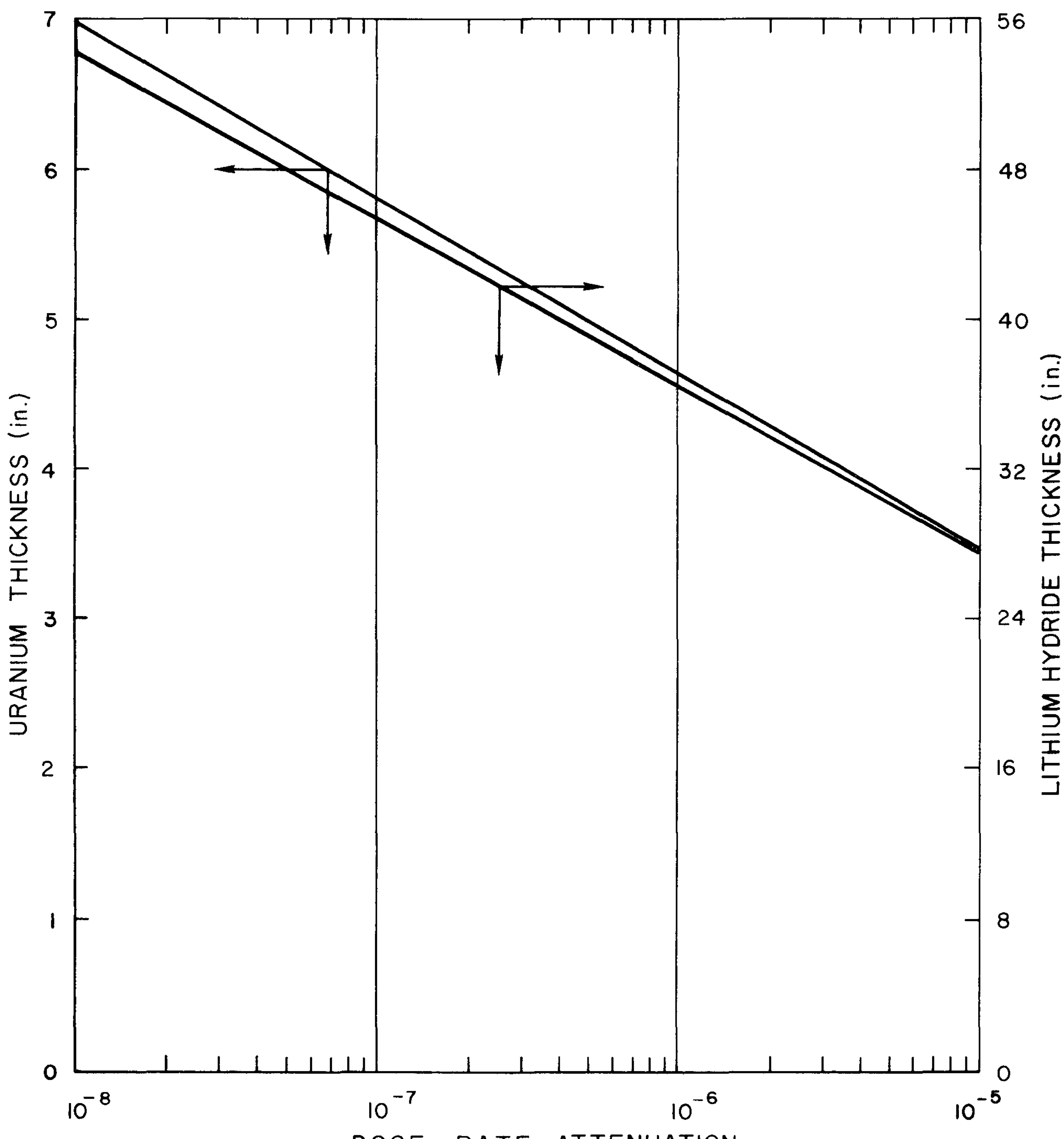

Figure 16. Station Shield Thickness vs Attenuation

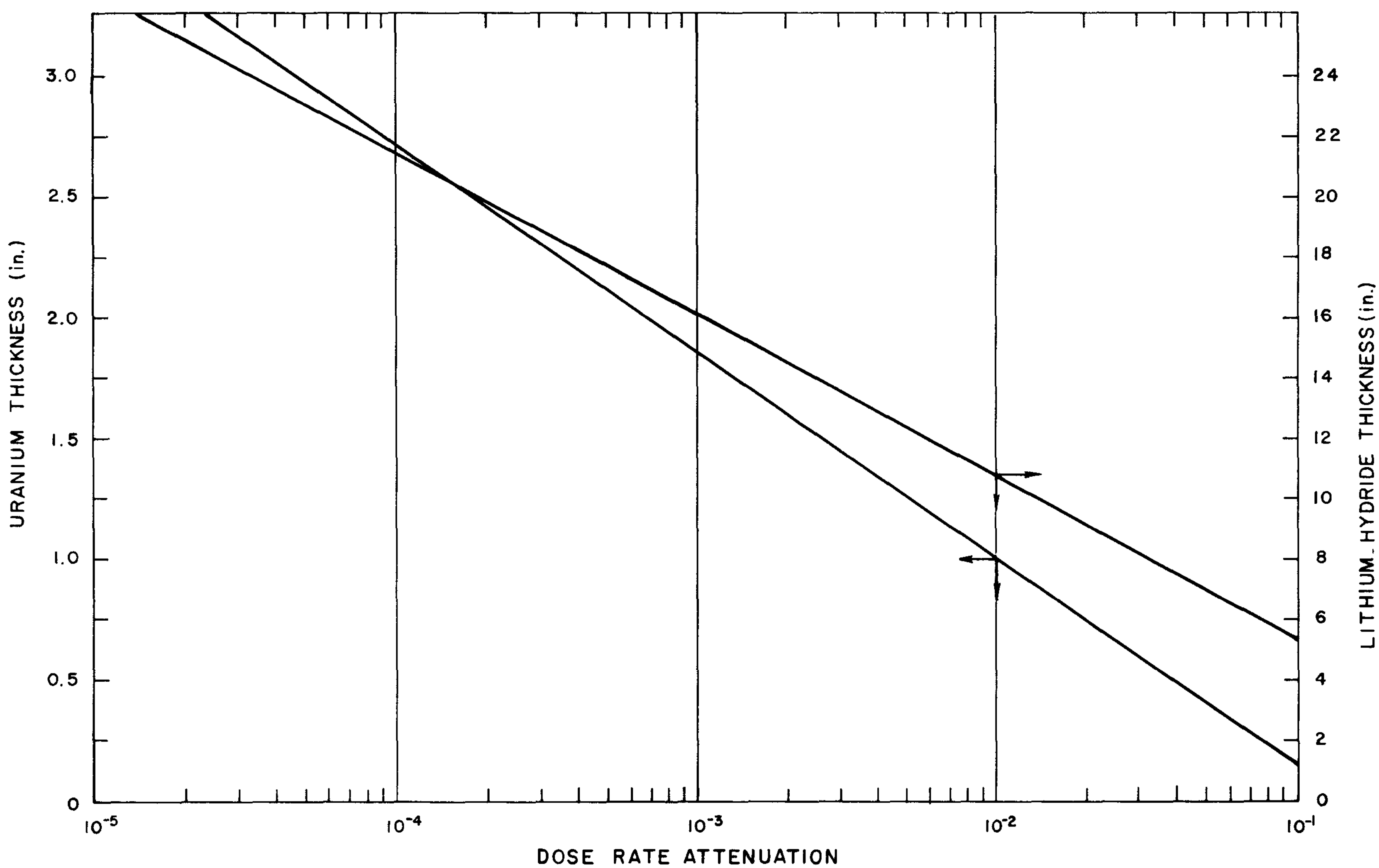

Figure 17. Rendezvous Shield Thickness vs Attenuation

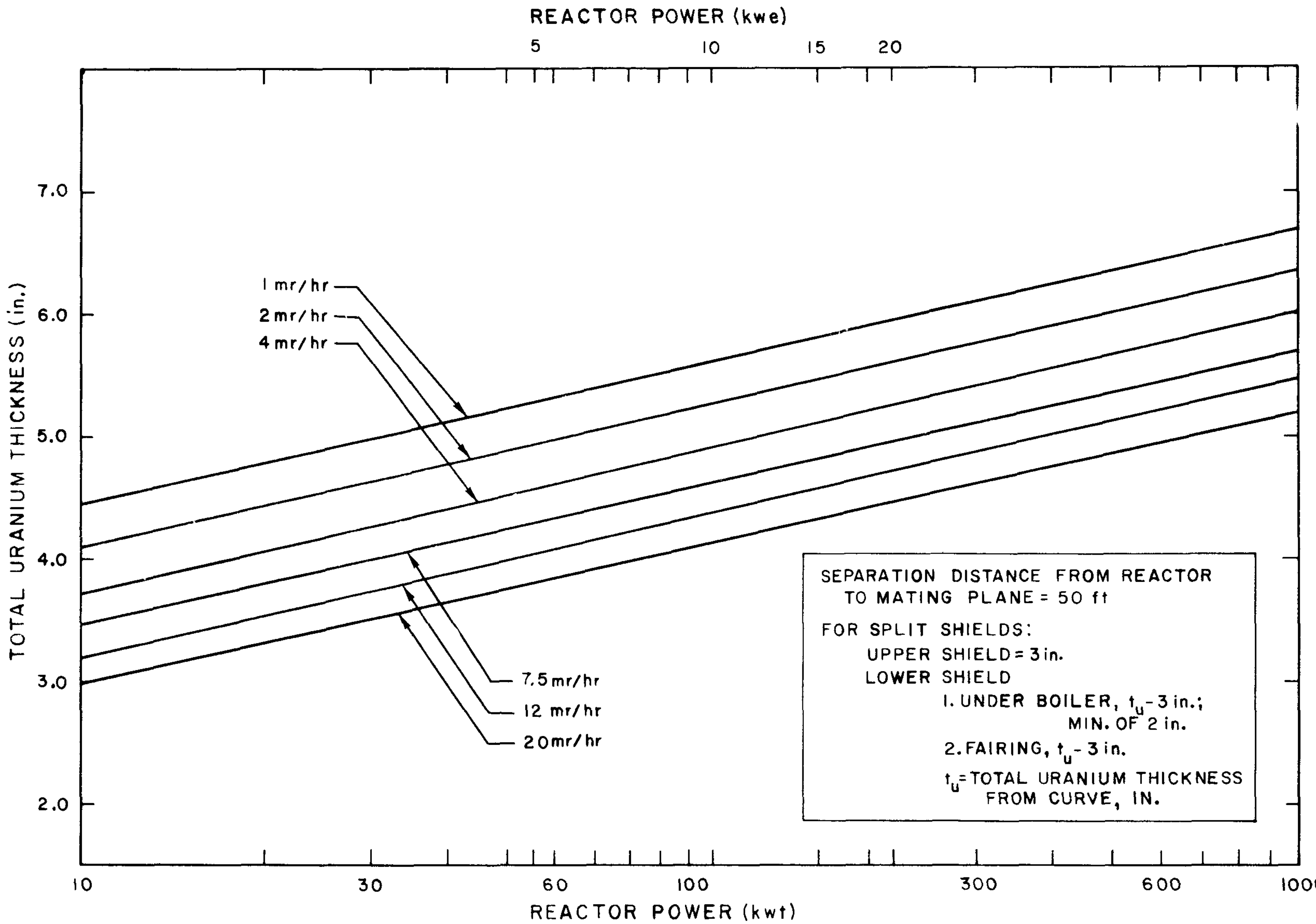

Figure 18. Gamma Shield Thickness vs Power

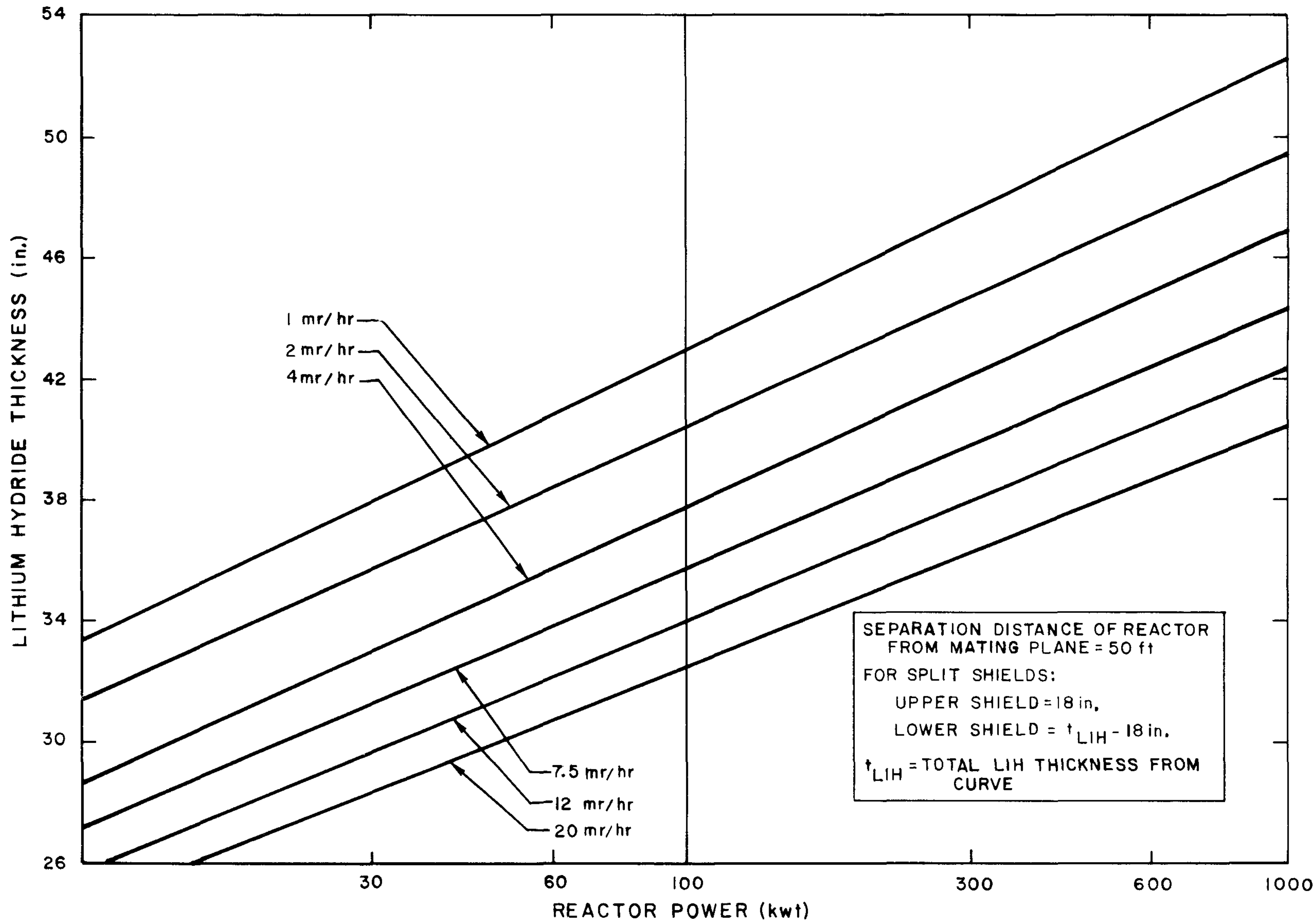

Figure 19. Neutron Shield Thickness vs Power

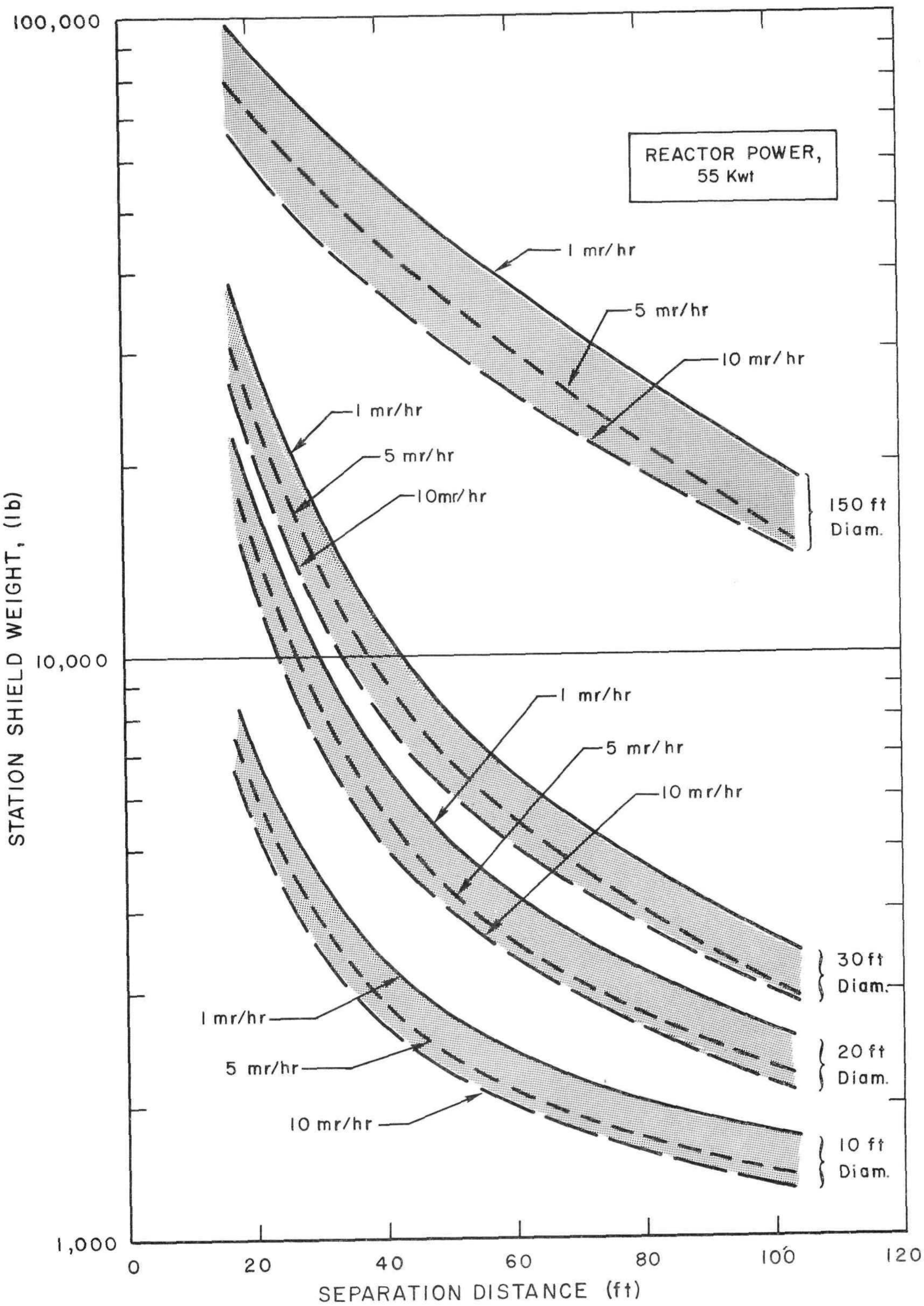

Figure 20a. Station Shield Weights vs Separation Distance

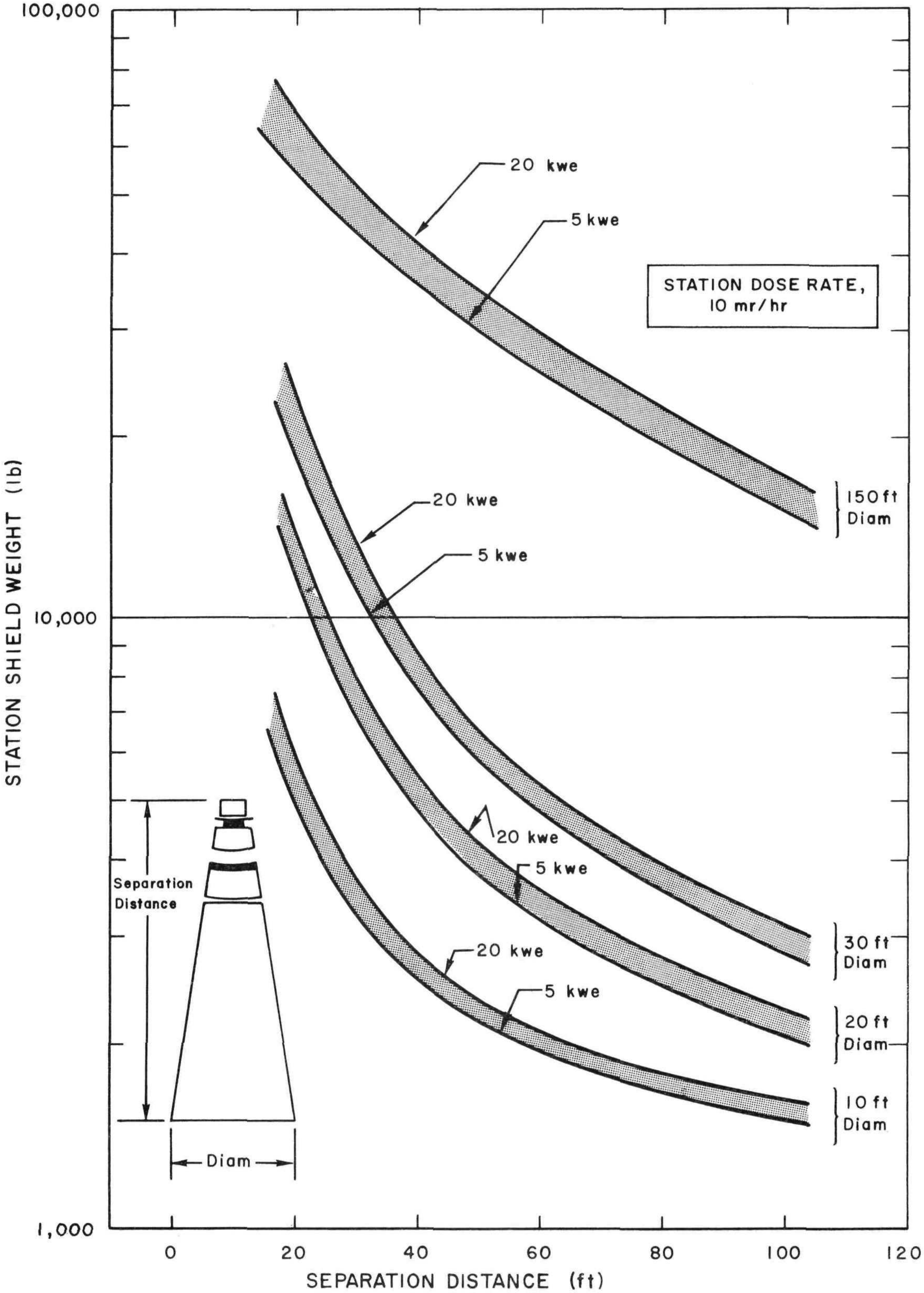

Figure 20b. Station Shield Weights vs Separation Distance

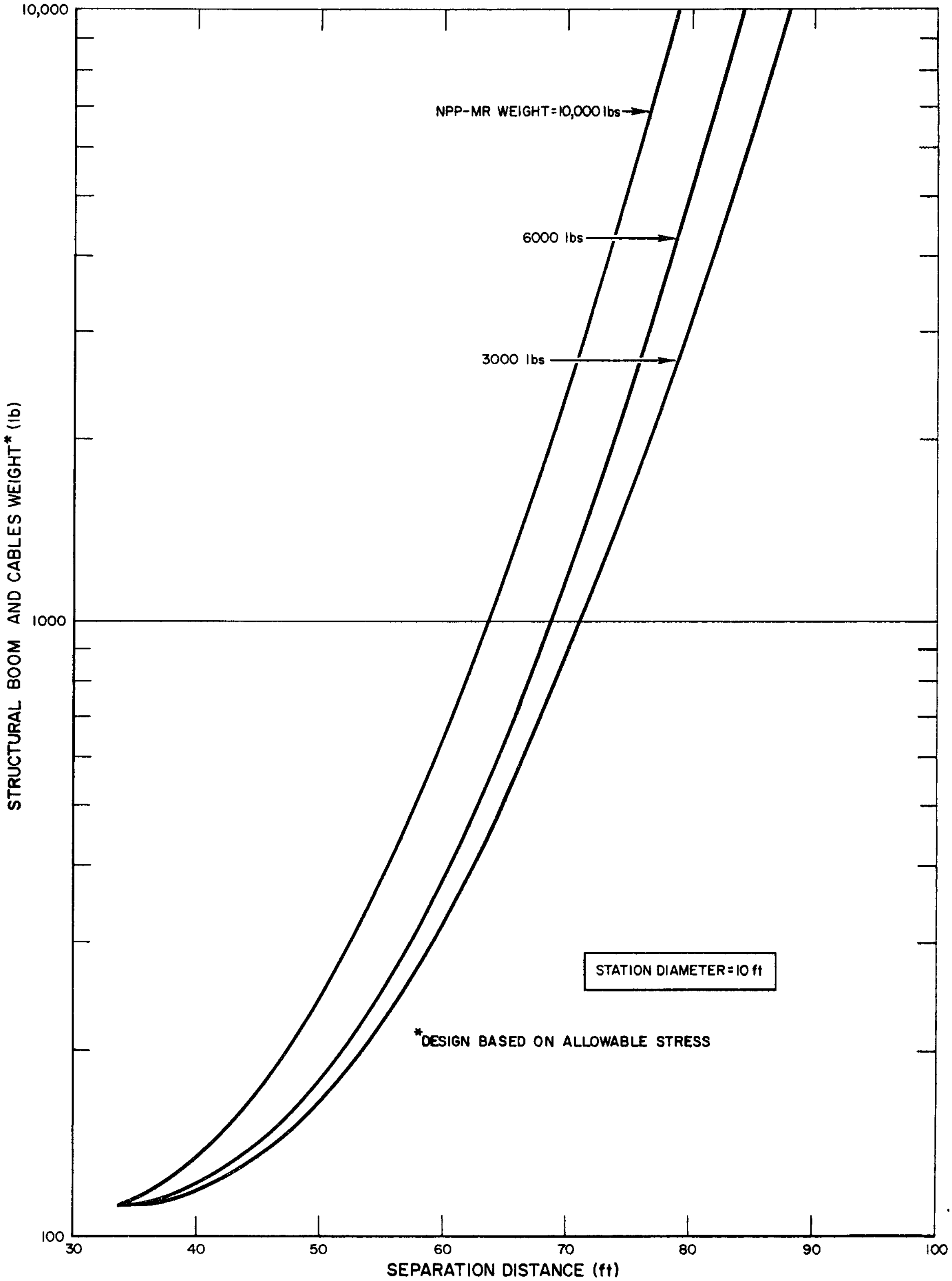

Figure 21a. Structural Weight vs Separation Distance

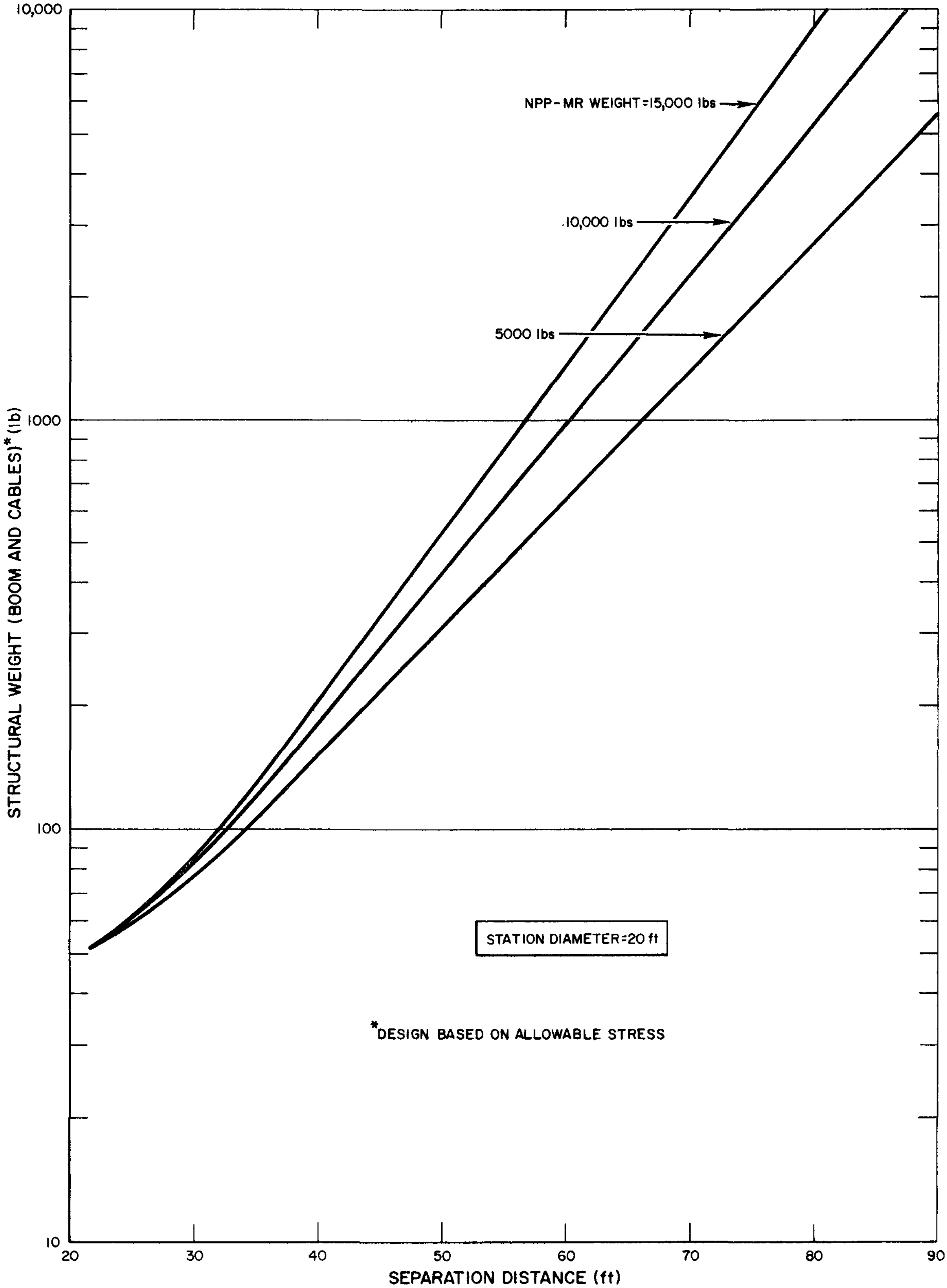

Figure 21b. Structural Weight vs Separation Distance

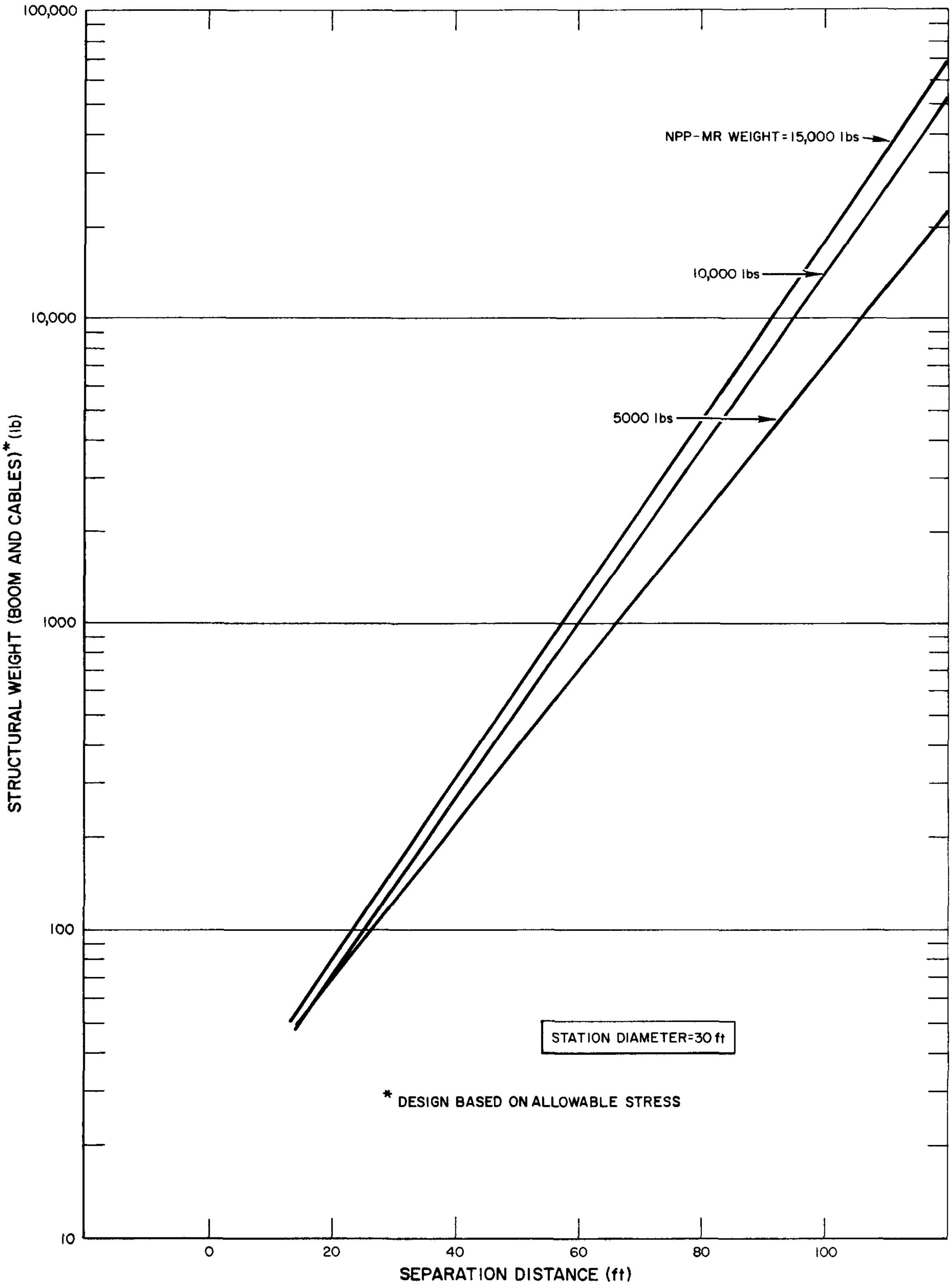

Figure 21c. Structural Weight vs Separation Distance

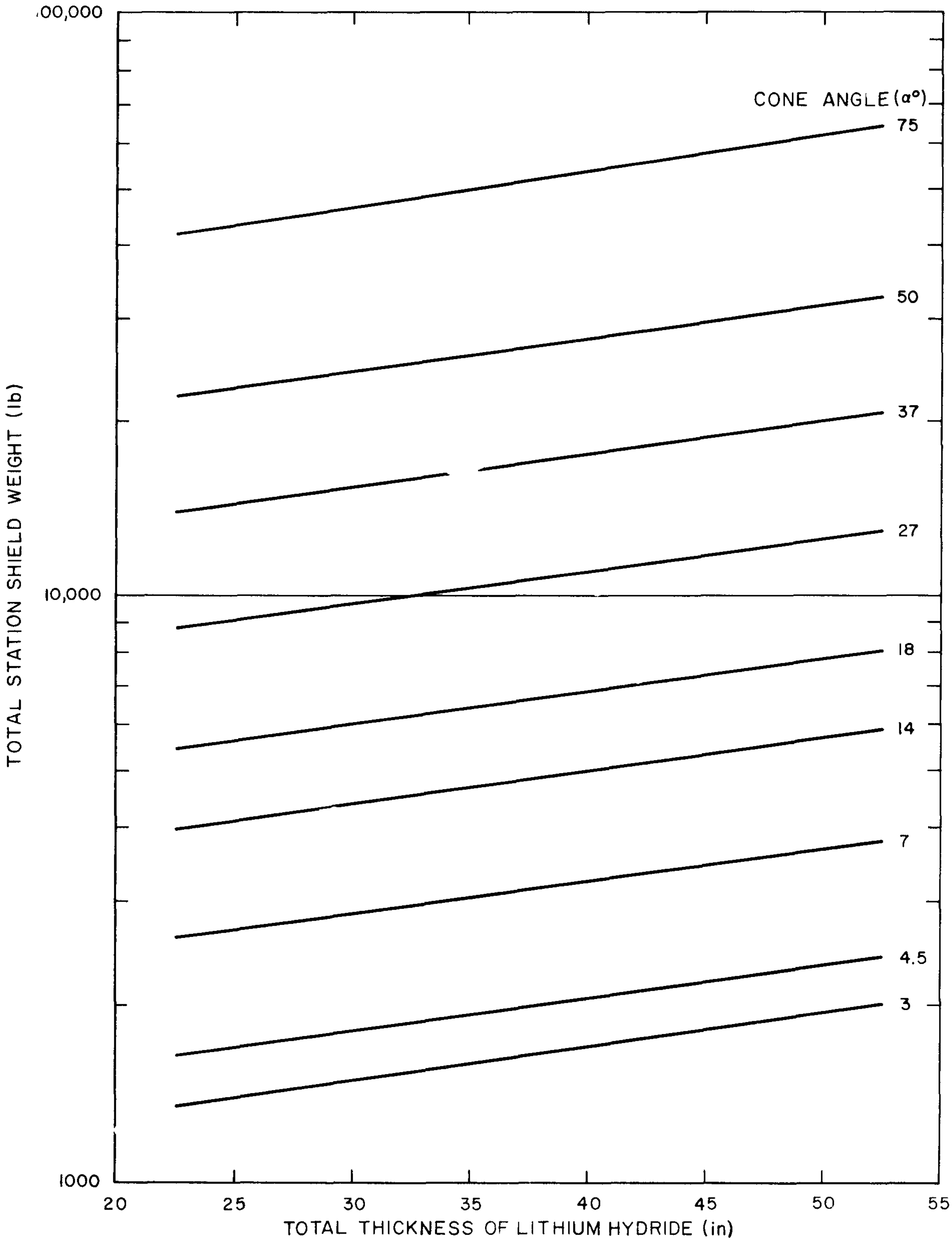

Figure 22. Station Shield Weights vs Thickness

$$\alpha = \tan^{-1}\left(\frac{B}{2S}\right) \quad , \qquad \ldots (5)$$

where the symbols are those shown in Figure 9. For a given space station diameter, B, different values of α are assumed as the reactor separation distance varies. The radiator area is fixed for a particular power level. For a fixed mating plane diameter, B, as S increases the base dimension of the RC shell decreases in such a way that the shield just shadows the space station. As the RC base diameter decreases, for fixed power the height increases in order to maintain a constant surface area.

Referring again to the nomenclature of Figure 9, the rendezvous shield casts a shadow of angle $\varphi + \alpha$, the rendezvous shield weight depends on α. Given in Figure 23 are rendezvous shield weights as a function of thickness, φ , and α. Neutrons entering the rendezvous shield are scattered approximately in accordance with a forward cosine distribution. The scattering of gamma ray photons is negligible. Some of the neutrons are scattered toward the payload, and additional LiH is needed to attenuate their contribution to payload dose rate. The thickness required for this scatter shielding is given in Figure 24 for a power level of 100 kwt and a 50 ft separation distance. The thicknesses of LiH to be placed in the line of sight between rendezvous shield and station for other powers and separation distances may be estimated using Equations 2 and 4. The weights shown in Figure 23 include allowance for shielding to reduce the scattered neutron contribution due to dose rate at the mating plane.

If for some reason the reactor is shut down, the dose levels in the vicinity of the reactor are considerably reduced as indicated in Figure 25. The unattenuated dose rates at different ranges from the reactor are given in Figure 26.

In the preceding section was presented a discussion of the use of a boom or extended structure. The distance S between reactor and mating plane which gives minimum weight for station shield and boom for different power levels is given in Figure 27. In Figure 28, the total of station shield plus boom and cable weight is plotted versus separation distance for the case of a 10 ft. diameter to illustrate the occurence of an optimum spearation distance.

As previously discussed, with a shuttle vehicle docked at the side of a small cylindrical station (both during docking operations and while two shuttle craft

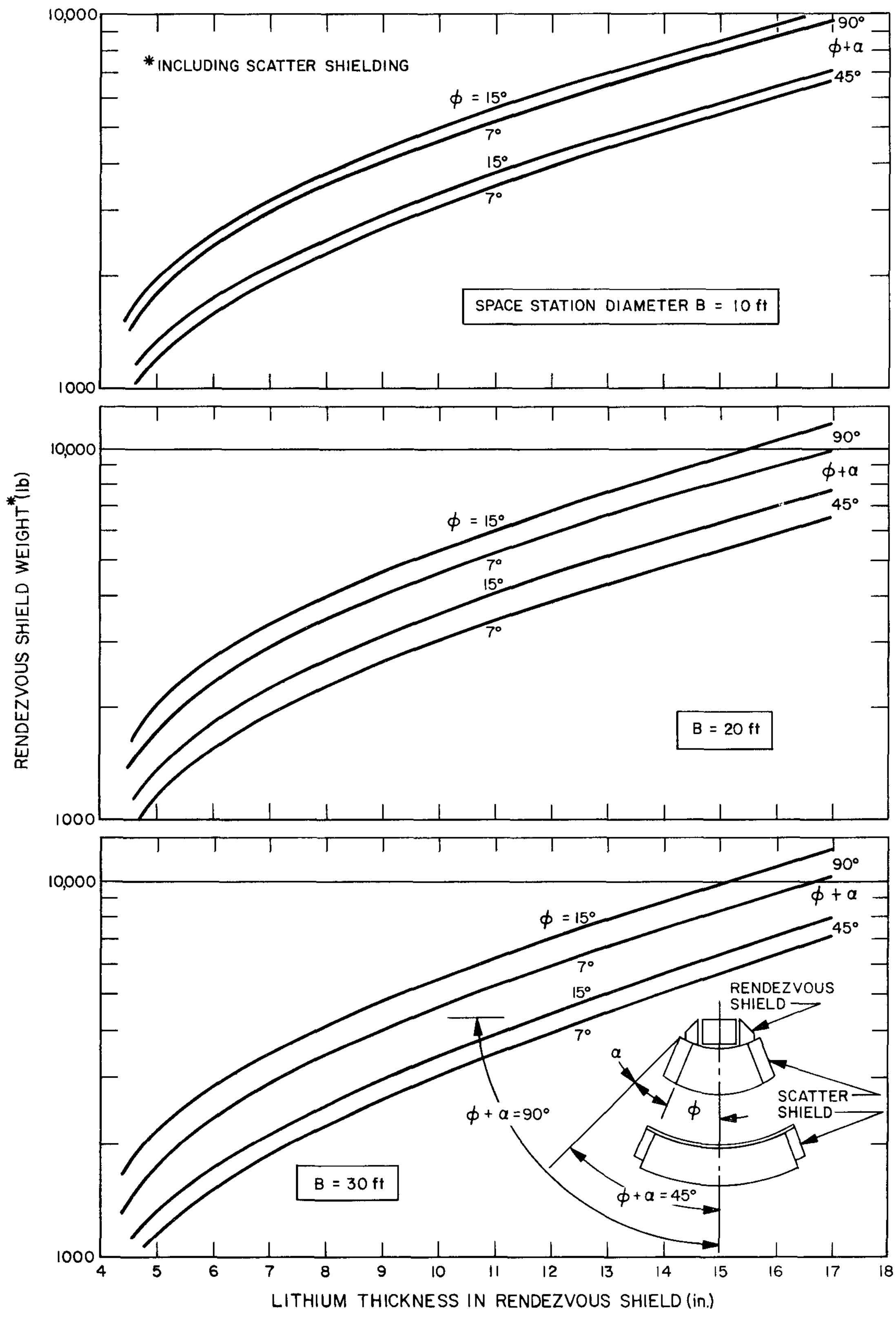

Figure 23. Rendezvous Shield Weight

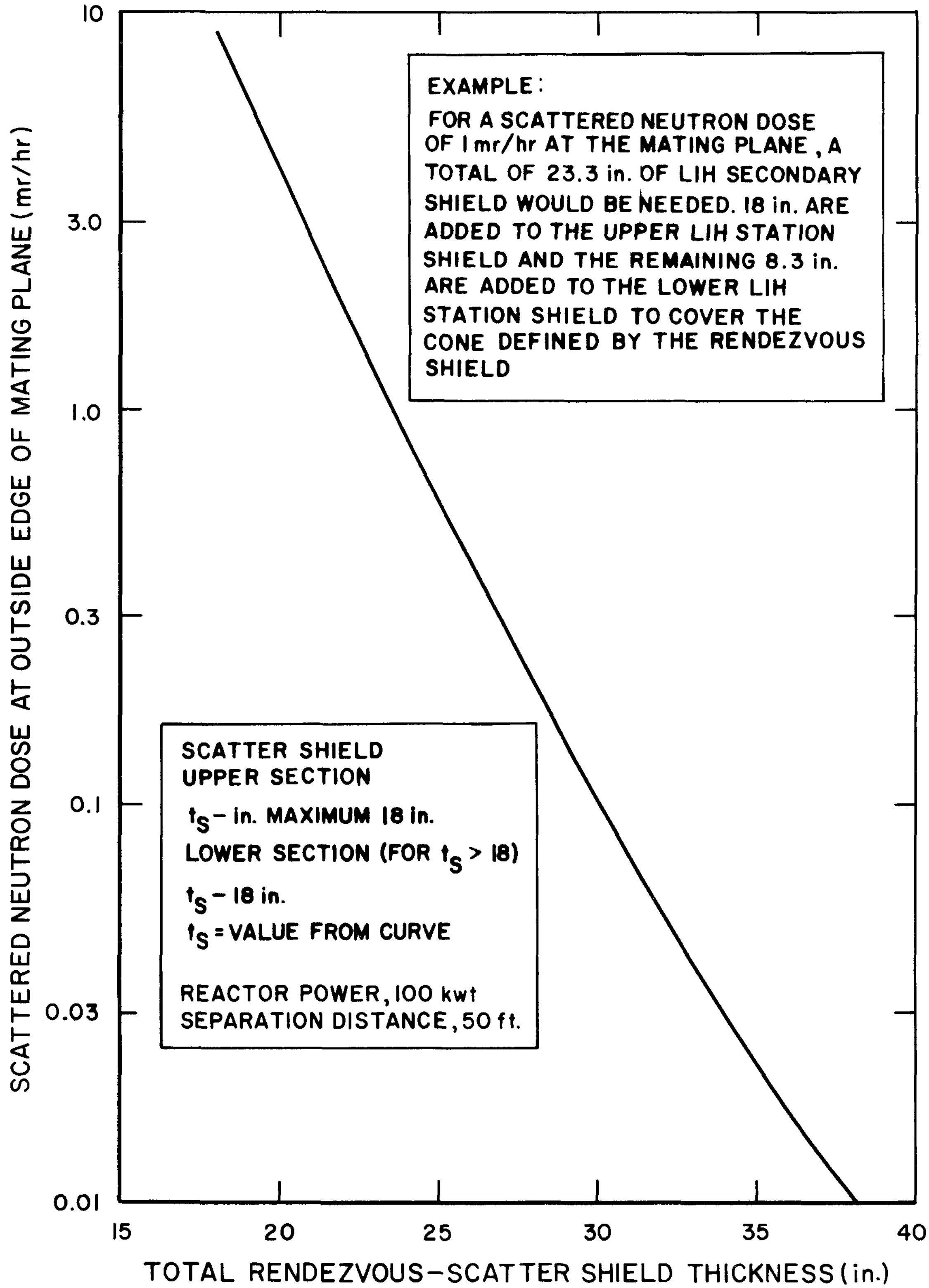

Figure 24. Rendezvous Scatter Shielding

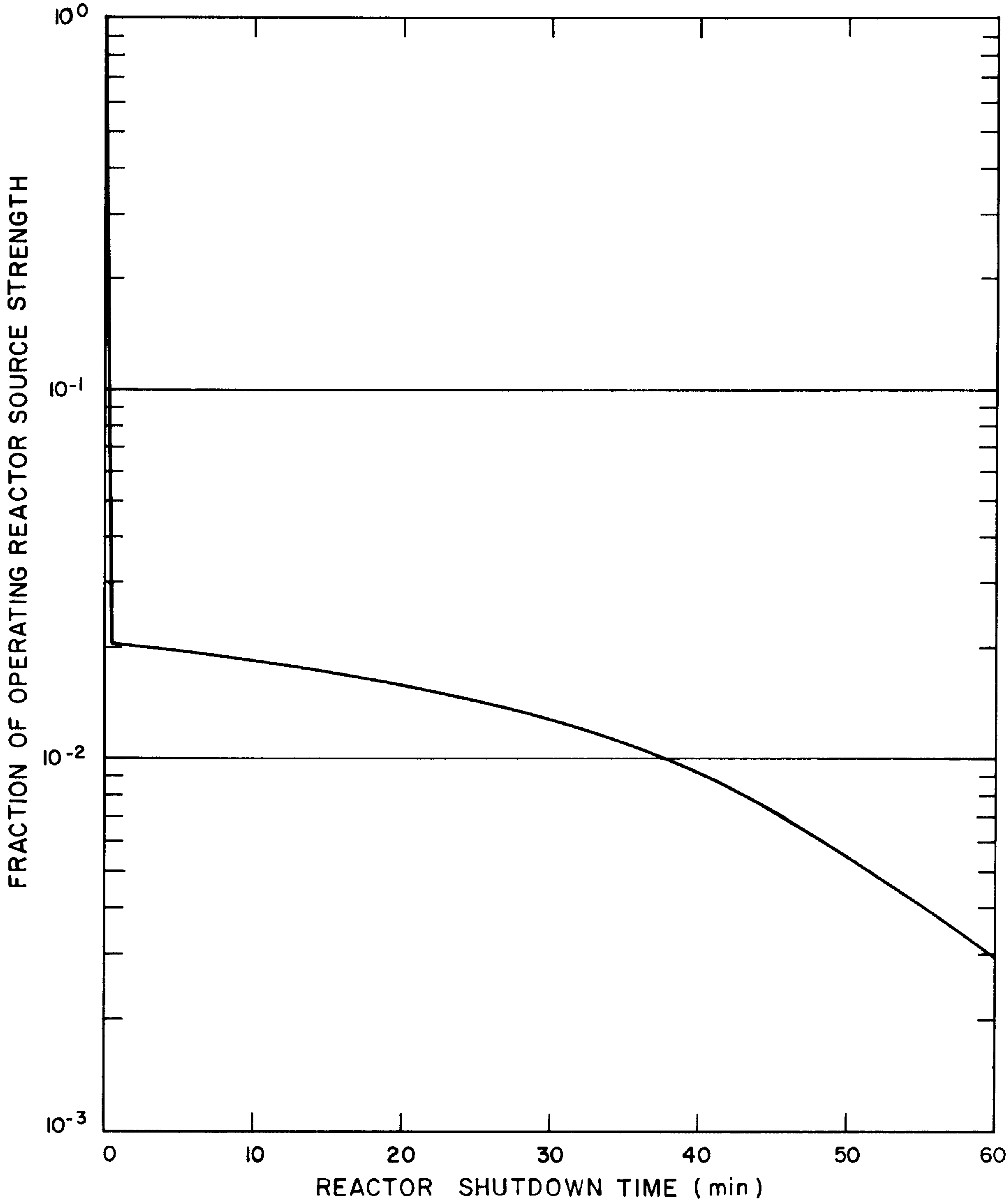

Figure 25. Reactor Shutdown Radiation

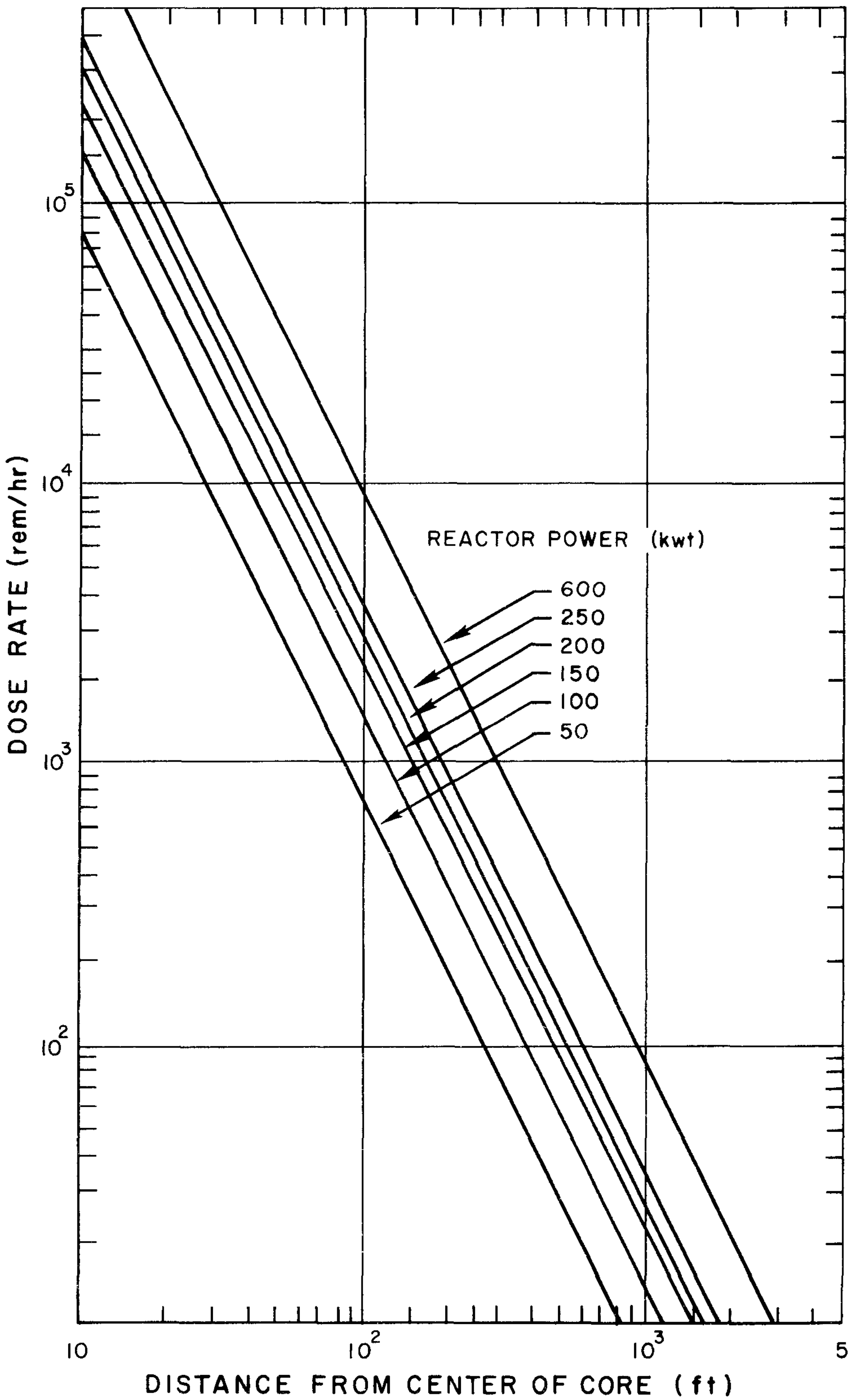

Figure 26. Dose Rates From Unshielded Reactor

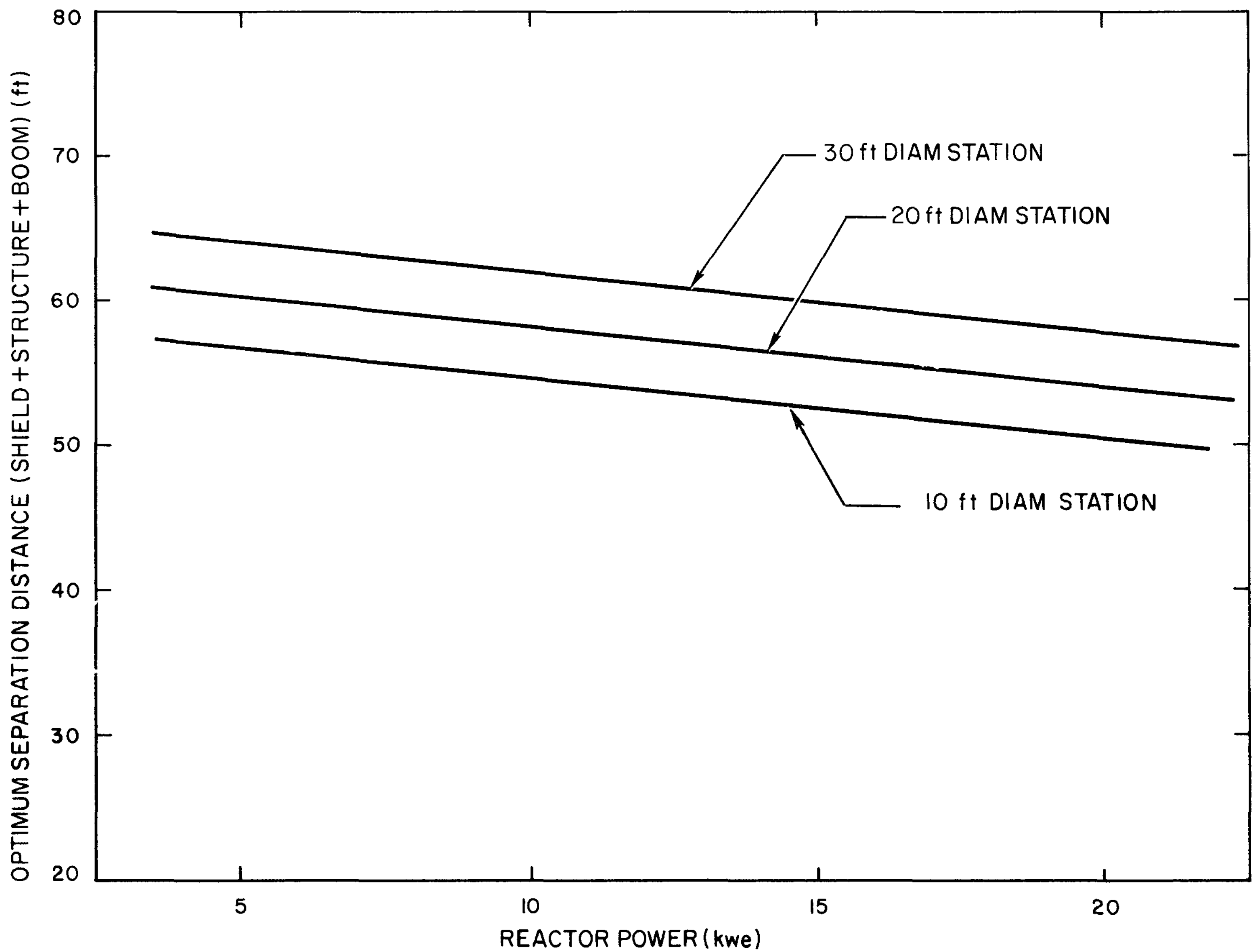

Figure 27. Optimum Separation Distance for Station Shield

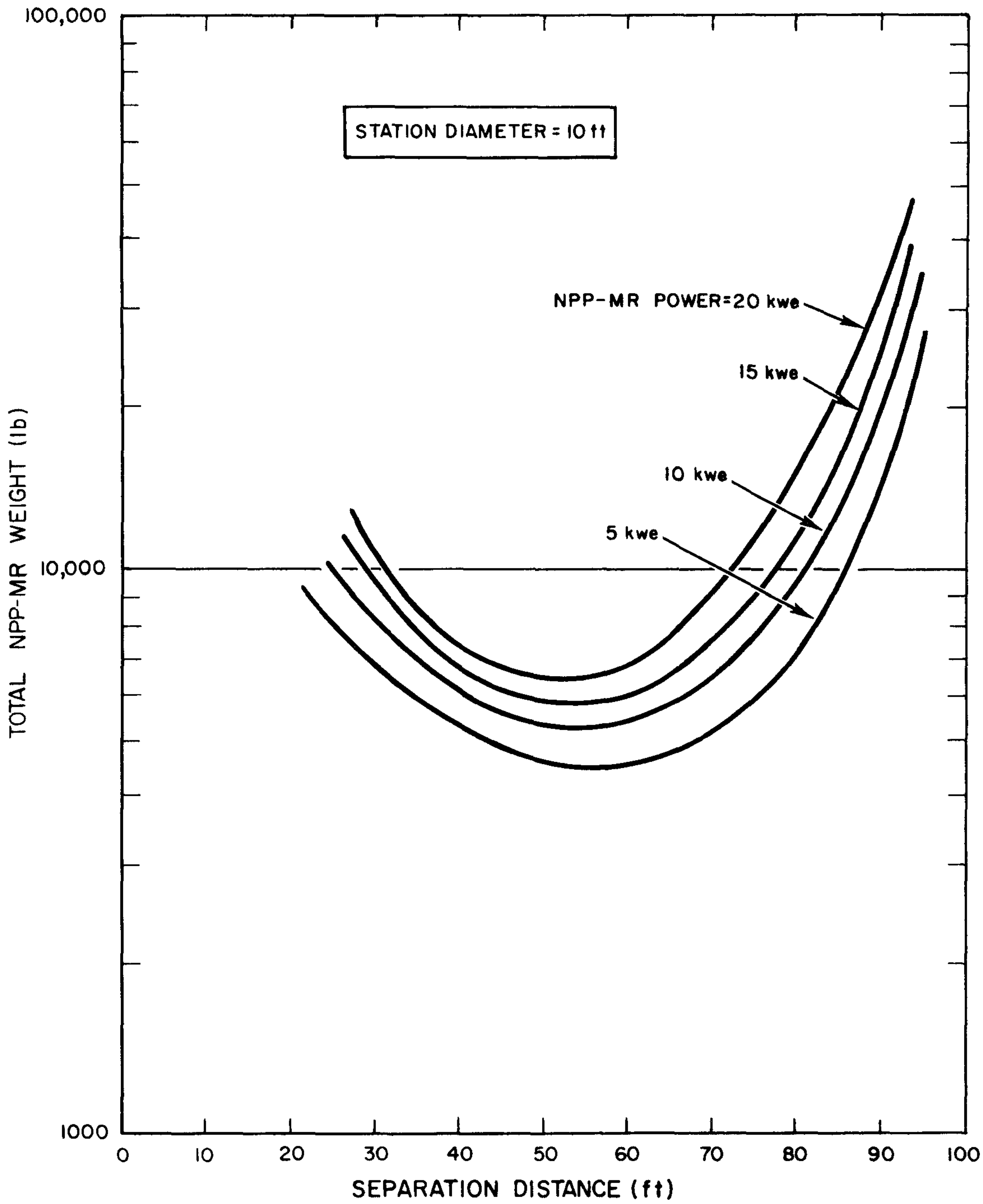

Figure 28. Total NPP-MR Weight vs Separation Distance

are attached for extended waiting periods) the vehicles(s) will cause neutron scattering back into the station of about 1% of the incident radiation. If a rendezvous shield is employed, this "vehicle scatter" will cause no problem. In the absence of rendezvous shielding, a "parking" shield is needed to reduce the intensity of neutron radiation received by the parked vehicle. This in turn will reduce the dose rate in the station attributable to scatter from the shuttle craft. The shielding curves already presented may be used to roughly approximate the LiH thickness required in the line of sight between reactor and exposed parts of the shuttle craft. With no scatter shielding, the payload dose rate derived from neutrons scattered from the vehicle will be roughly 1% of that indicated in Figure 26 for the range between craft and reactor. The LiH thickness required to attenuate the dose rate to the desired level may be estimated from Figure 16.

It is likely that worthwhile reductions in total shield weight may result for any particular station from more refined analyses. However, the foregoing information is considered to provide a reasonable basis for preliminary estimates of shield characteristics.

E. SPACE STATION CONFIGURATION

The shielding information presented in the preceding sections has been oriented primarily toward cylindrical stations of various sizes; however, the same data may be applied in a preliminary fashion to other station configurations. Studies of large space installations have extended to other configurations such as toroidal, hexagonal, and spoke-shaped. Many space station concepts, particularly for large facilities designed for long-mission duration, use spinning to create an artificial gravity environment. The effective concentrated mass of power plant and shield must be taken account of in designing for space station dynamic balance, stability, and control. In general, a good stability margin exists if the moment of inertia about the spin axis exceeds that about other axes by 40% or more.

A typical toroidal station is pictured in Figure 29. This station is described in Reference 17 and would accommodate a crew of about 20 men who would normally occupy the tubular sections of the rim. In this concept, the station would spin about an axis passing through the hub and normal to the station plane. At the hub would be the docking ports and the reactor support structure. The radial passages joining the rim and hub would be used for the limited access

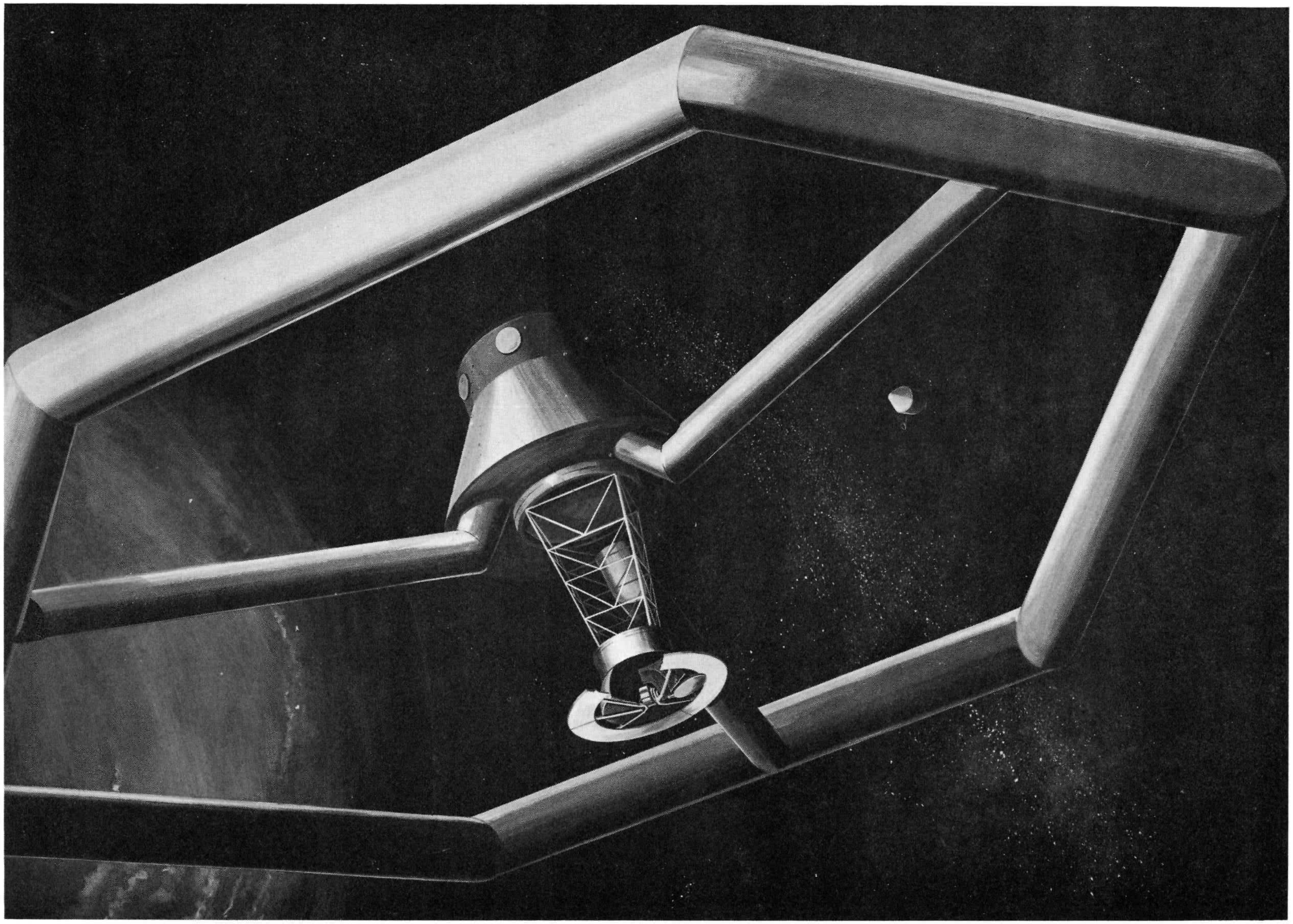

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Figure 29. Toroidal Space Station

required. The hub section would be disengaged from the spinning motion for rendezvous operations. The station shield would be hemispherical ($\alpha = 90°$) and would shadow the rim of the space station. For shield weight optimization, the station shield could be of variable thickness, corresponding to an acceptable distribution of dose levels over the various parts of the station.

The spur, or Y, station (illustrated in Figure 30) is another configuration receiving considerable attention. In this picture, one of the arms of the spurs is tipped with the nuclear plant. In other Y station designs that have been considered, the nuclear plant would be mounted on the hub. Space station stability can be achieved with either arrangement. With the plant positioned on the end of the leg as shown in Figure 30, a relatively low weight shield may be used. The station shield shape will approximate the frustrum of an elliptical cone. The thickness of the gamma and neutron shielding may be determined as previously described, and the corresponding shield weights may be calculated as illustrated in Figure 31.

It was earlier mentioned that for some long missions, economics might dictate that shielding remain permanently with the station rather than be replaced as part of the power plant package replacement. One deployment that is suitable for this approach is illustrated in Figure 32. The station shield would be selected as previously discussed. With this arrangement, however, additional shielding is needed to intercept radiation scattered back from the PCS toward the space station. Assuming isotropic scattering of neutrons and observing that λ scattering is negligible, the dose in the unprotected parts of the (cylindrical) station due to scatter from the radiator may be roughly approximated by:

$$D_{ns} = \frac{870}{(30.5S)^2} \left(\frac{S}{S + S_r}\right)^2 D\left(S_r\right) \qquad \ldots (8)$$

This equation is based on: (1) a 20% neutron contribution to total dose $D\left(S_r\right)$ at range S_r, and (2) on calculations[18] in which an "equivalent radiator" in the shape of a spherical segment was used. The radiator surface was assumed to be uniformly at a distance S_r from the reactor (reactor between RC and station). The effective weight of the RC and PCS for scattering was taken to be 10,000 lb, and a $\sigma s/A$ value of 0.04 was used, corresponding to an aluminum-steel RC. D_{ns} may be calculated for other weights using (8) and adjusting the result in direct proportion with weight. The scatter shield thickness may then be determined with the aid of Figure 16.

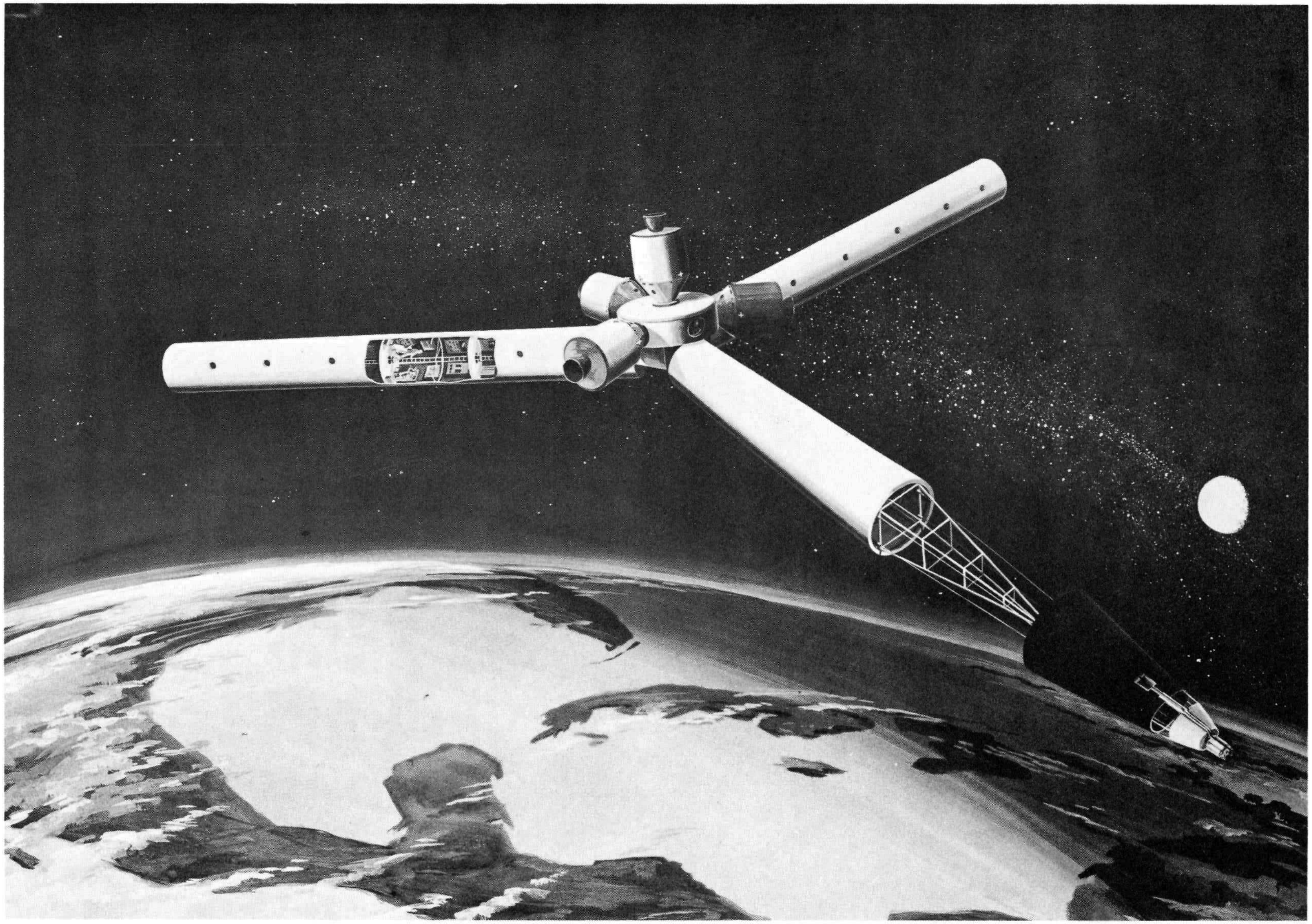

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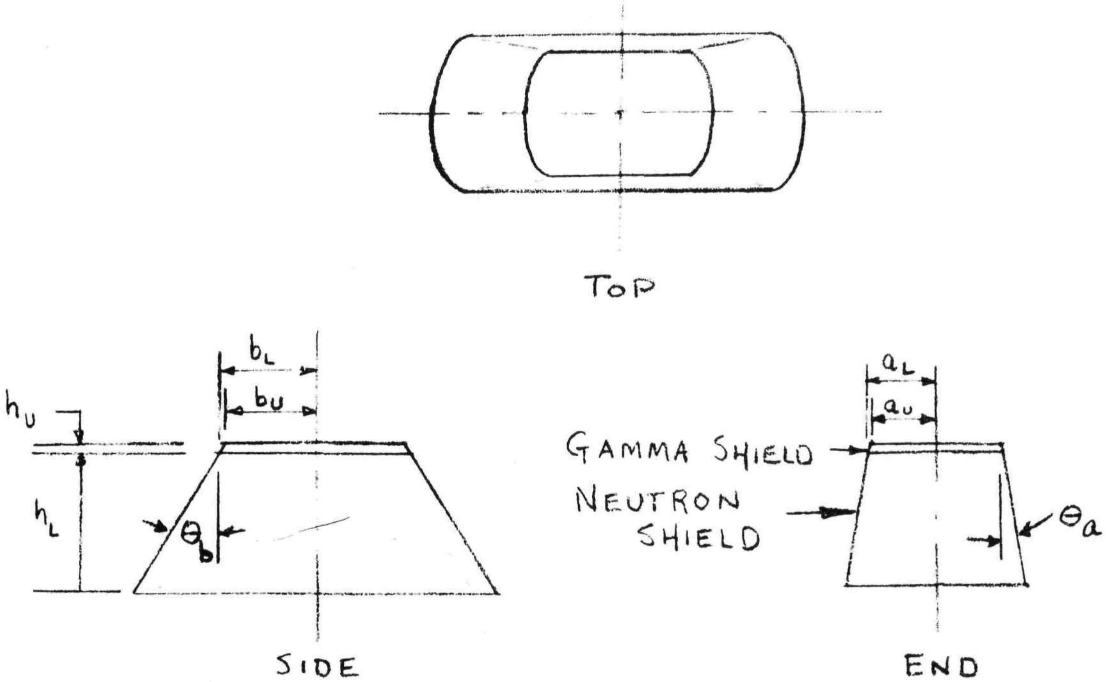
Figure 30. Spur Space Station



Approximate Weight, W, of Shield Section:

$$W_i = 2\gamma_i \left[(2a_i + h_i \tan\theta_a) b_i h_i + a_i h_i^2 \tan\theta_b + \frac{2}{3} h_i^3 \tan\theta_b \tan\theta_a \right]$$

i = U or L

U = uranium; γ_U = 1170 lb/ft^3

L = lithium hydride; γ_L = 44.2 lb/ft^3

Figure 31. Elliptical Cone Shield

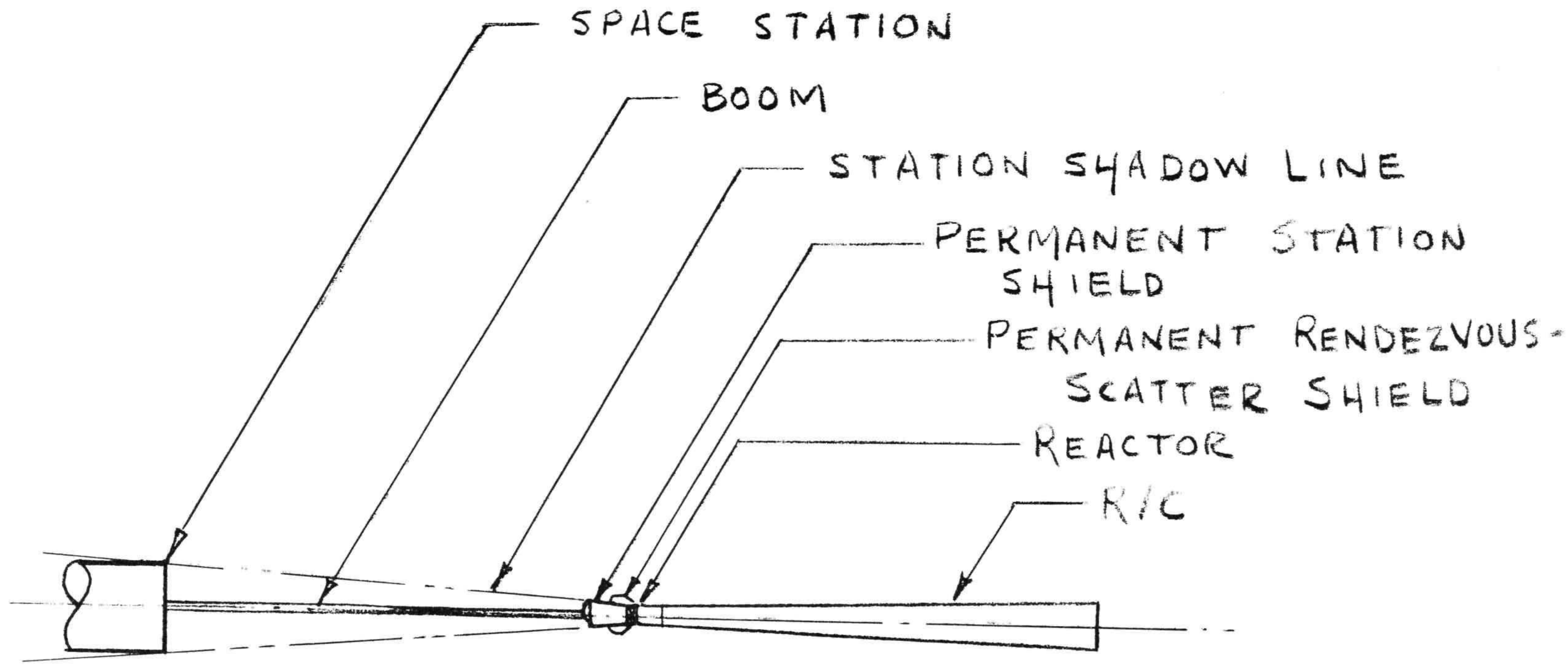


Figure 32. Station with Reusable Shield

IV. DESIGN CHARACTERISTICS OF SPECIFIC PLANTS

In this section are presented the layout, operating, and component characteristics of specific power plants designed respectively to provide 5,10, 15, and 20 kwe for a cylindrical space station of 10 ft diameter. These designs feature the modular (5 kwe unit) approach discussed previously with the exception of the reactor-reflector assembly. The RC is used only in a quasi-modular sense where each 5 kw PCS has an individual radiator that forms a horizontal segment of the total radiator area cone. This requires that the configuration be slightly different for each 125 square foot module.

A. LAYOUTS

The equipment layouts and flow diagrams shown in this section are an outgrowth of years of detailed engineering, design, and testing on the SNAP 2 program. In Figure 33 is shown the overall layout of a 20 kwe multiple Power Conversion System. The number of active and redundant units joined together would correspond to the number of 5 kw modules required. With this arrangement the total RC cone configuration remains constant (625 ft^2 including minimum of one redundant unit for 20 kwe) and false structure or an extendable boom is substituted in place of cone segments that are not needed for heat rejection when lower powers are required.

In Figure 33 may be seen other component arrangements previously described. The reactor is located at the opposite end of the power system from the station. The NaK pumps and boiler are nested in the gallery between the two sections of station shield. The CRU and other mercury components are deployed in modular fashion within the shell of the RC. In Figure 34 appear less detailed layout drawings of the 5, 10, 15, and 20 kwe plants. In all cases a nose cone would cover the reactor during launch and would be ejected after reaching orbit.

The P&I diagram for the 15 kwe system is presented in Figure 35. The system consists of a single NaK circuit passing through the reactor and four secondary mercury loops, three normally active and one standby. This P&I diagram is representative of plants using either the segmented or the tailored RC concept. The boilers and TE pumps and individual 5 kwe units are linked in parallel. This diagram also characterizes plants of larger and smaller power rating. The P&I diagrams for other plant sizes would change only in the number

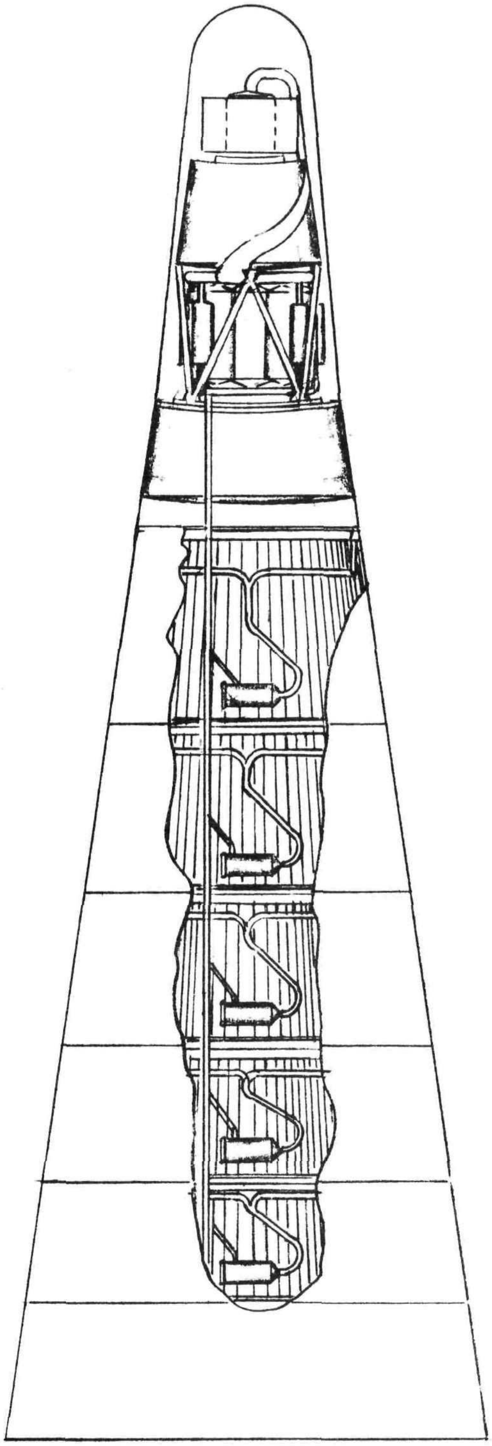


Figure 33. 20-kwe Power Plant

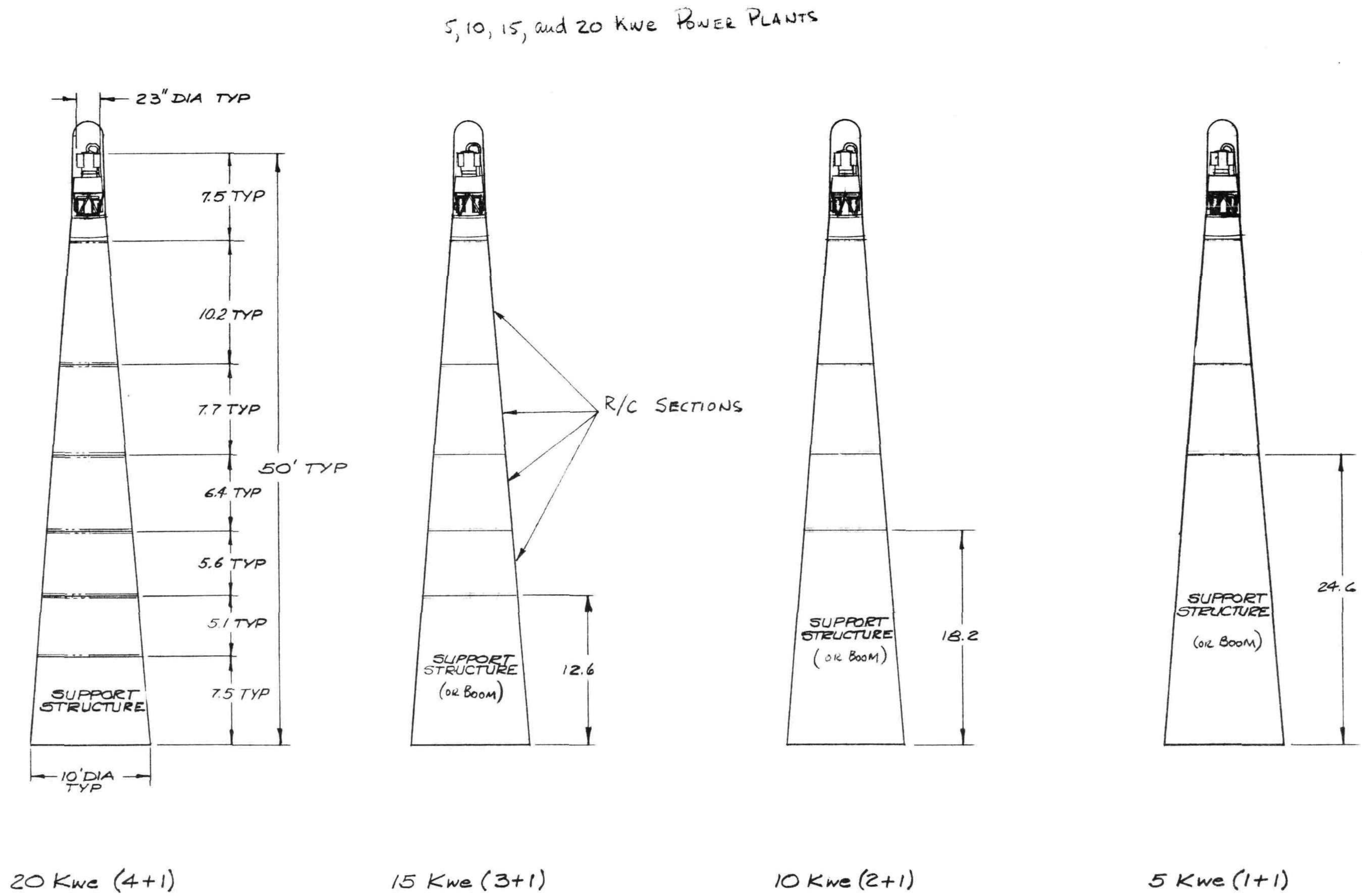


Figure 34. 5, 10, 15, 20-kwe Power Plants

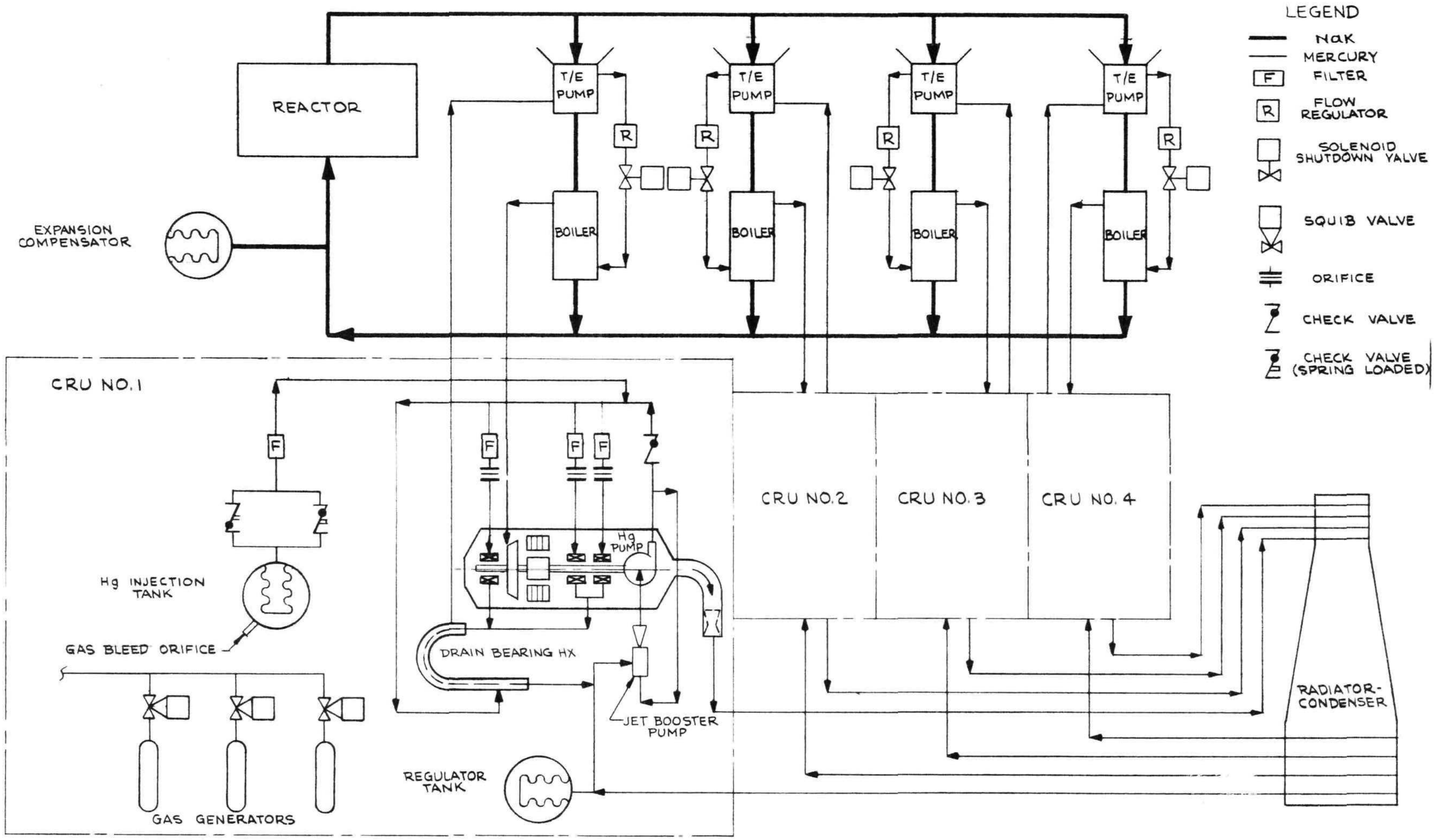


Figure 35. P & I Diagram for 15-kwe System

of PCU's shown, from two (1 + 1) in the 5 kw case to five (4 + 1) in the 20 kw situation. In the modular systems, each mercury loop is completely independent of the others, and the loss of one will in no way affect the integrity of the others. Corresponding components in each mercury loop are identical. Paralleling each TE pump and boiler combination would tend to cause reverse flow through the redundant boiler - TE system if it were not that each pump is cooled by radiating fins in addition to normal liquid mercury cooling. The temperature gradient due to heat transfer from the TE pump fins prevents reverse flow (thus avoiding the need for a mechanical check valve).

B. OPERATING CHARACTERISTICS

Normal operating conditions for the 5 kwe system are noted on the schematic drawing in Figure 36. It is seen that the turbine inlet temperature and pressure are 1185° and 120 psi, respectively. The radiator condenser heat rejection temperature is approximately 600°F. In going to higher power systems the PCS conditions, due to the modular approach, are identical and the NaK flow goes up proportionally with power (excluding the small flow requirements for the redundant unit). The NaK system pressure drop increases from 0.6 to 0.92 psi in going from 5 kw to 20 kw. Since the TE pump is designed to meet the highest power requirement, an excess of NaK flow will be available for the lower power systems. This results in boiling margin in the boiler (cf Section IV-C) or an increase in the allowable NaK flow degradation and, therefore, an increase in system reliability for the low power systems. There are slight NaK temperature variations with the use of a redundant loop; however, these have no significant effects on the system performance. In general, design allowance is made to assure satisfactory performance even after a 5% reduction in NaK flow due to pump degradation for all cases. The equipment and procedures for system startup are discussed in II-G. Shortly after normal operating conditions are established following startup, the conditions necessary for restart are automatically attained. Startup procedures are generally the same regardless of the number of loops involved.

In all plants, the redundant loop is operated in a standby mode and does not normally produce power. When incipient or complete failure of a loop is detected through loss of CRU power, the defective PCU is shut down and the standby loop is activated. During the startup period (~3 min) for the standby

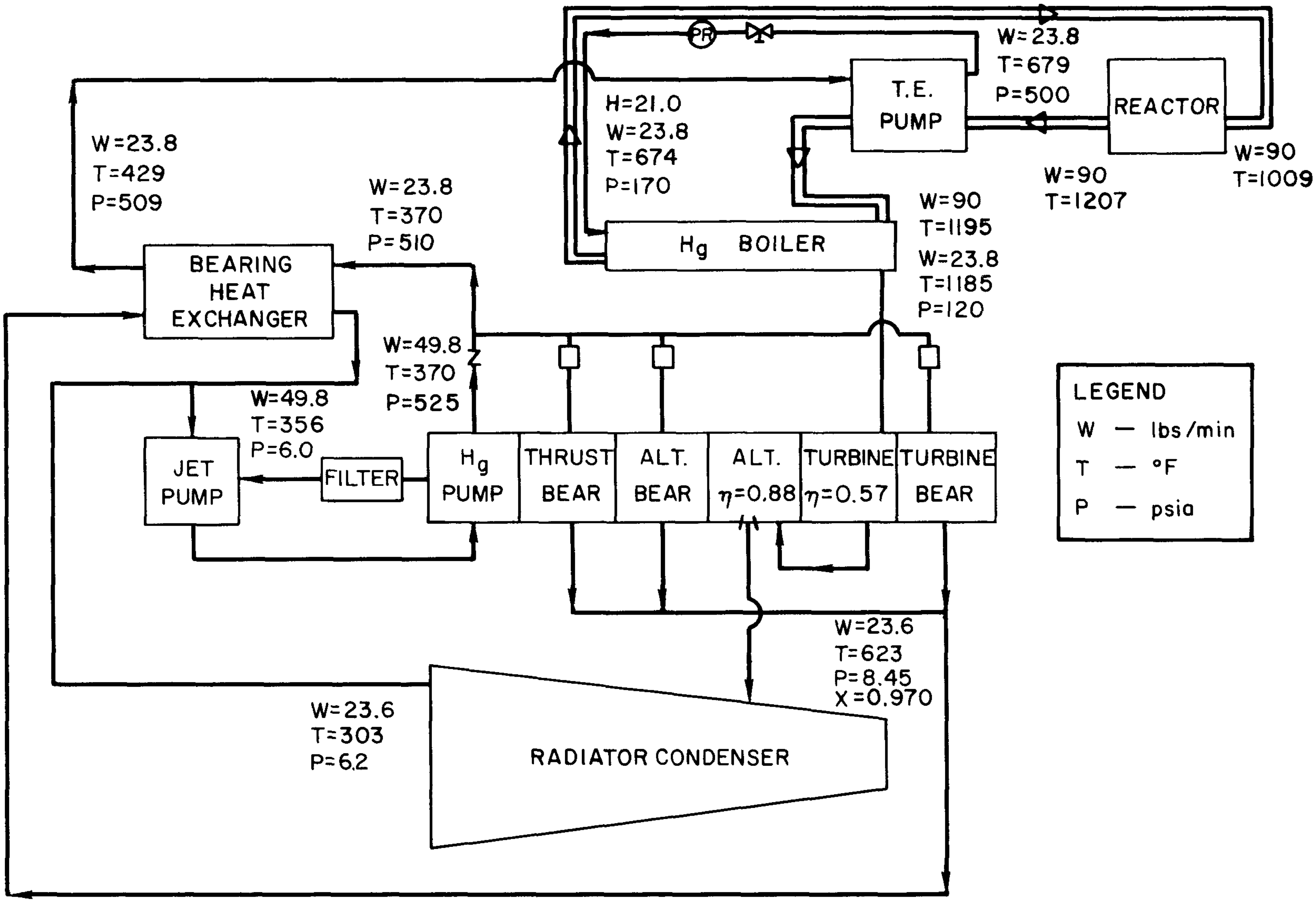


Figure 36. Design Point Characteristics

loop there is a small reduction in plant power output. After CRU shaft rotation stops, the failed loop mercury inventory will either bleed to space or remain in place, depending upon whether or not the failure mode was a mercury leak.

Presented in Figures 37 and 38 are preliminary block diagrams showing the electrical system and control functions. These are patterned according to the considerations discussed in Section II. Both 400 cps ac and 28 vdc electrical services can be provided, along with a station battery to supply vital loads in case of emergency and during periods of reactor replacement. Startup and long-term control is carried out automatically, with provisions for manual override. The control console contains a minimum of instrumentation, control actuators, and alarms for plant operations. Except for the alternators and parasitic load heaters, all instrumentation and electrical equipment is located within the station for ease of maintenance and replacement. Vital control equipment is redundant with provision to replace or repair a failed unit while operation continues.

C. COMPONENTS

As indicated later, the SNAP 2 components are for the most part well along in development testing. Many of these components are almost directly applicable in the 5 kw modules. For example, the CRU, thermoelectric pumps, expansion compensator, piping expansion joints, mercury regulator tanks, and valves are all in final development stages. This is also true of items such as wire, connectors, parasitic load controls, and heaters. In some instances previous SNAP 2 flight system (unmanned unit) radiation hardening and packaging requirements are alleviated because of the lower radiation levels required for manned systems.

The SNAP 2/10A and 8 reactors are capable of powering all plants discussed in Part IV, i.e., 5 to 20 kwe plants. Minor modifications are presently being undertaken, as previously discussed, which are designed to improve reactor reliability. These changes fall in the areas of multiple drum control and partial or complete redundancy in elements of the control and actuation systems and increased design margins. The fabrication measures called for in the shielding concepts are within the present shield state-of-the-art.

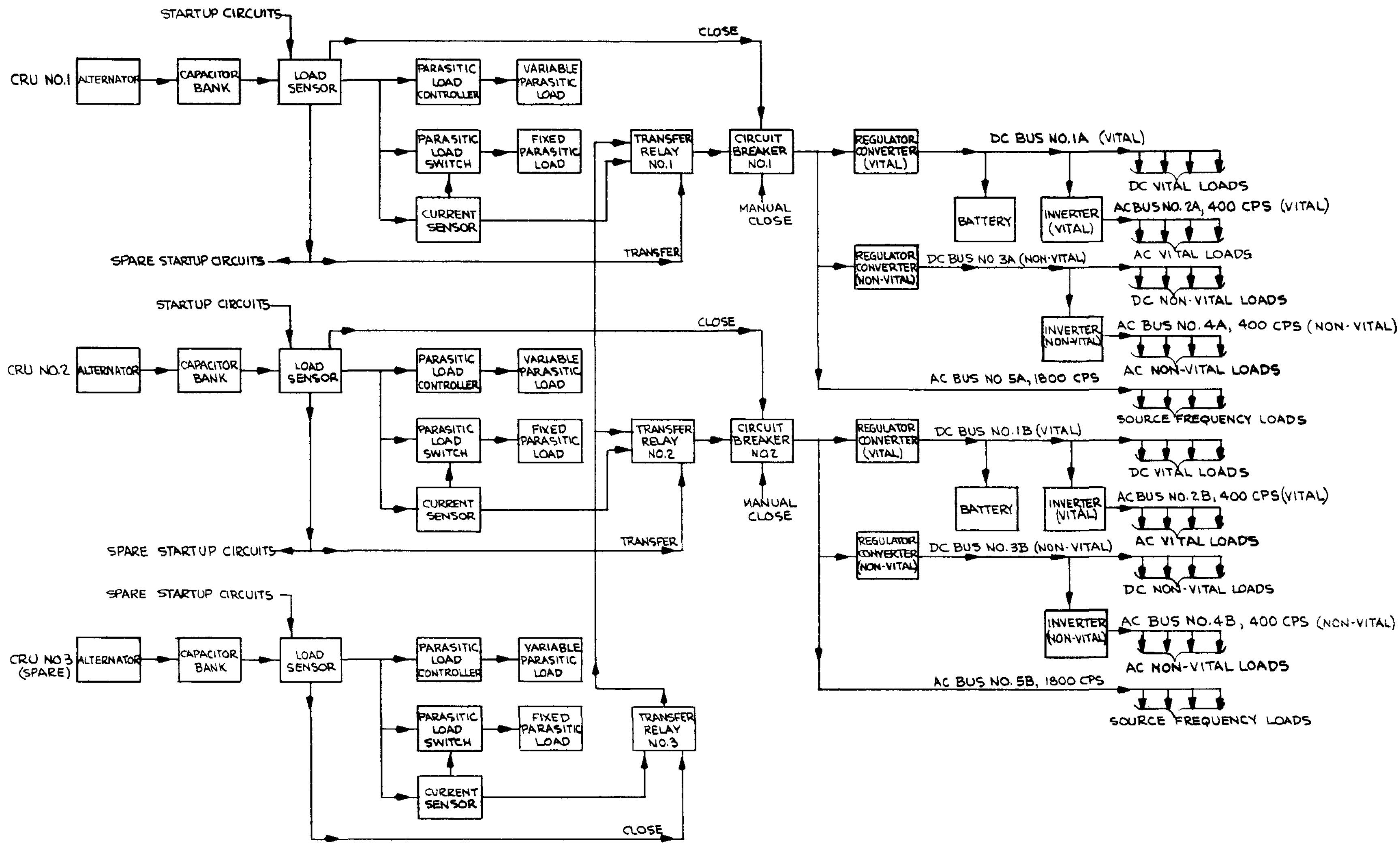


Figure 37. Electrical Diagram

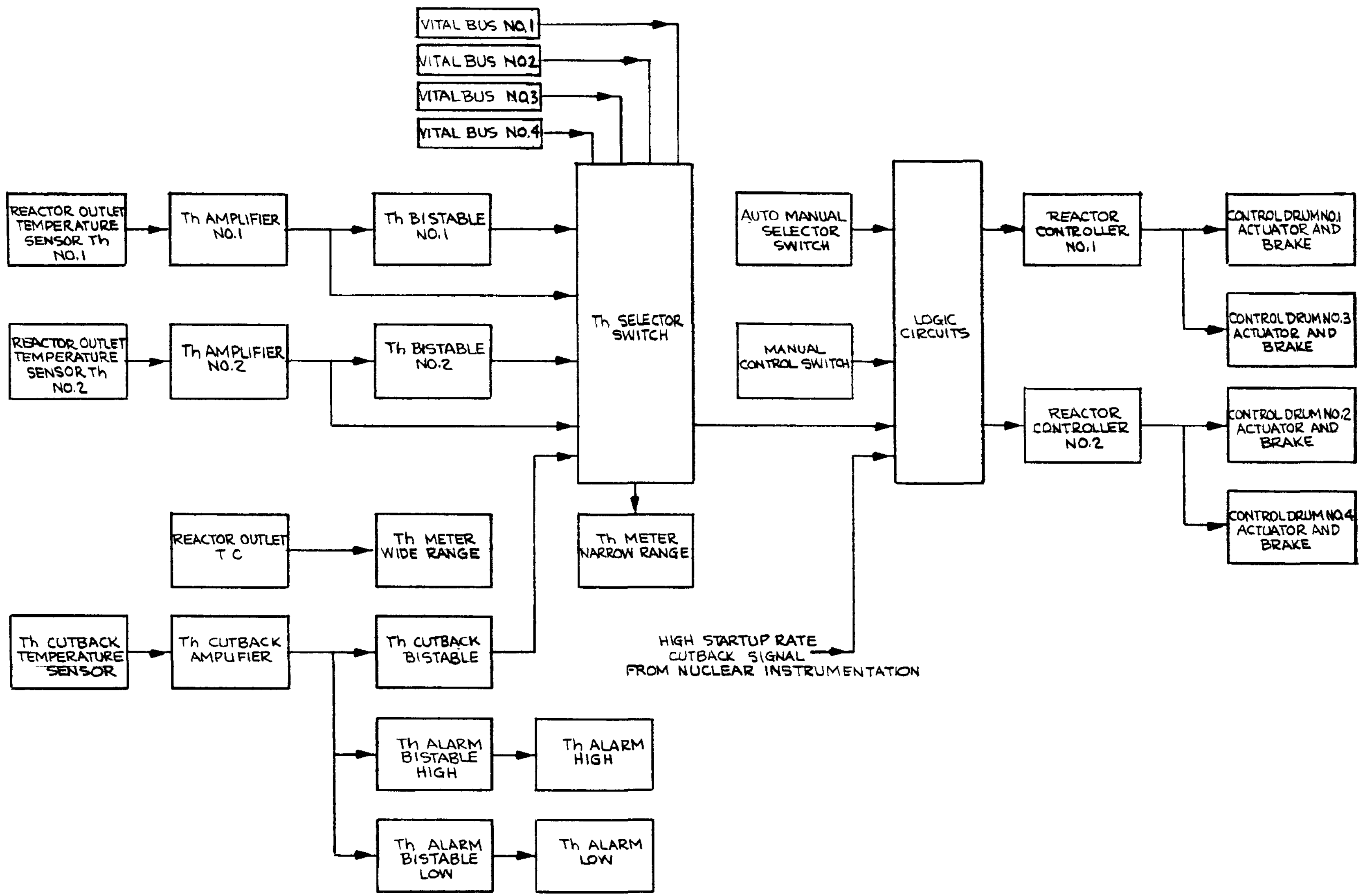


Figure 38. Control Block Diagram

The 3 kwe chromel-constantan TE pump is in an advanced stage of development and only a small redesign is required to upgrade these pumps to meet the 5 kwe module design requirements. Tests to date have been run on these pumps at the design temperature of 1200°F for extended periods and they have met performance requirements. At the present time, it is anticipated that this pump will exhibit negligible one year degradation in a vacuum environment.

The boiler and the RC involve the most changes from present configurations for incorporation in a multiple module manned plant. The new (model 8) boiler is shown in Figure 39 and is very similar to the model 5C boiler which is completely developed. The 5C unit has undergone development and prequalification and has performed exceedingly well. This new boiler is more compact than either of the preceeding ones so that it may fit between the two sections of shield. It is significantly lighter, and fits into the modular concept to make a very compact NaK system. The model 8 boiler represents a very small extrapolation of current technology resulting in a high degree of confidence in its predicted performance.

A typical 5 kwe RC section is displayed in Figure 40. The total surface area is 125 ft^2. Features of the design include: (1) all (tapered) tube sizes and lengths, and fabrication requirements fall within existing technology and experience; (2) the short tube lengths will result in low pressure drops without the use of large flow area tubes; (3) a minimum amount of extra mercury will be required for startup preheat (cf II-G); and (4) this approach allows minimum launch package heights and plant total surface areas. The principle disadvantages concomittant with the tailored RC are the multiplication of qualification testing required, the need for different tubing and fabrication tooling for each RC section, and the problem of thermally insulating the subcooler region (base) of one RC segment from the high temperature (upper) region of the adjacent segment.

D. SUMMARY

Summarized in Table 3 are the salient features of the four modular power plants described above. The power plants are for a 10 ft diameter cylindrical space station, and the shielding provided reduces the mating plant dose rate to 10 mr/hr. The weights designated in Table 3 as Basic Unit Weight include the entire power plant package (and nose cone) with the exception of the shielding.

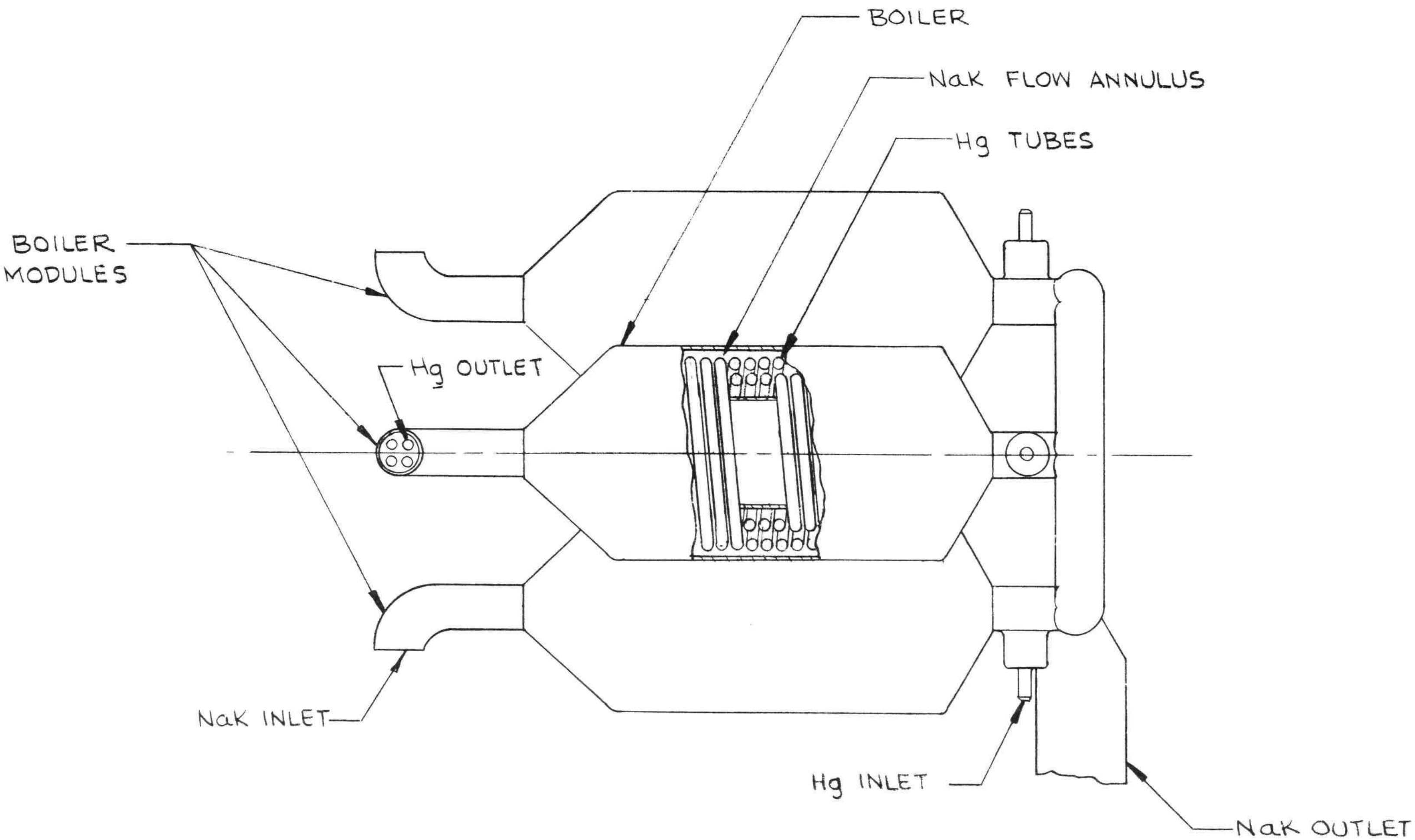


Figure 39. Boiler

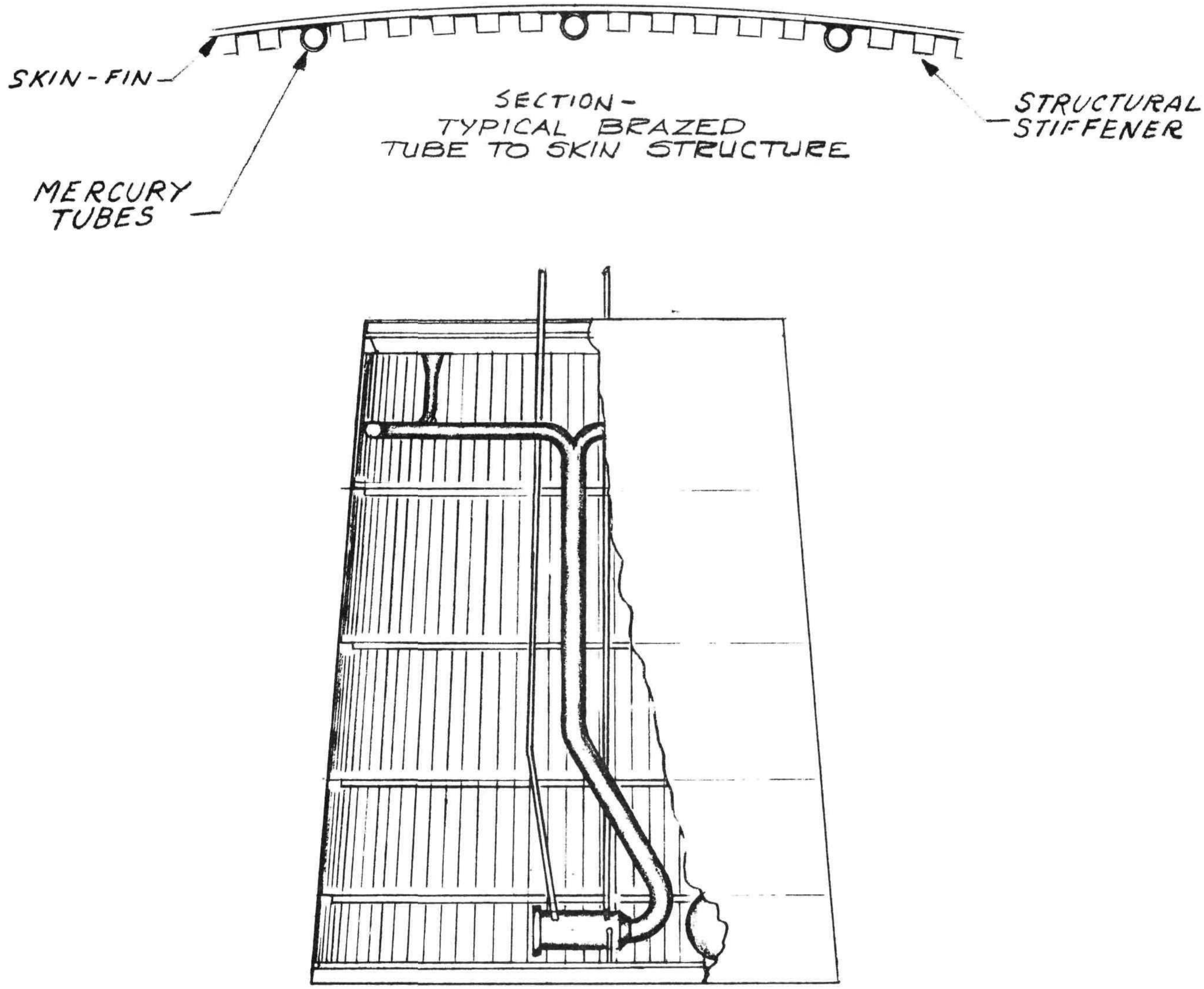


Figure 40. Radiator-Condenser Detail

TABLE 3

NUCLEAR SYSTEM CHARACTERISTICS (5-20 kwe)*

	Power (kwe)			
	5	10	15	20
Number PCU's (active and standby)	1 + 1	2 + 1	3 + 1	4 + 1
Basic unit weight (lb)†	1850	2530	3230	3940
Station shield plus boom (lb)	2460	2510	2530	2530
Total plant weight (lb)	4310	5040	5760	6470
Possible extra weight (lb)§	260	310	360	400
Radiator area (ft^2)	250	375	500	625
Plant launch height (ft)	25.4	31.8	37.5	42.5
Station dose rate from reactor (mr/hr)	10	10	10	10
Reactor outlet temperature (nominal)(°F)	1200	1200	1200	1200

*Cylindrical space station, 10 ft diameter.
†Total power plant weight exclusive of shielding, boom, and extras.
§Includes nose cone, power conditioning equipment, startup batteries, mating ring.

The figures given do not include an allowance for standby batteries or power conditioning equipment. The radiator areas shown are the totals for active and standby loops. Shutdown and restart capability is available for maintenance and emergency conditions.

V. LARGER POWER SYSTEMS

Looking beyond the nascent stages of space station development, it appears that needs will exist for power well in excess of 20 kwe. It is likely that second generation stations will require electrical power at levels up to 100 kwe, and subsequent space facilities should require even more power. A brief review is given below of some considerations and very preliminary study results relevant to power plants in the range 20 to 300 kwe.

As the plant size increases, more and more changes from the systems described in Part IV are required. At the first transition power level between 20 and 100 kwe, two important changes occur: (1) A SNAP 8 reactor must be substituted for the SNAP 2/10A unit (assuming dual SNAP 2/10A reactors are not used), and (2) a NaK pump capable of producing greater flows and pressures must be substituted for the TE pumps. Studies and experimental evidence show that either static EM or canned rotor pumps are suitable for this service, and some development has been started in this area. The 3 to 5 kw multiple units may be extended to power plant sizes of about 30 to 40 kwe size before weight and reliability penalties become significant.

For power plants of size larger than 25 to 40 kwe, considerations of weight and reliability suggest that a new more optimum module size be selected. Therefore, for power exceeding this second transition level it is necessary to develop a full set of scaled up PCS components. Selection of the optimum module size is dependent upon a variety of factors including total planned space program power plant requirements, costs, weight, and reliability. Preliminary evaluations centered on the last two qualities indicate that between 15 to 25 kwe is a reasonable tentative selection of module size to cover the power range up to about 100 to 125 kwe. In scaling up the present CRU to 25 kwe size, some beneficial design changes may be made. An electromagnetically excited alternator may be substituted for the permanent magnet machine, thus eliminating the increased rotor weight and packaging problems and providing good short circuit stability. The EM machine also gives very efficient voltage regulation. The machine speed would probably be adjusted to yield an output frequency corresponding directly to the station requirement. It is expected that the manned station rotating machinery would require 400 cps. To match power requirements not exactly a multiple of module size, the CRU's (i.e., PCS) may be operated at a flow rate less than design value. This results in a weight savings on some components (RC, shield, etc.) and an improved performance margin. This scale from CRUV to a 25 kwe design is not a major development problem. All present component technology would apply. Design studies and development of a larger CRU have already begun.

Another transition power level occurs in the vicinity of 100 to 125 kwe. Beyond this point, the advanced SNAP reactor may be used. This reactor is probably near the upper limit in SNAP reactor technology and is presently in the study stage and is a member of the same compact reactor family as are SNAP 2/10A and SNAP 8. It is capable of serving power plants of 300 kwe and greater size. As the power plant size progresses to 300 kwe, it appears there is incentive on the same grounds as before for changing the module size. Preliminary indications are that a nominal 100 kwe size may be appropriate.

Results so far obtained from the preliminary studies provide an indication of the characteristics that may be expected for nuclear plants based on the modular concept for the power range 20 to 300 kwe. The salient features of these plants are summarized in Table 4.

TABLE 4

ESTIMATED CHARACTERISTICS OF LARGE PLANTS*

Power (kwe)

	30	50	100	150	300
Module size (kw)	5	25	25	25	100
Number PCU's (active and standby)	6 + 2	2 + 1	4 + 1	6 + 2	3 + 2
Station diameter (ft)	20	30	30	30	50
Basic unit weight (lb)†	5,500-6,000	7,500-8,000	12,000-13,000	17,000-18,000	21,000-22,000
Station shield weight (lb)	3,000-3,200	4,000-4,800	10,000-12,000	15,000-17,000	20,000 23,000
Total NPP-MR weight (lb)	8,500-9,200	11,500-12,800	22,000-25,000	32,000-35,000	41,000-45,000
Radiator area (sq ft)	860	1,560	2,600	4,300	7,100
Station dose rate from reactor (mr/hr)	10	10	10	10	10
Reactor outlet and Temperature (°F)	1,200	1,200	1,200	1,200	1,200

*For cylindrical stations
†Total power plant weight exclusive of shielding

VI. CURRENT STATE OF TECHNOLOGY

In recent years, there has been a considerable yield of test experience applicable to NPP-MR from the SNAP 2, 8, and 10A* programs. The SNAP Experimental Reactor (SER) and the SNAP 2 Development Reactor (S2DR) have operated for extended periods at SNAP 2 conditions. Cumulative operating time for SER is 222,000 kwh and for S2DR is 250,000 kwh. Shown in Figure 41 are several views of the S2/10A reactor. The SNAP 8 Experimental Reactor has operated at its 1300°F rating at power levels meeting and exceeding the design value of 450 kwt. Performance during its several hundred hours of operation has been very stable and all characteristics verify design predictions.

Extensive development testing has been carried out at the subsystem and component level. Tests at both SNAP 2 and SNAP 10A conditions have gone far toward establishing the reliability of the reactor and reactor control system. A 1-yr test and several 90-day tests of control drum actuators have been carried out with design radiation doses at 700°F and 10^{-9} mm of Hg. Additional high vacuum tests of actuators at SNAP 2 conditions are underway. Gears and bearings with dry film lubricant have also been tested under irradiation and hard vacuum, 10^{-9} mm Hg, at and above S2 and S10A design temperatures and radiation levels. The S10 equipment has completed 90-day tests, and S2 units now under test are approaching the 500-hr mark. Results of the extended tests under high vacuum indicate self-welding is not a serious problem. Fuel element and diffusion barrier integrity has been good during approximately 380,000 hr of fuel rod tests at reactor temperatures. A temperature sensor-switch has completed 3,000 hr under S2 conditions, and has operated perfectly through 400 switching operations. Many similar components related to the reactor, such as safety and diagnostic elements, controller, etc., have been tested and performed as required under design conditions.

Most NaK and Hg system components are of basically simple design and are in an advanced state of development. A vital element in the PCS is the CRU, which includes turbine, alternator, and Hg pump. Figure 42 is a picture of a CRU just before installation in a test rig.

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*SNAP 8 is a nuclear power system designed for 30 kwe with mercury turbogenerator power conversion. SNAP 10A utilizes essentially the same reactor as SNAP 2, but a thermoelectric power conversion system designed for 0.5 kwe.

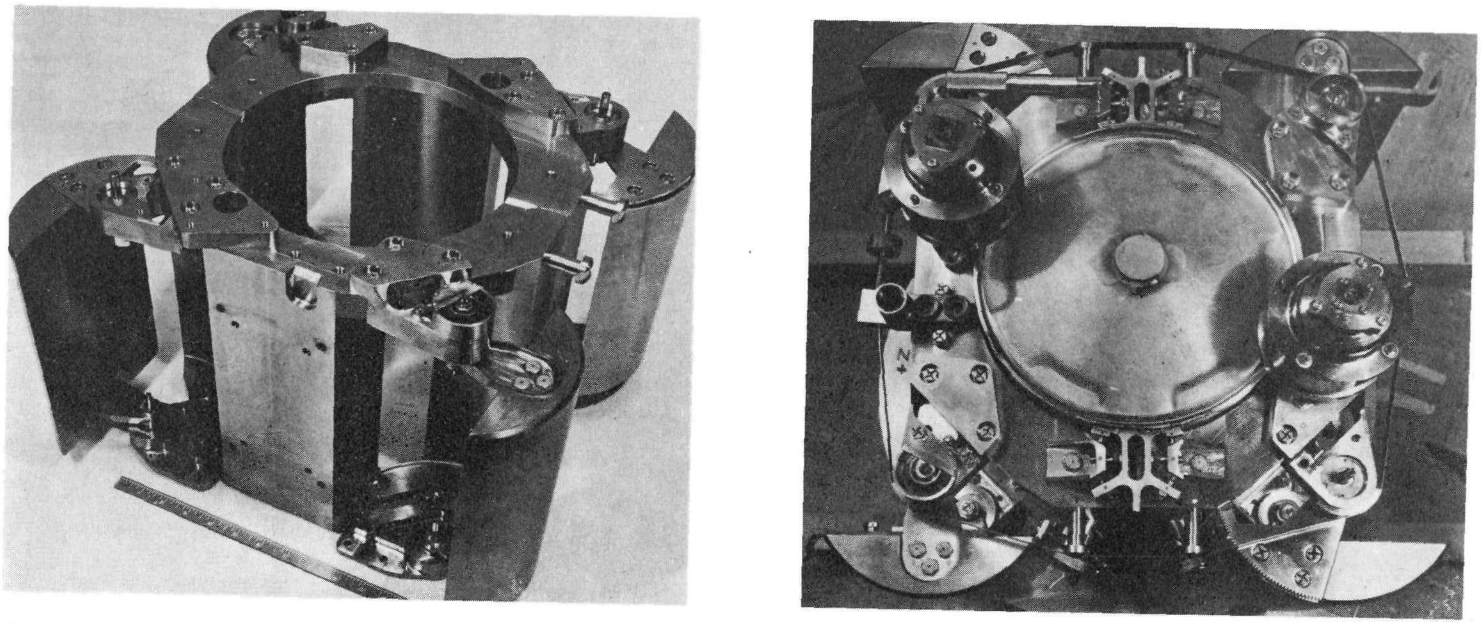

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Figure 41. SNAP Reactor

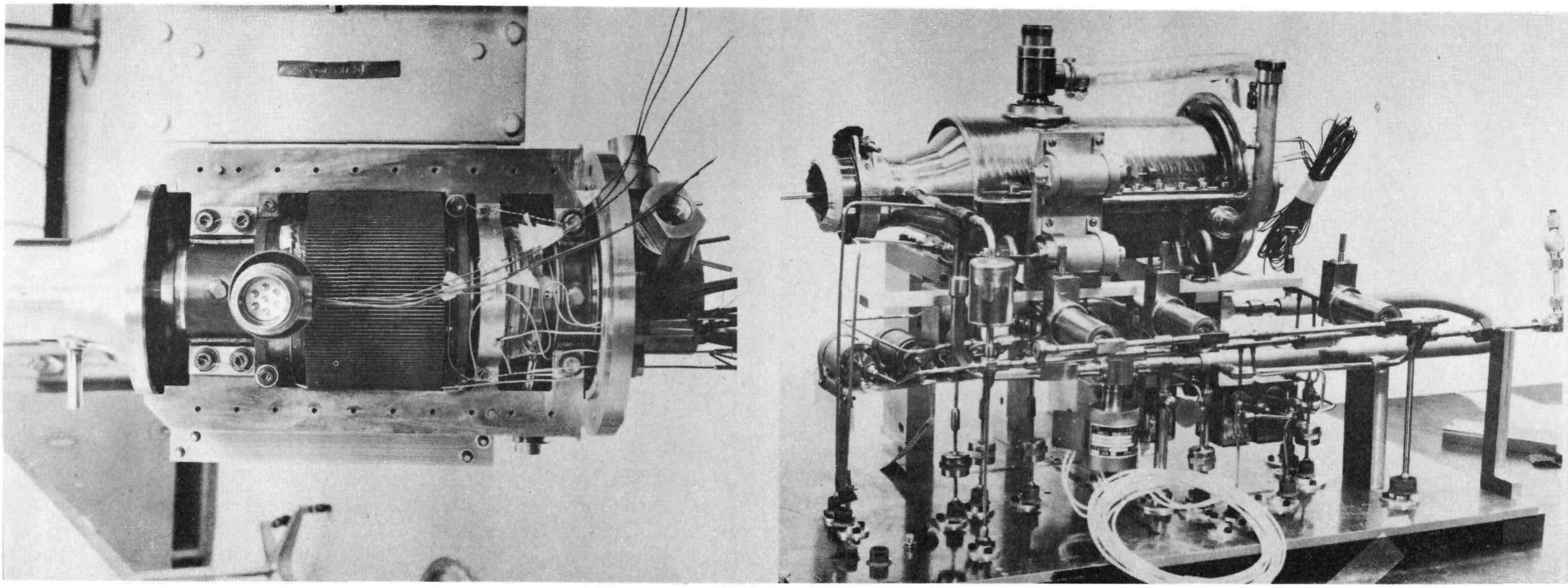

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Figure 42. CRU Hardware

Several years ago, a series of CRU bearing failures were experienced after the earlier, apparently successful development of individual CRU components. This brought about an intense effort to correct the troubles. The results have been very satisfactory. The feasibility of the CRU concept and the integrity of Hg-lubricated thrust and journal bearings has been clearly demonstrated.

In the last 2 years, 10 advanced CRU's of flight design and their rebuilds (designated IVM and V) have been fabricated and successfully tested under various startup conditions and for extended operating periods. Integrated endurance test time of these units presently totals 11,000 hr, and several units are now continuing extended endurance tests, producing better than design performance. It is anticipated that by the end of CY 1964, a total of 20,000 hr of endurance testing will have been accumulated. Also, SNAP 1 and Sunflower CRU units* exhibited in excess of 10,000 hr of integrated test time. Post-operation disassembly and inspection of the recent long endurance units has shown insignificant bearing and pump wear.

Thermoelectric pumps for NaK are nearing completion of development. In general, performance predictions have been verified and materials and fabrication problems appear to have been solved. Endurance testing is underway. Other key components are the boiler and RC. Several boiler units have been tested (see Figure 43), with performance being as predicted. In the case of the RC, it is required that this component integrate structural and heat-rejection capabilities with weight optimization and meteoroid protection. Two RC concepts are under development (honeycomb and aluminum-steel) and tests of several units are underway. Results of the development effort show that the aluminum-fin/steel-tube unit is superior with regard to cost, weight, and fabrication ease. Such a unit is pictured in Figure 44. Most other SNAP 2 components, including the radiation shield, T/E pump expansion compensator, pressure regulator and valves, electrical elements and instruments, expansion joints, and thermal barriers, are in the advanced development stage. A T/E pump for NaK is pictured in Figure 45.

On the strength of the component development foundation, sophisticated tests of integrated systems have proceeded. Long-term nonnuclear operating tests of NaK and Hg systems have been successful. Two test systems,† SNAP 10 FSM-1

*Of the same basic technology as CRU IVM and V.
†Part of the SNAP 10A program — but similar in NaK system technology to SNAP 2-NPP-MR.

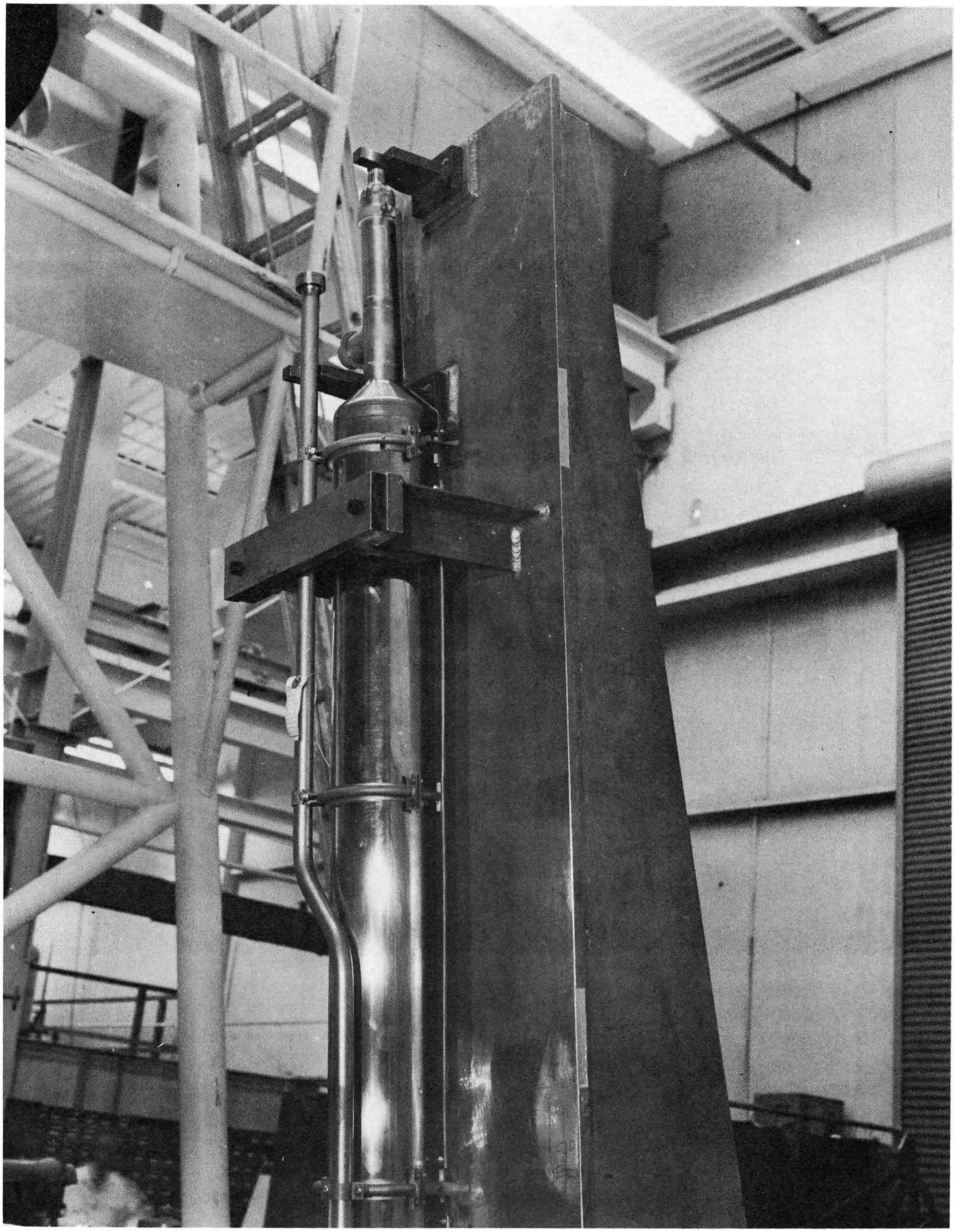

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Figure 43. Boiler

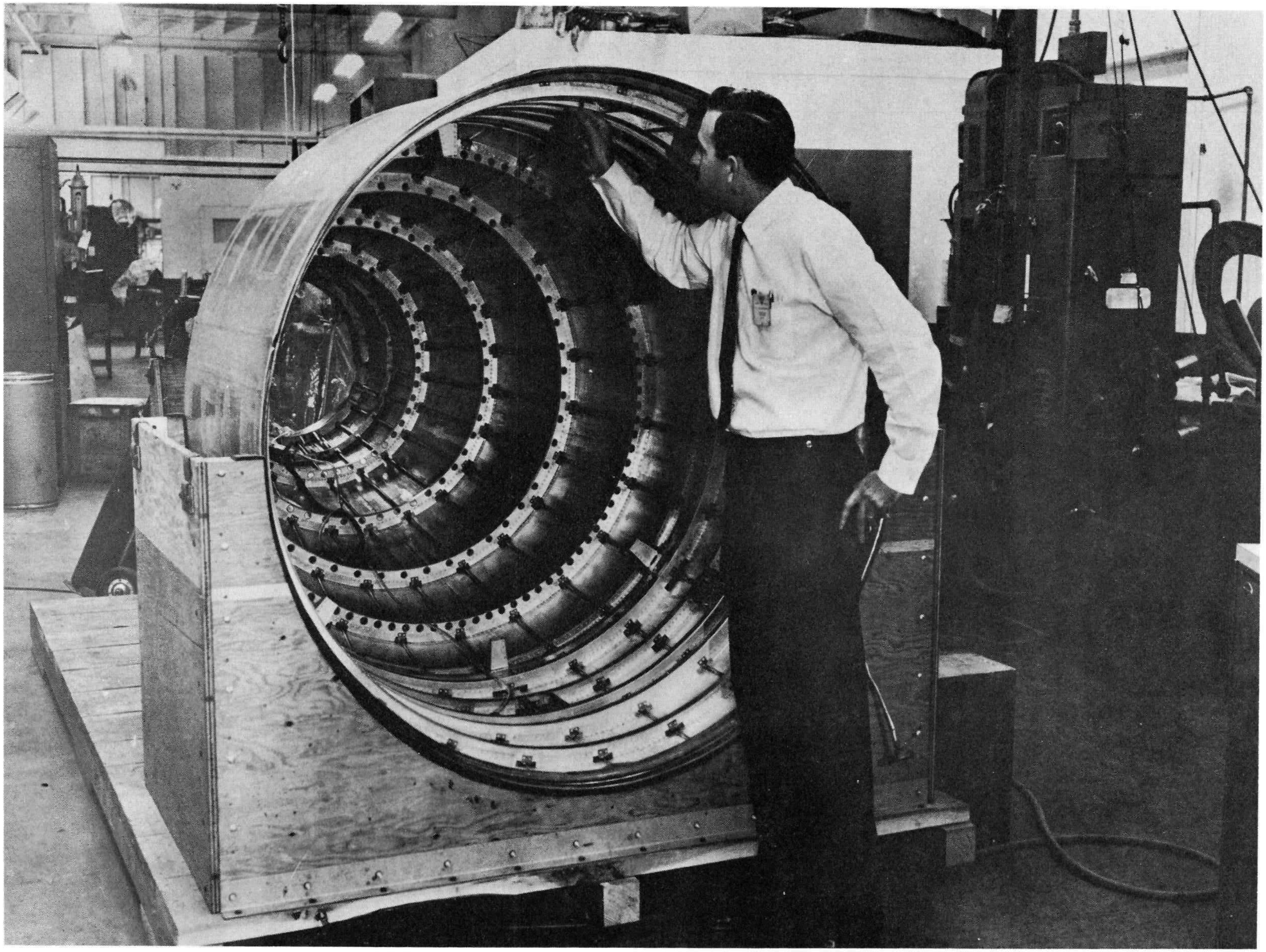

Figure 44. Radiator-Condenser

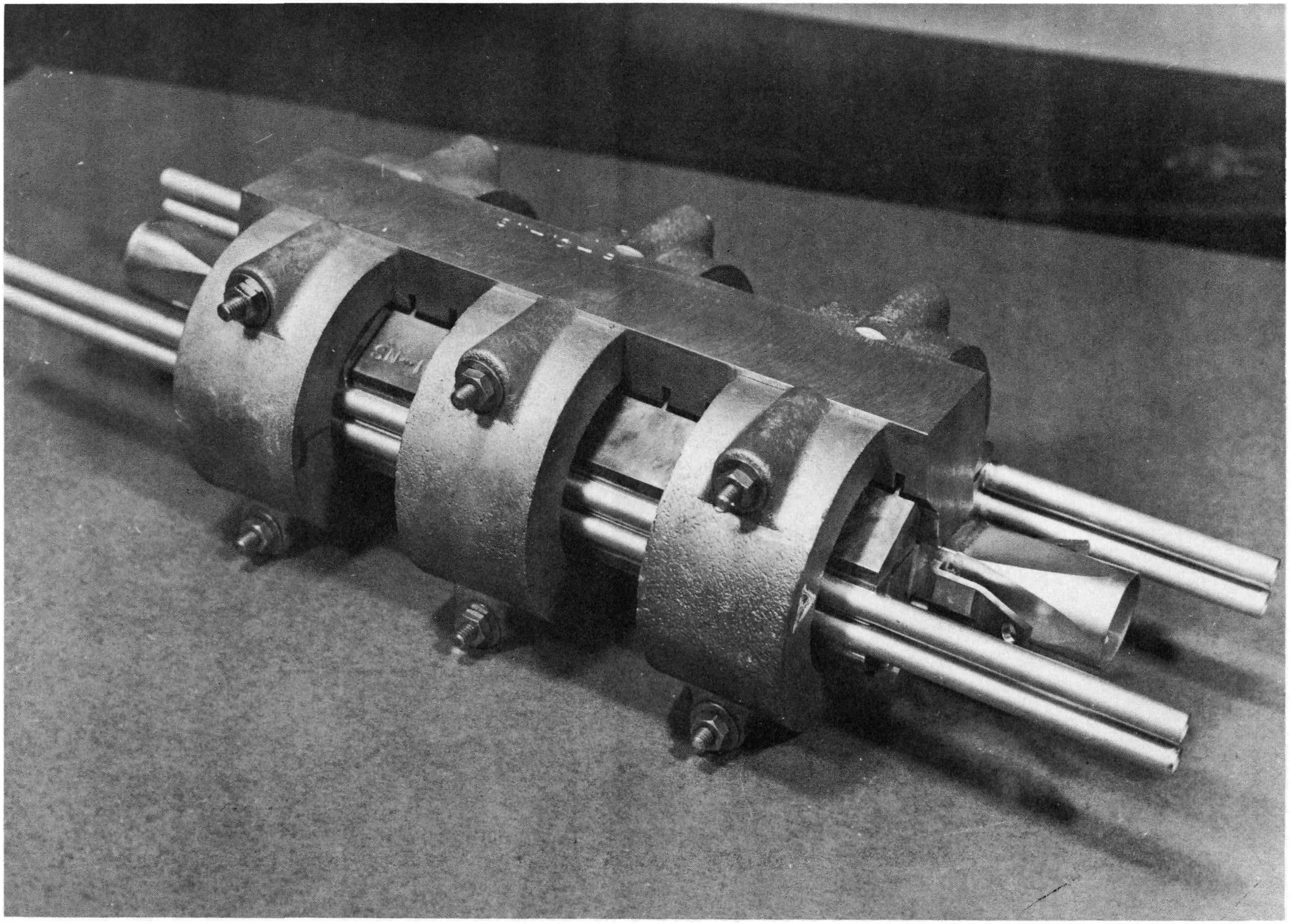

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Figure 45. T/E Pump

and DRM-1, have completed 90-day qualification tests at design temperatures under simulated space conditions. For several years, tests have been conducted at SNAP 2 conditions in Hg systems. Currently progressing are tests of SNAP 2 prototype PCS units, PSM-1, -2, and -3. With these systems it is possible to duplicate for the PCS practically all environmental and operating conditions of interest. The substitution of a carefully designed simulator for the reactor and control system for the reactor significantly reduces costs and safety measures required, without compromising the technical quality of the results. PSM-1 is the flight configuration prototype designed for study of system thermal characteristics in a simulated space environment, Figure 46. PSM-2 is a mechanical and structural mockup which, since mid-1963, has been undergoing tests covering the entire envelope of expected vibration, shock, aerodynamic heating, and static conditions. PSM-3 is a system designed to study orbital startup effects; all important components lie in the same horizontal plane (Figure 47) to minimize gravity effects. Table 5 is a summary of the current status of component development.

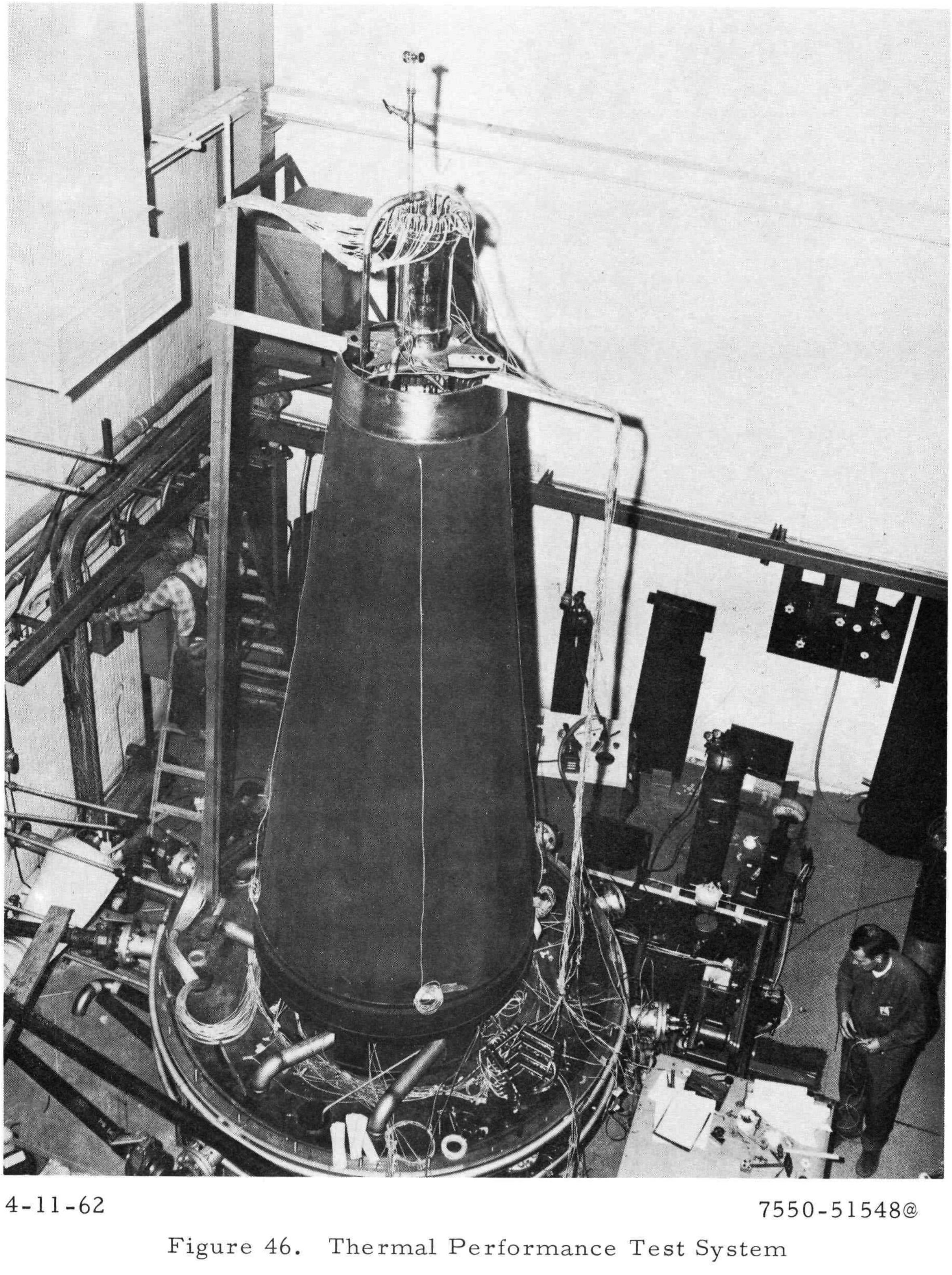

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Figure 46. Thermal Performance Test System

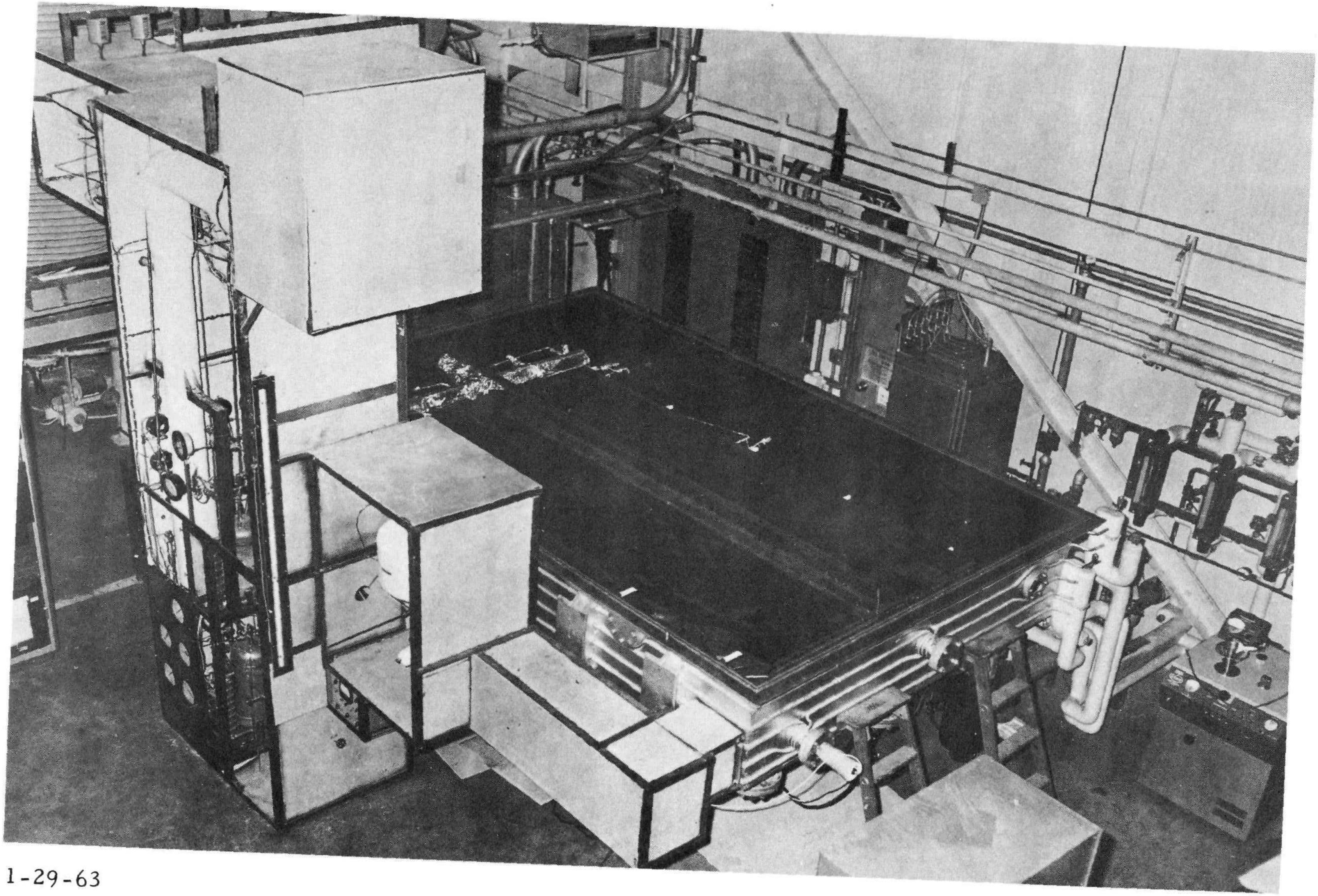

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Figure 47. SNAP 2 Zero-G Simulation

TABLE 5

STATUS OF COMPONENT DEVELOPMENT

Component	Number Fabricated (units)	Total Test Time (hr) (approx)	Longest Individual Tests (hr)	Shock Vibration or Static Tests (No. units)	Maximum Startup Cycles (unit)	Performance Verified	Remarks
Combined rotating unit	18	11,000	2,500	1	29	yes	CRUV long term endurance tests underway
Boiler	19	5,600	2,160	3	20	yes	5 c boiler prequalified
Radiator condenser	5	1,100	500	3	115	Thermal and hydraulic yes	
Thermoelectric pump	14	5,000	2,700	In process	10	yes	
Expansion compensator	3	550	500	0	15	yes	Prototype component in fabrication
Expansion joints	8	150	50	0	4	yes	Prototype component in fabrication
Mercury pressure regulator	4	100	0	1	25	no	New design concept
Mercury injection tank	6	1,000	0	1	500	yes	New design concept
Parasitic load control	11	6,000	2,466	1	81	yes	
Reactor simulator heater	4	1,000	500	N.A.	15	yes	On test — PSM-1 and 3
Parasitic load heater	11	10,000	8,400	0	1,440	yes	

APPENDIX A
RELATIVE MERITS OF NPP-MR

Nuclear and solar power systems are the only systems which can supply space stations with significant levels of power for periods of time exceeding a few weeks. For missions of this type, batteries and fuel cells systems are not practical because of their excessively high weights. Nuclear (reactor and radioisotope) and the various solar power systems (basically solar cell and solar-dynamic systems) each offer their own favorable and unfavorable features. The selection of one over the others for a particular mission must be made in the context of overall mission requirements, total cost, reliability, and other factors. In making comparisons for such selections, the distinct advantages offered by NPP-MR systems have previously been published (References 3 through 6). The advantages of these nuclear power systems become more decisive as mission duration and electric power requirements increase. NPP-MR units are compact, rugged, single-package, closed-loop, complete electrical power plants, and provide safety and relative economy without imposing significant constraints on space station design. NPP-MR's require minimum power storage and no collector (or other area) deployment while furnishing the advantages of continuous power and high power per unit radiator area (~40 watts/ft^2).

The modular, or building-block approach, based on the SNAP 2 reactor and current state-of-the-art components, yields early availability, reliability, and considerable design flexibility. This approach also yields economic advantages. Development costs for such building-block systems would be well under the costs for large, single unit systems. Three important reasons for this are:

1) It will be unnecessary to develop new components for each individual spacecraft power requirement.

2) The actual cost of developing a low-power power conversion subsystem (PCS) module is less than that for a specific high-power PCS due to savings on hardware, facilities, and test costs. Also, flight tests of smaller PCS's may be carried out with smaller launch vehicles, and the money already expended in SNAP 2 development provides an "incremental" investment picture that favors the smaller units.

3) The cost of the reliability demonstration program will be less for smaller PCS's.

The use of an NPP-MR package eliminates the need which exists with solar systems for preferential plant orientation and for the thermal or chemical energy storage necessary for power generation during periods when the station is shaded by the earth.

A key economic factor is weight placed in orbit during a mission, and in this connection nuclear power plants afford important advantages. The basic power plant weight for NPP-MR's is generally much lower than that for other systems as indicated in some detail in References 3, 4, 5, and 6. In addition, weight advantages are indirectly gained by NPP-MR's in other areas. For example, solar voltaic and solar dynamic systems require far more surface area for normal requirements (for 10-kew plants, a factor of ~10 larger than NPP-MR systems); also in the case of solar cells a substantial amount of excess area must be provided to allow for power source attrition due to meteorite damage and Van Allen Belt proton irradiation (assuming gamma and x-ray shielding is provided). Nuclear dynamic systems are not subject to degradation from these causes. In relatively low altitude orbits, the large surface area of solar plants causes significant drag and a portion of payload weight must be devoted to providing thrust to maintain orbit. Nuclear plants cause much less orbital drag, and in addition SNAP flight system development has produced a configuration well suited for launch and easily adaptable, without redesign, to both deployable and non-deployable space stations.

For long missions involving power plant renewal, the replacement weight of a nuclear system is small compared with systems such as solar cells, particularly if one of several feasible designs providing reusable nuclear radiation shields is adopted. However, for some applications, making the shield an integral part of the disposable package may be advantageous — such as providing simplicity, compactness, and better weight distribution. During periodic power plant replacements, the entire package may be safely disposed of and a new unit installed in its place. Only mechanical and electrical connections are broken and rejoined since the reactor, components, and complete fluid systems are contained within the plug-in power plant package.

As a space station power source, nuclear dynamic systems have considerable growth potential. Weights and surface areas of other systems escalate rapidly with increasing power, in contrast with proportionately small increases in nuclear system weight and areas. Extension of Mercury-Rankine nuclear plant designs to specific applications is largely an engineering task. Design flexibility is such that adequate shielding protection may be provided for astronauts during normal operations and various rendezvous maneuvers. While the relative advantages offered by nuclear systems at low power levels (<10 kwe) are less imposing than in the case of higher power level, the basic technology is the same. The use of nuclear plants for early space missions with low power requirements will provide a valuable foundation for the use of nuclear power with attendant substantial advantages to meet future demands for higher power and longer missions.

In summary, the more important conclusions regarding NPP-MR plants for manned space stations are: (1) 7 years of intense engineering, design, and hardware development activities have established a firm basis for NPP-MR technology; (2) the weight of a shielded NPP-MR is competitive with or less than other power sources with the weight advantage increasing considerably as power level and mission duration grow; (3) the comparatively small surface area required permits low altitude operation permitting escape from space radiation effects with minimum drag penalty; (4) NPP-MR's are safe, and safety is enhanced by the presence of onboard personnel; (5) there exists no orientation requirement (or sun-shade variation in operations) so that the interaction of power system/station is minimum; (6) the total cost of development plus utilization is comparable for all systems; and (7) early use and integrated nuclear system experience will accelerate growth to larger future systems.

APPENDIX B

NPP–MR RELIABILITY

The equation for overall NPP-MR plant reliability is:

$$R_o = R_e R_b^i R_p \sum_{i=o}^{r} \binom{n}{i} R_{he} \left(R_{hs}\right)^s \left(1 - R_{he} R_{hs}\right)^s$$

where R_o is overall reliability, R_e is reliability of electrical power distribution system, R_b is boiler NaK-Hg interface reliability, R_{he} and R_{hs} are mercury loop steady-state and shutdown-restart reliabilities,* R_p is reactor and primary loop reliability, s is the number of restarts, i is the number of PCU's required for full power, r is the number of redundant loops, and n is the total number of modules. Load switching is accomplished external to the basic power distribution system. The numbers in parentheses are NPP-MR reliability objectives.

An overall system reliability goal of 0.95 - 0.99 has been used in some studies in the industry. For given reliability of each power conversion (mercury) loop ($R_h = R_{he} R_{hs}^s$), the reliability required of the reactor and primary loop ($R_p = R_n R_{re} R_{rs}^s$) in order to achieve $R_o = 0.98$ is given in Figure 9b for several power levels (5 kwe module) assuming one redundant PCU in each system and the SNAP 2 reliability values given in Table 2.

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*The best information available on rendezvous maneuvers indicates reactor shutdown for that operation is unnecessary (cf Sections II-B and III-C). However, the equation is written as shown for generality.

APPENDIX C

RADIATION – ENVIRONMENTAL AND BIOLOGICAL EFFECTS

Listed below are the probable early effects of acute doses of whole body radiation exposure. Some evidence available tends to indicate the effect of protracted doses in general are less severe for the same exposure.

TABLE 6

BIOLOGICAL EFFECTS OF ACUTE RADIATION DOSES

Acute Dose (rem)	Effect
0 to 25	No detectable clinical effects
25 to 50	Possible blood changes, but no clinically detectable effects
50 to 100	Depression of blood elements (recovery in nearly all cases in 3 to 6 months)
200 to 400	Same as above with immediate disability, some deaths possible
600	Fatal to nearly all within two weeks

In the natural space environment there exist very intense radiation fields which probably will contribute more to the dose received by astronauts than will the nuclear plant. In near-earth space, there is considerable non-uniformity in the environment, and the protection required depends on the path followed by the particular station. There are four major sources of radiation: Van Allen radiation belts, the Starfish or artificial electron belt, solar flares, and galactic cosmic rays. The Van Allen belts consist of electrons and protons, and the Starfish belt is composed of electrons alone. Solar flares and galactic cosmic rays consist primarily of high energy protons, and the solar proton streams may also be accompanied by x-rays, electrons, and gamma rays.

Van Allen belt radiation imposes a limit on operational celing of about 300 miles for extended missions, since the shield weight requirements above that altitude become prohibitively high. Similarly, the presence of extremely high energy radiation from solar flares and galactic radiation in the higher latitudes establishes an upper limit of about 45° latitude on the orbital inclination. At lower latitudes, the earth's magnetic fields shield the station from solar flare and cosmic radiation, and the acute dose hazard is nearly eliminated. Atmospheric drag and sputtering effects become increasingly important at lower altitudes, and, based on these effects, a lower limit on orbital altitude is probably about 200 miles.

The threshold for radiation damage to the most sensitive hardware components (transistors) is about 2000 rad for fast neutrons (~ 10^7 rad for gamma rays). The thresholds for biological damage depend on the part of the anatomy involved. As indicated above, in the expected envelope of orbital operation, there is protection from acute doses of radiation. Thus, the risk-limiting effects are those associated with protracted exposure. On the Apollo moon mission program the basic criteria being employed[19] are the National Committee on Radiological Protection recommendations for permissible integrated lifetime doses, although there is no official sanction for this position. The assumption is made that each astronaut will have a five-year career and thus may receive his lifetime dose over this period. These conditions are tabulated in Table 7.

TABLE 7

APOLLO CRITERIA

Critical Organ	Maximum Permissible Integrated Dose (rem)	Average Yearly Dose Rate (rads)	Maximum Permissible Single Acute Emergency Exposure (rads)
Skin of whole body	1630	233	500*
Blood forming organs	271	54	200
Feet, ankles, hands	3910	559	700†
Eyes	271	27§	100

*Based on skin erythema level
†Based on skin erythema level; these appendages are less radiosensitive
§Slightly higher RBE assumed because eyes are believed more radiosensitive

Tabulated in Table 8 are various other figures relevant to shielding design for radiation.

TABLE 8

RADIATION FACTORS

Dose	Condition
Permissible Levels	
3 rem/13 weeks (12 rem/year or 0.033 rem/day)	AEC occupational dose limit
5 (N-18) rem	AEC limit on cumulative exposure, N = age of individual
Space Radiation Levels*	
0.5 to 8.5 rad/day	Van Allen belt protons and galactic cosmic radiation
NPP-MR	
0.01 rem/hr (0.24 rem/day)	Typical basis for reactor station shield design for 90-day missions

*Considering present contributions by Starfish and other electrons to be negligible; based on 30° orbital inclination, 125 to 310 mile altitude, 420 mil thick Al wall shielding (3 gm/cm^2)

The reactor produces a gamma and fast neutron radiation against which biological shielding must be provided. During plant operation the sources of significant gamma radiation are prompt-fission gammas, fission product gammas, and activation gammas from neutron capture by structural and coolant materials. Protection against fast neutron leakage from core and reflector must also be provided. During shutdown, the (biologically) important radiation is gamma ray flux associated with fission product decay and activated NaK in the primary coolant system.

APPENDIX D
ARTIFICIAL GRAVITY EFFECTS ON DESIGN

Depending upon the rate of spin and distance of the plant from the axis of rotation, the artificial gravity may induce sufficient fluid motion due to natural convection in primary and secondary system loops to importantly influence the plant layouts. The influence of "g" effects is also reflected in the design measures required to assure flow stability in the radiator condenser. For a given design situation, three possible types of flow instability must be considered: (1) flow regime stability, (2) liquid leg instability, (3) liquid-vapor interface stability. With reference to the first, it is necessary only to assure that the conditions required for maintenance of annular or semi-annular flow are obtained. There is an abundance of technical experience in this area (at least 150 studies are reported in the literature), and flow regime instability will not be a problem. Considerable attention has also been directed toward the latter two areas, particularly in connection with the SNAP 2-MRP effort (viz. Reference 20-24).

With reference to condition (2), for stable operation of a multi-tube condenser, it is necessary that the change in pressure drop between tube entrance and exit due to change in condensing length must be positive. That is, the criterion for "liquid leg" stability is $d(\Delta P)/dl > 0$, where l is the tube length in which condensing occurs. This is true whether the total pressure drop is positive, or negative, as it may be if the static pressure rise due to momentum recovery exceeds the friction losses down the tube and pressure change due to gravity. It was determined that the maximum permissible artificial g force (due to package tumbling) opposite the flow direction and before the onset of instability was 0.05 to 0.14 g for the SNAP 2 flight system. The reason behind the stability criteria is that for positive $d\Delta P/dl$, an increase in condensing length of a particular tube causes a decrease in pressure at the liquid-vapor interface. This results in a net force on the liquid leg which tends to restore the interface to its original position. Similarly, with reduction in condensing length, the net force tends to restore the interface to its original position. When $d\Delta P/dl < 0$, the net force is such as to accelerate the liquid leg in the direction of the initial disturbance and the system becomes unstable.

The third potential problem arises from Taylor instability, i.e., conditions arising when the direction of acceleration at an interface is from the denser to the lighter fluid. The requirement for stability (in round tubes) in this case is given by

$$D \leq 1.835 \sqrt{\frac{\sigma}{a(\rho_f - \rho_v)}}$$

where D is the tube diameter, σ the surface tension, a the local acceleration, and ρ_ℓ and ρ_v the liquid and vapor densities. For some acceleration in a direction opposite to the flow in a tube of given diameter, the liquid-vapor interface will become unstable. Bench model tests and system tests (PSM-3) have shown for the present SNAP 2 system that no such flow stability problems exist. In general, it will be possible by the selection of RC orientation and configuration, tube geometries, and performance conditions to provide a satisfactory stable range of operation of the unit regardless of what the g level might be. In fact, by having the direction of artificial "g" the same as the flow direction, stability is enhanced.

Two collateral and less important effects related to spinning stations are worth mentioning. First, the g force should be taken into account in designing the control drum positioning fixtures. Secondly, the g effect may be used to advantage (although startup in zero g is possible) in connection with system startup by arranging for the artificial gravity to control the distribution of liquid mercury in the desired manner. For example, the liquid distribution at startup (and shutdown) could be exactly the same as exists for ground tests.

APPENDIX E
RENDEZVOUS MECHANICS

An abundance of information has been published on the rendezvous and docking of space craft. The data available (for example References 7-16) indicate that it should be feasible for a shuttle craft to approach and dock at a space station without being exposed to significant radiation from the operating reactor. That is, it should be possible for the shuttle craft to remain in the shadow cast by the station shield from the time that the station-to-craft range is about 1500 ft until the time of contact. To clarify and support this view, a simplified account of some aspects of rendezvous is presented in the paragraphs below.

The mode usually considered for rendezvous of a ferry vehicle with a target vehicle in earth orbit involves first placing the ferry in a co-planar intermediate orbit, then transferring it to the orbit of the target. This approach gives far greater launch time allowance than is available when rendezvous is accomplished by direct ascent. Two types of intermediate orbit are often referred to: (1) an elliptical or chasing orbit with apogee which matches the altitude of the (circular) target orbit, and (2) a circular parking orbit. The latter case is the approach adopted in several earth orbit rendezvous studies, with parking orbit altitudes of about 100 miles and station orbit altitudes of about 300 miles.

Although nomenclature relative to the rendezvous maneuver varies in industry practice and in the literature, the following tabulation (Table 9) characterizes the four basic phases of the operation following departure from the parking orbit.

TABLE 9

RENDEZVOUS NOMENCLATURE

Phase	Description
1	Transfer orbit injection
2	Mid-transfer orbital corrections
3	Terminal homing (begins 5 to 100 miles from target)
4	Docking (begins 500 to 1500 ft from target)

Illustrated in Figure 48 is a typical rendezvous sequence. Different studies have covered the possibilities of: (1) the shuttle craft closing at about the same altitude as the target, as shown in the figure, and (2) the shuttle craft departing from the transfer orbit at a lower altitude and closing while the station maintains an earth-centered, vertical attitude.

Before beginning Phase 1, complete equipment and navigational checkout will take place in the parking orbit. In general it is probable that several guidance, navigation, and control modes will be available with both on-board and ground derived information. It is possible that some orbital maneuver such as an orbit plane change may be carried out prior to commencement of Phase 1.

Phase 1 will be initiated by impulse into the transfer orbit, and navigation and guidance updating will take place during the flight — Phase 2. At or near the apogee of the transfer orbit, either a second impulse will be applied to circularize the shuttle craft orbit, or else the terminal homing phase will begin with no separate circularizing impulse. Various error analyses have been reported relative to the amounts by which shuttle craft position and velocity differ from desired values at the end of the transfer orbit. These have covered different control modes, orbital conditions, and equipment accuracies representing both current state of the art and projected capabilities. Typical results are presented in Table 10.

TABLE 10

TERMINAL ERRORS — Transfer Orbit

	Typical Errors			
	Single Impulse*		Two Impulses†	
Number parking orbits	0	1	0	1
Range (n. mi)	5	1.5	2	1
Altitude (mi)	2	0.2	1	0.2
Velocity (fps)	35	10	15	5

*To initiate transfer orbit
†Initial plus final circularizing impulse

Phase 3, terminal homing, would probably be executed automatically without manual intervention. In general the methods proposed for Phase 3 correspond closely to guidance schemes long in use for aircraft interceptions, etc.

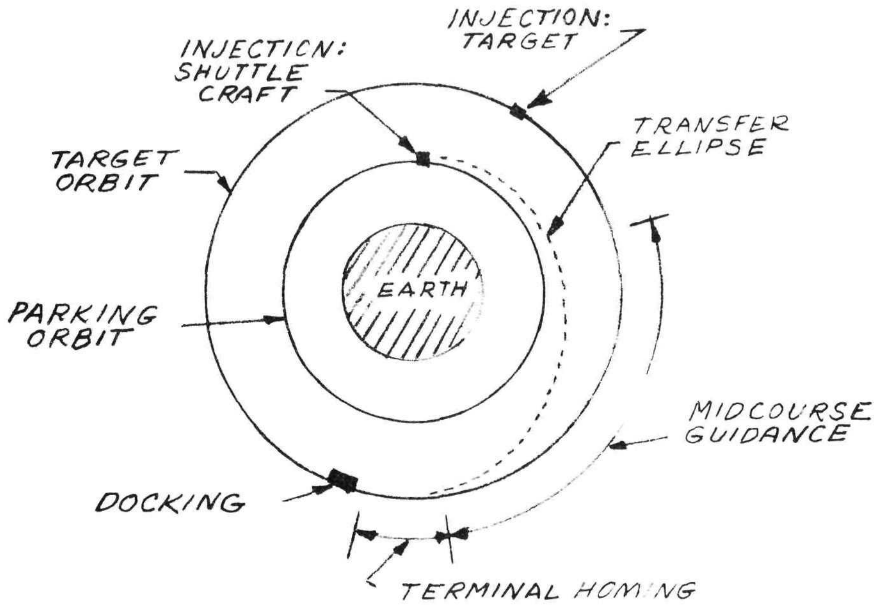

Figure 48. Rendezvous Profile

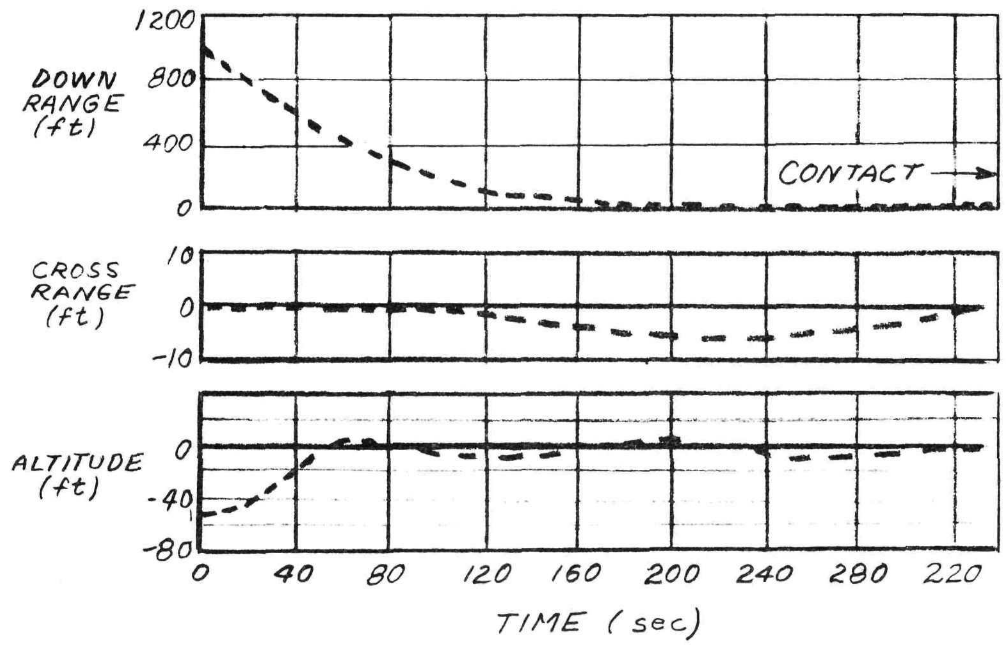

Figure 49. Shuttle Craft Trajectory During Docking

The systems are low in complexity, and are further simplified because of the near absence of atmosphere. Range, range rate, and target-ferry line of sight angular turning rate are sensed and processed, ultimately resulting in commands to the propulsion system. The current capabilities of typical sensing equipment of the type called for in Phase 3 are tabulated below.[14]

TABLE 11

CHARACTERISTICS OF HOMING PHASE SENSORS

Variable	Characteristic
Maximum range (mi)	150
Range accuracy (ft)	± 0.5% ± 5
Range rate accuracy (fps)	± 0.5% ± 0.5
Angle accuracy (°)	0.25
Angle rate accuracy (milliradians/hr)	0.25

A number of parametric studies of terminal homing have been carried out analytically and with simulators. In general it was found very practical for the ferry to achieve a range from, and velocity relative to, the target which was very suitable for initiation of the docking phase. This was true even in cases with built-in errors, deviations in thrust and measurements of kinematic variables. In a typical case, the miss distance at the end of a homing maneuver beginning at 200,000 ft range was ~50 ft. The results of these studies, as might be expected from the information in Table 11, indicate the desired initial conditions for the docking phase may be established with good accuracy. Currently on the Apollo program, the reference values used for 1σ variation from desired position and velocity at the end of the homing phase (beginning of docking phase) are 100 ft and 1 fps.

In order for the docking phase to be executed with the reactor operating and without shuttle craft departure from the station shadow cone-corridor, it is necessary that the Phase 3 rendezvous objective be a point astern of the station (such as point 0 in Figure 11). This would require some change from the maneuver contemplated in many studies, and would involve a small ferry fuel weight penalty. The total fuel consumption estimated for most docking phase studies is roughly in the range 200 to 400 lb. The weight penalty for the modified maneuver discussed above would probably be a fraction of the total fuel allotment for docking.

The docking phase would begin (for a station with NPP-MR) at a range of about 1500 ft and would be carried out under manual control. The station attitude would remain stable during this phase (about 1° limit cycle). A large number of docking phase studies have been carried out analytically and with simulators. These efforts usually have been designed to evaluate effects such as control mode, thrust levels, system failures, lighting conditions, and visual aids. They have encompassed a variety of initial conditions and possible system failures. The results generally indicate that the craft can remain within the specified corridor and dock within a reasonable time with either astronaut or automatic control. In Table 12 are compared the NASA standards for allowable docking terminal error with the results of one typical simulator study.[14] In Figure 49 is shown a typical reported[12] shuttle craft trajectory during the docking phase. The run shown was the sixth executed by that particular astronaut, and it therefore reflects a moderate amount of practice.

TABLE 12

TERMINAL ERRORS – DOCKING

	NASA Criteria	Typical Simulator Results[13]
Distance (ft)	1	0.7
Relative velocity (fps)	2	0.4
Alignment (°)	10	4.0

A reliability study contained in one publication[6] indicated a very low probability of failure to rendezvous. Even if during the docking phase the ferry strayed from the corridor and an emergency condition developed (as might be indicated by a gamma ray detector on the craft or extended from the craft on a boom), there would be sufficient time to take corrective action before a dangerous amount of radiation exposure occurred. In such circumstances the astronaut might, for example, use reaction jets to accelerate the vehicle away from station and reactor. For the Apollo case, if one quadrant of the propulsion system fails, the other quads compensate and the craft should remain in the shadow cone. It is estimated that a "fly" by the reactor would occur only if three of the four quads failed. The probability of this occurrence is estimated to be of the order $< 10^{-6}$.

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