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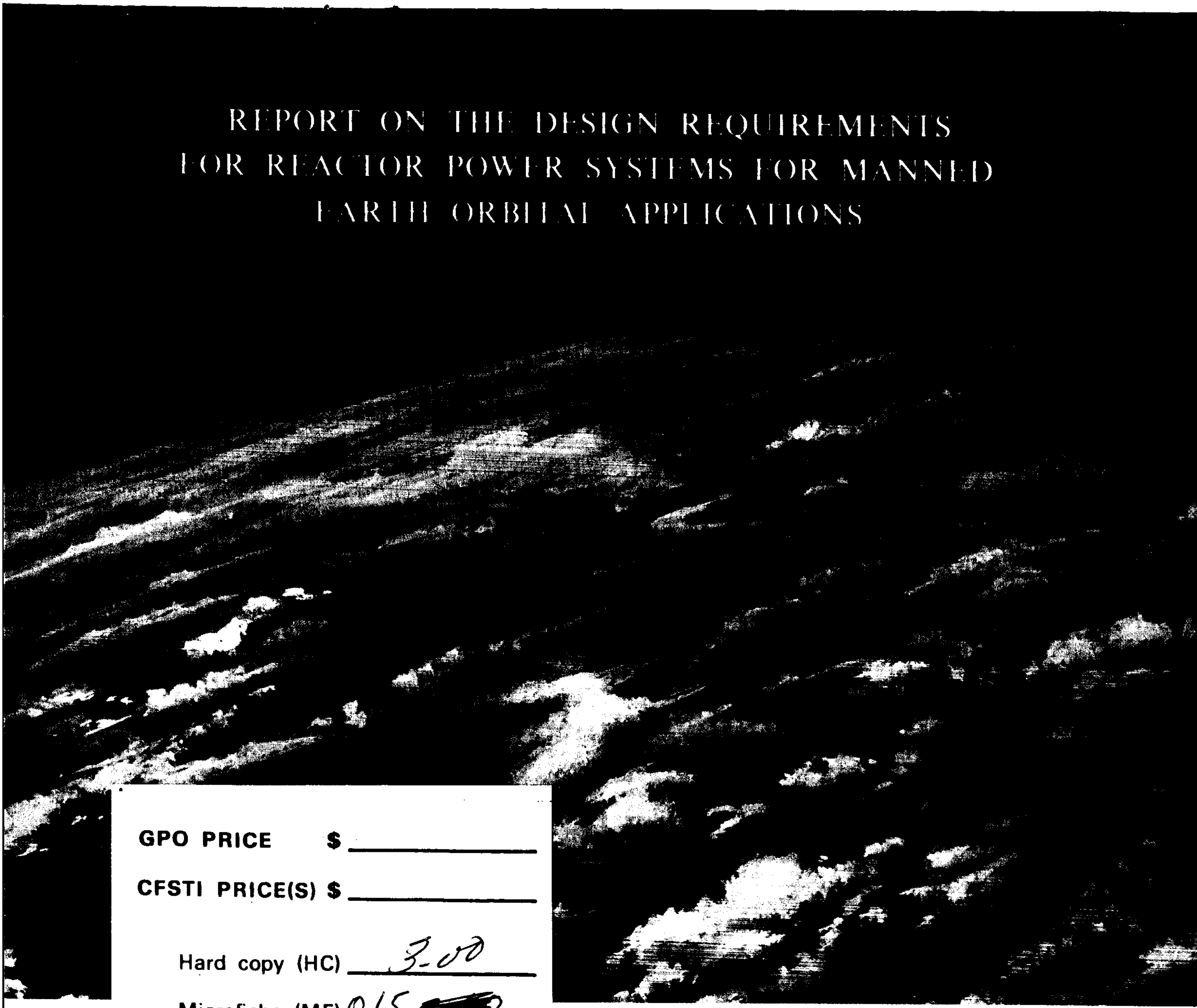
REPORT ON THE DESIGN REQUIREMENTS FOR REACTOR POWER SYSTEMS FOR MANNED EARTH ORBITAL APPLICATIONS



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REPORT ON THE DESIGN REQUIREMENTS FOR REACTOR POWER SYSTEMS FOR MANNED EARTH ORBITAL APPLICATIONS

FINAL REPORT

PREPARED UNDER CONTRACT NAS 1-5647
BY/DOUGLAS AIRCRAFT COMPANY, INC.
MISSILE AND SPACE SYSTEMS DIVISION
FOR NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION
LANGLEY RESEARCH CENTER

JANUARY 1967
DAC–57950

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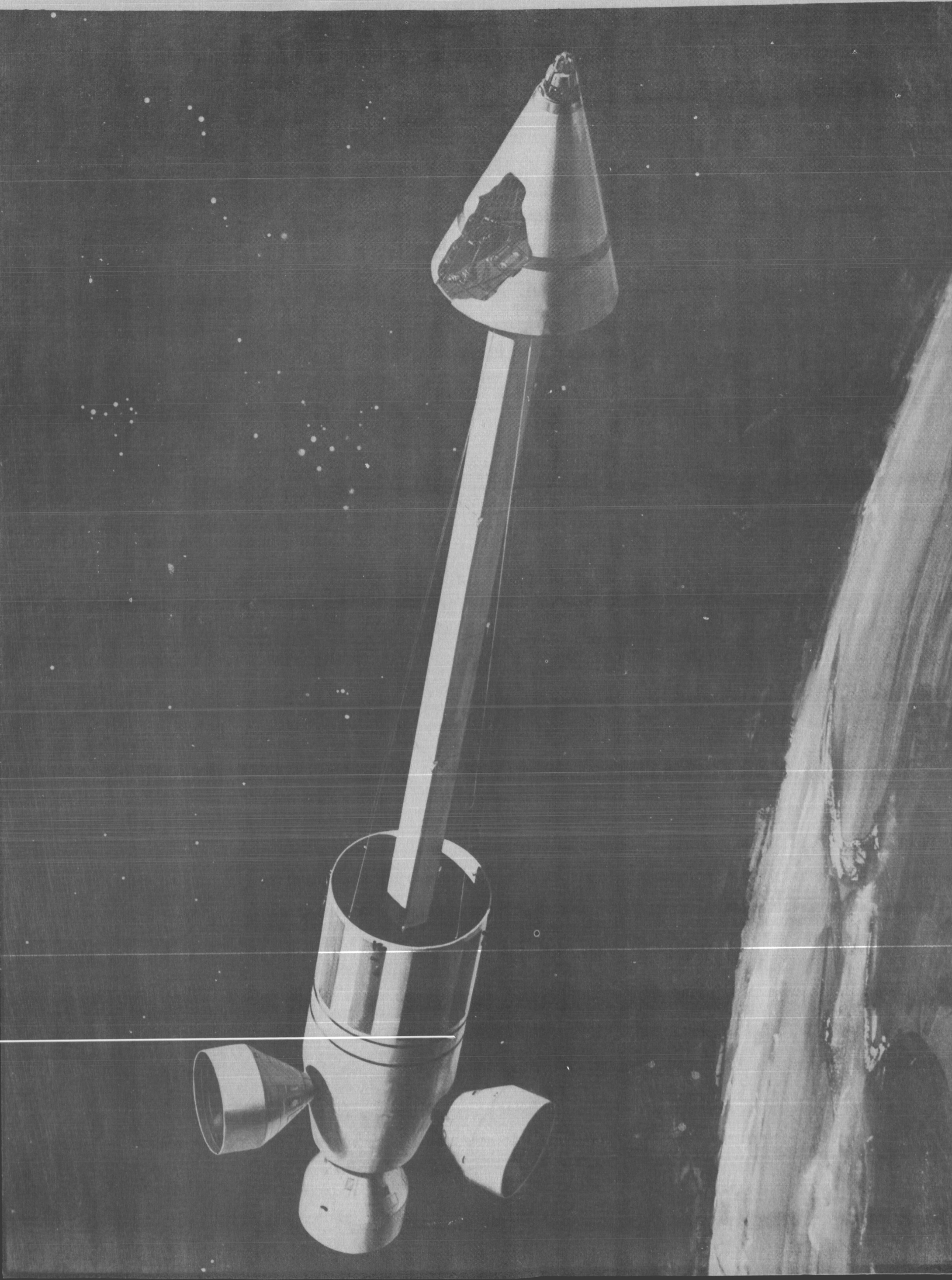
DOUGLAS MISSILE & SPACE SYSTEMS DIVISION



ACKNOWLEDGMENT

During this program, Douglas Aircraft Company, Inc., collaborated with an associate contractor, under the cognizance of the Atomic Energy Commission, and several subcontractors whose contributions have made this report possible. These companies and their respective areas of effort are as follows:

Company	Support Area
Atomics International, Division of North American Aviation, Inc.	Reactor and Shield
Westinghouse Astronuclear Laboratory, Westinghouse Electric Corporation	Thermoelectric Power Conversion System
Von Karman Center, Aerojet-General Corporation	SNAP-8 Power Conversion System
Atomics International, Division of North American Aviation, Inc.	SNAP-2 Power Conversion System
AiResearch Manufacturing Company of Arizona, Division of the Garrett Corporation	Brayton-Cycle Power Conversion System

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PREFACE

This report is submitted by the Douglas Aircraft Company, Inc., to the National Aeronautics and Space Administration's Langley Research Center. It has been prepared under Contract No. NAS1-5547, and it describes the results of an assessment of the Design Requirements for Reactor Power Systems for Manned Earth-Orbital Applications.

The Final Report, Douglas Report No. DAC-57950, presents a summary of the approach, scope, and conclusions of the overall study. Supplementing the final report are the seven reports, each relating to one of the five Task Areas, which were completed sequentially during the course of the study. The Task Area reports consist of the following: Task Area I, Program Definition, Book 1, SM-51965; Task Area II, Parametric Analysis, Book 1, DAC-58213; Task Area II, Parametric Analysis, Book 2, DAC-59214; Task Area III, Design and Integration Analysis, Book 1, DAC-57932; Task Area III, Design and Integration Analysis, Book 2, DAC-57933; Task Area IV, Comparative Analysis, DAC-57942; and Task Area V, Technology Planning, DAC-57942.

In addition to these documents, the Study Plan, Douglas Report No. SM-51962, includes the study plan task area definitions and study milestones.

On the following pages is a Cross Reference Index which is designed to help the reader locate responses to specific elements of the reactor power systems for Earth-orbital applications and to work statement requirements.

Requests for further information concerning this report will be welcomed by R. L. Gervais, Study Director, Reactor Power Systems, Space Stations and Planetary Systems, Missile and Space Systems Division, Douglas Aircraft Company, Inc., 5301 Bolsa Avenue, Huntington Beach, California.

TECHNICAL STUDY AREAS	PRELIMINARY STUDY PLAN, SM-51962, JANUARY 1966	TASK AREA I, PROGRAM DEFINITION, BOOK 1, SM-51965, JANUARY 1966		TASK AREA II, PARAMETRIC ANALYSIS, BOOK 1, DAC-59213, JUNE 1966	TASK AREA II, PARAMETRIC ANALYSIS, BOOK 2, DAC-59214, JUNE 1966
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		PART I	PART II		
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NOTE:

░ PRIMARY DISCUSSION

▨ SUMMARY OR SUPPLEMENTARY DISCUSSION

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INTRODUCTION AND SUMMARY

A realistic appraisal of reactor power technology development is vital if reactor power systems are to meet effectively the constantly increasing power demands and the progressively more ambitious objectives being set for manned space exploration. This appraisal must consider the specific requirements, constraints, and mission criteria applicable to manned orbital, lunar, and planetary programs. In view of the pending definition of the nation's next major goal in space, development of an Orbital Research Laboratory (ORL) appears logical because an ORL is not only an end in itself but can also provide the test development requisite to manned planetary programs. It follows that the primary power system of this laboratory must be flexible and must exhibit growth potential for expanded Earth-orbital research programs and for lunar and interplanetary missions. A reactor power system has the potential for satisfying these requirements.

The purpose of this study was to determine those reactor power system concepts that could meet effectively the constantly increasing power demands for ORL missions and beyond, and satisfy a postulated 1974 to 1977 launch date.

The Manned Orbital Research Laboratory (MORL), representing a specific Earth-orbital application of well-advanced design studies, was chosen as a representative mission to assess the applicability and potential of various advanced reactor power concepts. Continuing in-depth studies of station concepts, operating modes, mission objectives and system requirements render MORL excellent as a model for this assessment and for the development of realistic and meaningful guidelines for such reactor technology programs.

Detailed study objectives were as follows:

1. Development of guidelines for on-going and future reactor power system technology programs.
2. Evaluation of technology capabilities derived from the Systems for Nuclear Auxiliary Power Programs (SNAP-2, -8, and -10A) and other technology programs (compact converter thermoelectric Brayton cycle) to accomplish the ORL mission over the 10- to 30-kWe power level range, and to identify potentially fruitful applications of these capabilities to more advanced space missions.
3. Identification and evaluation of orbital mission requirements which influence reactor power system design and operation, using the ORL missions as a representative case.

4. Identification and evaluation of reactor power system design and operational requirements which influence manned Earth-orbital mission requirements.

Projections of present requirements indicate that a 20-kWe power level best satisfies the power demand of an ORL-type application in the mid-1970's. Laboratory and orbit-keeping requirements for a 9 to 12-man station are accommodated in conjunction with the assurance of adequate experimental program flexibility; a 30-kWe power level accommodates a growth version of the laboratory and/or an expanded experimental program.

Design and subsequent operation of a MORL/reactor power system is feasible with a SNAP-8-type reactor with any of the power conversion systems studied. Presently defined ORL system requirements can be achieved with these power system combinations, but require long lifetime and high reliability potential of the reactor/power conversion system combinations. Use of a SNAP-8-type reactor with 349 fuel elements and 600-kWt nominal capability can satisfy the 5-year MORL mission lifetime and reliability requirements. The application of installed redundancy in combination with reactor power system replacement as required provides compatibility with the individual power conversion systems (thermoelectric, SNAP-2, SNAP-8, and Brayton cycle). The design approach provides capability for maintenance of the systems, but does not rely on such maintenance in determining the required redundancy; maintenance capabilities have yet to be demonstrated, and the benefits to be derived are uncertain when consideration is given to overall mission objectives.

Integration of the reactor power system with the MORL results in modification or redefinition of the following mission parameters and systems: low-inclination and polar-orbit mission altitudes, stabilization and control system, environmental control and life support (EC/LS) systems, standby power system, and launch systems and operations.

The radiation flux from the reactor source is attenuated to a level compatible with MORL personnel exposure limits with minimum weight penalty by deploying the reactor power system with a shadow shield approximately 125 ft from the MORL. The resulting MORL/reactor power system configuration resembles the classic dumbbell shape used in stability and control analysis, and requires extensive modification of the MORL stability and control, and reaction control systems (RCS). An increase in orbit altitude from 164 to 218 nmi is recommended for the 50°-inclination and for polar orbits, to minimize the reaction control system propellant usage.

The EC/LS system must reject the entire power load; consequently, the growth in EC/LS radiator area is proportionate to the power level. Since deployable radiators interfere with extravehicular activities and the MORL experimental program, these increased heat dissipation requirements are accommodated by increased laboratory length; 5.2 ft for 20-kWe, and 14 ft for 30-kWe power levels.

The major impact of the reactor power system on the MORL is seen in the launch systems and the reactor power system support structure. The thermoelectric power conversion systems have a potential operating lifetime of 5 yr. The dynamic power conversion system designs are based on component/system lifetime goals of 1-1/4 and 2-1/2 yr; respectively, and consequently must be replaced at least once during the 5-yr MORL mission. Replacement of the power conversion system alone results in excessive design complication; hence, complete reactor power system replacement is recommended. It is systematically desirable and economically desirable that the replacement reactor power system utilize the same launch vehicle and launch complex as the MORL logistics program. Use of a launch vehicle with greater payload capability than is presently exhibited by the routine MORL logistics vehicle, the Saturn IB, is necessary and a product-improved Saturn IB with approximately 5,000 lb increased payload capability was selected.

The replacement reactor power system configuration sets the limiting design conditions, constraining the weight and allowable radiator area of the reactor power system. Elimination of this replacement operation on an unscheduled basis would enhance the entire MORL/reactor power system concept, and divorce the replacement reactor power system launch from the routine MORL logistic operations. This would permit selection of a replacement system launch vehicle which would not affect MORL logistic operations nor constrain reactor power system design. Attaining these goals, without inordinate power system weight increase, requires an increase in power conversion system component lifetime from 1-1/4 to 2-1/2 yr without increase in the failure rates.

Allowing power system weight increase permits use of a 2π shield, on a reactor power system that is abutted to the MORL. This abutted design would provide operational flexibility for unlimited EVA, accommodation of radial docking, and minimization of power system deployment complexity. However, the resultant MORL/reactor power system weight is approximately 100,000 lb which requires a MLV-SAT-IB-11.7 or a Saturn V for initial launch and an upgraded Saturn IB for replacement launch.

The major impact of MORL application on the reactor power systems includes development of man-rated system designs for prolonged mission lifetimes in either a zero-g or artificial-g environment, and provision of adequate biologicial shielding for protection of laboratory personnel. Flexibility to meet the operational requirements and reliability for the 5-yr MORL mission dictates system shutdown and restart capability; during shutdown periods, the fluids within the radiator and reactor power system components must be maintained in a liquid state at a suitable viscosity. Continued operation of the reactor up to 10% of rated power prevents such freezing while still permitting limited access for maintenance. However, provision must also be made for eventual reactor shutdown, and the application of thermal shields, retractable during normal operation, has been selected to maintain acceptable fluid temperatures. Utilization of a radiator fluid that has a sufficiently low freezing temperature to preclude the need for thermal shields ultimately is indicated; although a eutectic mixture of sodium potassium and cesium (NaK-Cs) appears to have excellent potential for this application, further test experience and knowledge of fluid properties are required before this fluid is used in the design.

A shadow shield configuration, having a 35° cone angle dictated by the 125-ft separation distance and 80-ft MORL dose plane diameter, is capable of satisfying all presently indentified MORL requirements and has been adopted for all reactor power systems. A dual-shield design with an intervening gallery sized to accommodate primary system components has been applied to effectively attenuate primary and secondary radiation sources and to minimize shield weight. Unmanned application would not generally require the use of a dual shield concept because of the higher tolerable radiation levels. Since deployable power system radiators are not compatible with either shadow shielding or the MORL experimental program, all reactor power system configurations are of the same geometric shape (35° cones) with maximum diameters of 154 or 260 in. with the conical external surface serving as both the principal support structure and the power conversion system radiator. As illustrated in Figure 1-1, the power conversion system components have been arranged near the aft end of the configuration to provide maximum accessibility and to minimize the radiation dose to crewmen performing maintenance.

Table 1-1 summarizes the principal effects of manned Earth-orbital applications on reactor power systems and, conversely, the influence of reactor power system application on ORL systems and mission parameters.

Table 1-1

REACTOR POWER SYSTEMS EFFECTS

Effects on Reactor Power Systems

- Installed redundancy to attain reliability/lifetime
- System maintenance potential
- Intermediate loop for increased accessibility
- Increased component lifetime advantages
- In-space startup and shutdown requirements
- Standby/emergency power source
- Shutdown system protection
- Reactor disposal provisions
- Commonality of system configurations
- Reactor-MORL separation distance and deployment system
- Modified deployment for artificial-g mode

Effects of Reactor Power Systems on ORL Systems and Mission

- Standby/emergency power source
- Environmental control/life support system radiator
- Crew size and power utilization
- Radiation environment
- Stabilization and control system
- Launch vehicles and launch facilities

1. 1 STUDY APPROACH

The study was organized into and reported sequentially in a series of five task areas as follows:

	Douglas Report No.
Task Area I--Program Definition	SM-51962 and SM-51965
Task Area II--Parametric Analysis	DAC-59213 and DAC-59214 (C)
Task Area III--Design and Integration Analysis	DAC-57932 and DAC-57933 (C)

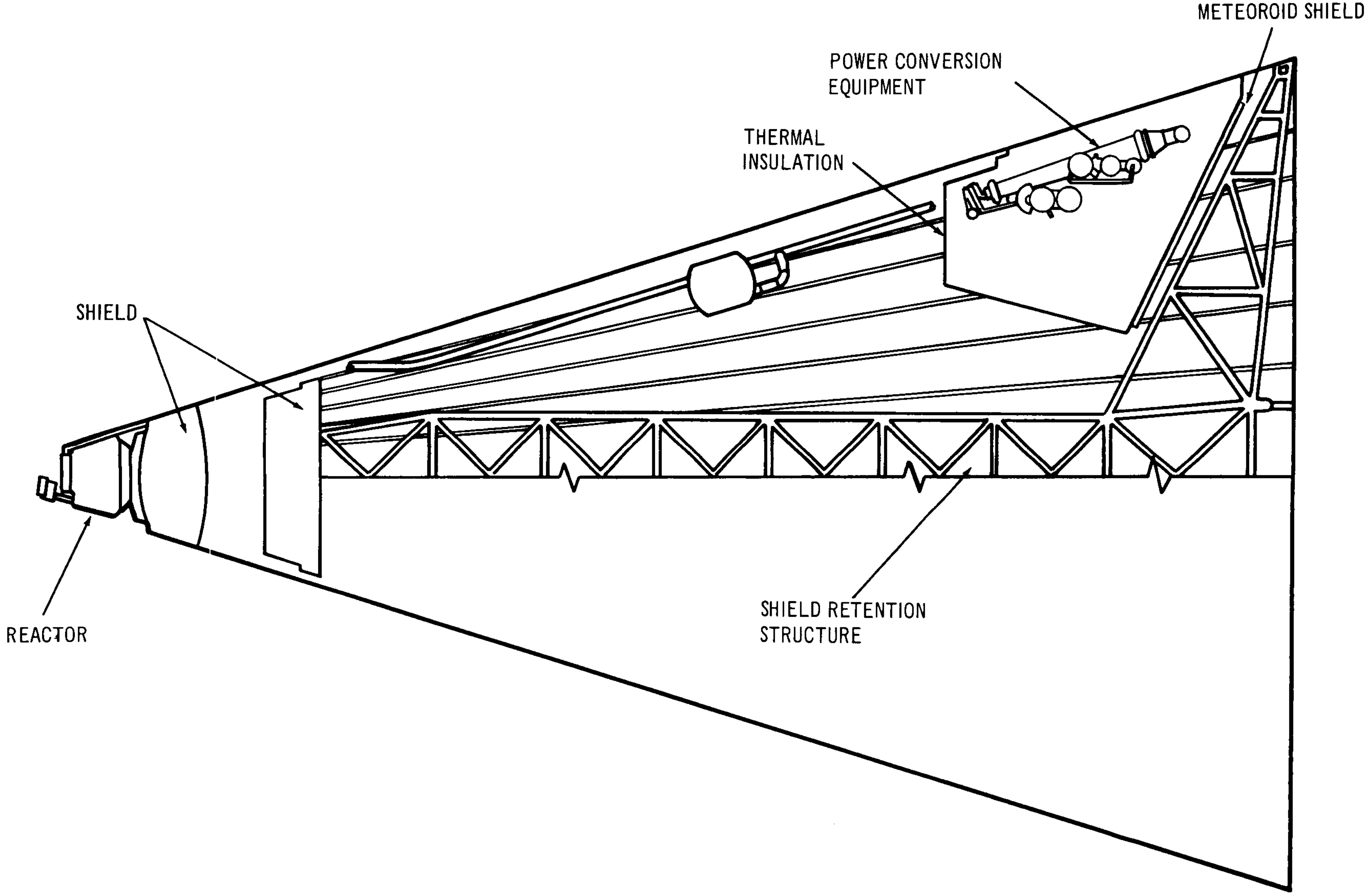


Figure 1-1. Typical Reactor Power System Configuration

	Douglas Report No.
Task Area IV--Comparative Analysis	DAC-57942
Task Area V--Technology Planning	DAC-57942

In Task Area I the principal MORL/reactor power system guidelines, design criteria, and integration constraints used as the basis of the design analysis were initally established. These included definition of the low-altitude, polar, and synchronous missions, the zero-g and artificial-g operating modes and orientation requirements, the MORL system requirements and environmental conditions, and the associated launch systems. Basic performance requirements and constraints, peculiar to the reactor and each power conversion system concept to be analyzed by the associate reactor contractor and the power conversion system subcontractors, were specified in concert with NASA and AEC. Primary emphasis was placed on maximum utilization of current reactor power system technology and demonstrated performance. Eleven distinct combinations of reactor power conversion system power levels (totaling 43 design variations) were identified for investigation, Table 1-2.

Table 1-2

REACTOR POWER SYSTEM DESIGNS INITIALLY INVESTIGATED

	Net Power to Load (kWe)		
	10	20	30
SNAP-8 mercury Rankine			
A II design			X
Modified design		X	X
SNAP-2 mercury Rankine	X	X	
Brayton cycle	X	X	X
Thermoelectric	X	X	X
SNAP-8 reactor	50 to 1, 200 kWt range		

A detailed study plan, divided into 21 functional study areas, was also prepared. Within each study area, the work accomplished was further divided into individual tasks. Each of these tasks detailed other affected tasks, expected results, expected completion date, expected level of effort, responsible contractors, and a correlation of the task with the contract work statement.

1.2 ANALYSIS, DESIGN, AND INTEGRATION

In Task Area II, a parametric analysis was conducted to determine the relationships of thermal performance, lifetime, reliability, weight, and size of the reactor and power conversion systems over a practical range of parameters and sensitive to estimated vehicle integration penalties. To guide the parametric investigation, a parallel study of the affected MORL system and mission parameters was conducted.

This initial analysis resulted in development of reactor power systems that were responsive to the MORL mission objectives. Midway through this analysis phase, the number of reactor power system variations was reduced so that more detailed design and integration could be accomplished on these selected systems. Criteria for selection of reactor power systems that received continuing analysis included: (1) the requirement to assess each power conversion system concept, (2) compatibility with the MORL mission and vehicle, and (3) maintenance of the 10-kWe reactor power system as a potential alternate to use of a 10-kWe isotope system as a prime MORL power source. MORL compatibility criteria were derived from the major integration parameters, including reactor power system weight, radiator area, reliability/maintainability, and performance/flexibility. Table 1-3 presents the system weights and radiator areas used as selection criteria as they existed at that time of selection; subsequent changes were of the order of 15% maximum for any given system. The five systems selected for further in-depth analysis (Task Area III, Design and Integration Analysis), and those designated for further cursory investigation, are presented in Table 1-4.

The MORL/reactor power systems evolved from these investigations exhibit the following performance and design characteristics which generally apply to orbital space station application.

1.3 MORL SYSTEM AND MISSION

To fully utilize the laboratory potential created by application of the 20- and 30-kWe reactor power systems, a MORL having a 9-man crew and using a completely closed oxygen cycle can be considered. In contrast, application of the 10-kWe reactor power system is based on a 6-man crew and the use of an open oxygen cycle. Electrical power requirements for the MORL mission can be grouped into housekeeping, orbit keeping, and experimental loads. A load analysis of the typical 20-kWe application is shown in Table 1-5. The experimental load allocation of 4.5 kWe represents a 1.5-kWe growth over the baseline MORL requirement. The electrical systems used for the 20- and 30-kWe reactor power system applications are based on operating the reactor power system to provide a constant base load, thereby achieving high efficiency and simplified control. The standby power system operates as a peak power source to follow load profiles and to provide supplemental power necessary to trip short circuits.

The standby power system must provide 5.5 kWe (gross output) for a continuous period as long as 42 days during replacement of the reactor power system; this requirement dictates an essentially self-sufficient power source. Three candidate standby power systems were evaluated for use with the 20- and 30-kWe reactor power systems: (1) a Pu-238 Brayton cycle (PBC) system, (2) a solar cell/battery system, and (3) fuel cells. Although both the PBC and solar cell/battery systems have the capability for indefinite operating periods without resupply, the PBC system is preferred because of system invariance to the MORL orientation, supplementary capability in handling laboratory peak loads and supplying essential EC/LS thermal load requirements, and minimal interference with the experimental program. The solar cell/battery system was selected for the 10-kWe application, which was based on unavailability of the PBC system for prime power.

Table 1-3

PRELIMINARY MORL/REACTOR POWER SYSTEM WEIGHTS

Cycle	Thermoelectric			SNAP-2		SNAP-8			Brayton		
Power level (kWe at load)	10	20	30	10	20	20	Reference (A-II) Design-30	Modified Design-30	10	20	30
Basic design	SiGe direct radiating	PbTe compact	PbTe compact								
Number of installed units				10	15	2	2	2	3	5	8
PCS unit rating				4.6	5.6	20	30	30	10	10	10
Radiator area, sq ft	1,000	2,050	3,000	425	830	797	1,104	923	576	1,152	1,728
Weight (lb)											
Reactor and primary loop	1,360	1,510	2,180	926	1,106	1,261	1,343	1,328	988	1,077	1,212
Shield	7,300	7,600	9,500	6,350	7,150	7,000	8,800	7,700	5,400	6,000	6,900
PCS (total)	1,970	7,100	10,900	4,051	5,762	7,319	8,034	8,156	1,277	2,095	3,451
Armor and thrust structure	2,200	3,800	5,500	800	1,672	1,700	2,300	1,900	1,100	2,200	3,200
Subtotal	12,830	20,010	28,080	12,127	15,690	17,280	20,477	19,084	8,765	11,372	14,763
Standby power deployment and cable	6,480	4,960	5,030	6,330	4,300	4,410	4,240	4,240	6,280	4,260	4,100
Electrical system	1,320	2,080	2,860	1,650	2,520	2,300	3,120	2,970	1,650	2,520	3,400
Miscellaneous	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Total	21,630	28,050	36,970	21,107	23,510	24,990	28,837	27,294	17,695	19,152	23,263
Initial launch weight, (MORL and RPS)*	55,576	62,664	72,964	54,048	56,932	59,608	64,223	62,372	49,833	52,602	57,535
Replacement launch weight*	11,016	19,452	27,996	11,772	15,567	16,536	19,292	18,280	8,307	10,046	13,575
Replacement launch height, ft	220	233	246	218	226	221	219	219	222	219	224

---

*Includes 20% power system weight contingency

Payload Available: Initial Launch = 69,400 lb, Replacement Launch = 18,600 lb.

Table 1-4

SELECTED REACTOR POWER SYSTEMS

Detailed Analysis

Cycle	Power Level (kW)	Module Rating (kW)	Component Life/ System Life (yr)	Description
Thermoelectric	10	---	Potential 5	SiGe direct radiating
Thermoelectic	20	---	Potential 5	PbTe compact converter
SNAP-2	20	5.6	1-1/4, 2-1/2	Radiator-condenser CRU-V
SNAP-8 (EGS-2)	30	30	1-1/4, 2-1/2	No intermediate loop, centrifugal pumps, low-temperature cooling
Brayton	20	10	1-1/4 2-1/2	Indirect radiators

Cursory Analysis

Cycle	Power Level (kW)	Module Rating (kW)	Component Life/ System Life (yr)	Description
SNAP-2	20	10	1-1/4, 2-1/2	Radiator-condenser
SNAP-8	30	30	2-1/2, 5	Intermediate loop, dc conduction pump in primary and intermediate loops
SNAP-8	20	20	1-1/4, 2-1/2	Intermediate loop, dc conduction pumps in primary and intermediate loops
SNAP-8	20	20	2-1/2, 5	Intermediate loop, dc conduction pumps in primary and intermediate loops

Table 1-5

20-KWE POWER SYSTEM--LOAD ANALYSIS SUMMARY

(Normal Operation)

A. Load Analysis Summary (Watts)

Requirement	Square Wave ac Connected	Square Wave ac Average	Sine Wave ac Connected	Sine Wave ac Average	56 (±28) Vdc Connected	56 (±28) Vdc Average
Guidance and control	1,183	1,101	89	68	421	236
Communication and data acquisition	150	150	175	175	2,155	1,142
Environmental control and life support	3,269	2,718	---	---	3,008	2,790
Display, control, and instrumentation	---	---	---	---	760	311
Logistic vehicle and maintenance	780	740	2,368	87	---	---
Lighting and miscellaneous	1,063	268	---	---	---	---
Propulsion	5,850	2,283	---	---	---	---
Total housekeeping load	12,295	7,260	2,632	330	6,344	4 479
Reflected to the source bus (unconditioned):						
Housekeeping load (supplied as conditioned power)	---	8,580	---	400	---	5,720
Housekeeping load (supplied as unconditioned power)	---	3,300	---	---	---	---
Experimental load	---	---	---	1,500	---	3,000
Total allocated load	---	11,880	---	1,900	---	8. 720

B. Source Bus Load Summary (Watts)

Housekeeping	18,000
Experimental	4,500
Contingency	1,500 (3,400 for thermoelectric)
Total	24,000 (25,900 for thermoelectric)

NOTES:

1. Approximately 2.7 kW of EC/LS heating is assumed to be available from the standby power source fuel block for a 9-man crew, in addition to the power allocations shown.
2. Connected loads represent the total of all equipment load if operated simultaneously.
3. Average load is the integrated 24-hour average load requirement, based upon the duty-cycle.
4. Propulsion load is based on possible application of resistojet thrustors.

The EC/LS system interfaces with both the reactor power system and the standby power system. The EC/LS system radiator must reject the total heat load dissipated in the laboratory; the usable net radiator surface of 2, 150 sq ft on the baseline MORL provides sufficient area to readily accommodate the output power of the 10-kWe thermoelectric system; however, the combined standby power source and EC/LS radiator area requirements for all 20-kWe system designs require a 5. 2-ft extension of the MORL. Further surface extension would be required to accommodate higher power level requirements, but such extension is not considered practical unless a growth version of the MORL is selected. These radiator area requirements are not unique to the MORL application and are, therefore, applicable criteria, within reasonable limits for any large manned Earth-orbital application under equivalent orbital conditions. Estimated PBC standby power system and EC/LS radiator area requirements are shown in Table 1-6.

Selection of the deployed reactor power system configuration results in greatly increased astrodynamic torques and drag. Control moment gyros (CMG) located on the MORL have been selected as the primary control actuators since their momentum storage/reuse capability minimizes fuel usage; however, an RCS is also required to desaturate the CMG and provide special high thrust needs. Several RCS arrangements were considered for the MORL/reactor power system configuration, including the baseline MORL RCS system. Use of the baseline MORL RCS system was discarded because location of the reactor power system 125 ft from the MORL required excessive propellant. The selected concept performs all maneuvers by the CMG and two separate RCS systems, one on-board the MORL, and one located at the aft end of the reactor power system configuration. The reactor power system-located RCS thrustors are mounted radially to take advantage of the long moment arm. The selected long-term orientation of the spacecraft/power system keeps the vehicle oriented along the local horizontal to eliminate gravity gradient torques, thus minimizing gravity gradient propellant requirements. The weight penalty (accounted to reactor power system weight) over the baseline MORL for the resized CMG ranges from 1, 200 to 1, 500 lb for the 5 reactor power system investigated in depth. RCS propellant requirements were considerably greater for the reactor power system configuration than for the baseline MORL.

Table 1-6

NOMINAL MORL RADIATOR AREA REQUIREMENTS

Conditioned Output Power Level (kWe)	Approximate Radiator Area (sq ft) EC/LS	Combined Power System and EC/LS
10	1, 275	-
20	2, 150	2, 500
30	2, 750	3, 100

To further minimize propellant usage, a resistojet RCS was considered as an alternate to the baseline chemical bipropellant RCS. However, it was concluded that further analysis and mission definition are required before specific advantages of this concept can be established; therefore, the RCS propellant penalty over the baseline MORL, approximately 100 lb/month, has been minimized by adopting a new mission altitude of 218 nmi for the 50°-inclination and polar missions. For the 50°-inclination mission, this orbit provides a 3-day subsynchronous repeating orbital trace.

The launch concept of initially placing the MORL/reactor power system into orbit as an integral system was adopted over the separate launch mode, where the MORL and the reactor power system are separately launch and then integrated, based on considerations of cost, reliability, growth accommodation, and alternate mission compatibility. On the basis of preliminary MORL/reactor power system weights, an upgraded Saturn IB launch vehicle, the MLV-SAT-IB-11.5, was selected for integral launch into the baseline, 50°-inclination, 218-nmi circular orbit. However, the 30-kWe SNAP-8 and thermoelectric systems, and possibly the 20-kWe thermoelectric system, exceed the 69,000-lb payload capability of the MLV-SAT-IB-11.5, suggesting requirements for another upgraded Saturn IB with greater payload capability if these PCS's are used.

Launch of most replacement reactor power systems is accomplished with a product-improved Saturn IB because it represents the most economical launch vehicle in the payload class of interest and is compatible with the MORL logistics program. All replacement reactor power system launch weights are within the 18,110-lb available payload of the product-improved Saturn IB with the exception, again, of the 20- and 30-kWe thermoelectric systems and the 30-kWe SNAP-8. The weights of the replacement reactor power systems have been minimized by the retention of the secondary shield during the replacement operation.

Because of the additional height resulting from the Apollo CSM stacked atop the replacement reactor power system, launch vehicle height becomes a limitation. Preliminary structural analysis indicates a height limitation of approximately 230 ft for the Saturn IB stage in the replacement vehicle assembly to avoid stage redesign and subsequent requalification. However, all replacement reactor power system launch assemblies essentially meet this limitation. In the replacement reactor power system configuration, the critical mode from a launch height standpoint, a maximum radiator area of 1,900 sq ft can be accommodated by a Saturn IB launch vehicle with a reactor power system and Apollo CSM without structural modification of the Saturn IB stage and interstage.

The Saturn V is required for all launches into polar and synchronous orbits; the limiting height for the Saturn V payload assembly is 380 ft, which corresponds to the crane height limitation of the launcher-umbilical tower (LUT) used in Launch Complex 39 operations. A radiator area limit of 3,310 sq ft is obtained for the Saturn V when adhering to the present shadow cone angle of 35°.

1.4 REACTOR POWER SYSTEMS

A single SNAP-8-type reactor design with 349 uranium-zirconium hydride fuel elements, a nominal 600-kWt capability at 1,300°F coolant outlet temperature, and a potential operating lifetime of 5 yr can effectively accommodate the operating characteristics and unique features of the various power conversion systems. This lifetime is feasible with the use of a burnable poison selected from identified candidates which exhibit favorable lifetime characteristics. Operational reactivity control is obtained by eight operating control drums which are tapered to provide a minimal shadow cone envelope for the shadow shielded configurations. If a 4π or 2π shield is used, the higher reflector temperatures necessitate the application of alternate external reflector and control drum materials. The extended reactor lifetime provides desirable margin in reliability and performance capability regardless of the generally shorter power conversion system lifetime.

Thermal energy generated in the reactor core is transported to the power conversion system by the primary coolant system, consisting of multiple closed loops. The coolant pipes from the reactor are routed into the gallery around the primary shield in stepped longitudinal depressions in the neutron shield casing. Expansion compensators are provided in each primary coolant system to accommodate NaK volumetric changes during startup and to maintain sufficient coolant system pressure for ensuring compressive fuel element cladding stresses during the system lifetime. The SNAP-8 primary coolant system utilizes canned rotor centrifugal pumps (one active, two standby). The remaining systems used direct-radiating thermoelectromagnetic pumps similar to those used on SNAP-10A for primary coolant circulation.

The dual shadow shield arrangement consists of two depleted uranium alloy gamma shields and two canned natural lithium hydride neutron shields, arranged to accommodate the primary coolant system components in an intermediate gallery region. The first neutron shield is structurally reinforced to serve as the basic structural component for the reactor, primary gamma shield, and primary coolant system components. The secondary neutron shield is divided into two sections to allow retention of the major portion of this shield on the deployment boom, and thereby reduce the replacement power system launch weight.

The use of an intermediate liquid metal heat transfer loop installed in the shield gallery between the primary coolant loop and the power conversion system loop is of prime importance and interest in the compact converter thermoelectric, Brayton, and SNAP-8 systems. Adaptation of this intermediate loop minimizes the possibility of leakage of activated NaK behind the secondary shield and provides increased accessibility to the power conversion system components. Because each power conversion system is unique, the five systems considered in this study are discussed separately in the following paragraphs.

1.4.1 Thermoelectric

Both the 10-kWe silicon-germanium (SiGe) direct radiating thermoelectric system and the 20 kWe lead telluride (PbTe) compact converter system provide the potential for a 5-yr operating lifetime because of the inherently high reliability associated with a completely static energy conversion concept. These systems use converter components already developed or under active development to minimize development risks. Reliability requirements are satisfied through degradation allowances and redundancy provisions; consequently, extensive on-board maintenance is not considered essential. The PbTe compact configuration provides a greater potential for on-board maintenance than the direct radiating configuration, should this become necessary.

However, the direct radiating thermoelectric system design provides the simplest fluid system arrangement of all the conversion systems studied because the SiGe converters are provided integral with the radiating surfaces.

Specifically, the PbTe compact converter system is designed to produce 22.5-kWe net output power. Although a 20-kWe power level was originally specified, the utilization of the standby power system for load following resulted in a net improvement in the power conditioning efficiency and a consequent increase in net output power for the same installed converter capacity. The selected system design consists of 8 direct-radiating thermoelectromagnetic pumps, 3 expansion compensators, and 7 NaK-to-NaK heat exchangers located within a 20 in. shield gallery, as well as a total of 14 power conversion loops behind the secondary shield. Each of these loops is serviced, in turn, by an independent heat rejection loop. Operation of 6 of the 7 heat exchangers and 12 of the 14 converter loops is required to produce full power.

The converters operate at a hot side average coolant temperature of 1,150°F and a temperature differential of 200°F. The selected average cold side temperature is 550°F, based on the optimization of system weight and radiator area. A radiator surface area of 1,891 sq ft is required for the selected design. Accessibility for maintenance is provided by locating the 14 compact converter modules at the aft end of the power system configuration.

The SiGe direct radiating thermoelectric system is designed to produce 9.8 kWe net output power. The slight reduction in output power below the initially specified 10 kWe results from a nominal variation in the power conditioning efficiency because of design integration. The selected system consists of 4 direct radiating thermoelectromagnetic pumps, 2 expansion compensators, and 6 NaK-to-NaK heat exchangers located within a 14-in. shield gallery. Six independent converter loops are provided, consisting of an expansion compensator, thermoelectromagnetic pump, and the thermoelectric converters. Five of the six loops are required to produce full power. The average temperature of the NaK coolant supply to the converters and the temperature differentials within the NaK coolant loop are the same as for the compact converter system. A radiator area of 1,068 sq ft is required for this design. Although an increase in average cold side temperature from 550° to 650°F would decrease this radiator area requirement, a total surface equivalent of about 1,150 sq ft must be provided to adapt to a 260-in. configuration base diameter. A slight increase in weight would result from the lower converter efficiency at 650°F.

1.4.2 SNAP-8

The baseline SNAP-8 system design consists of 3 independent power conversion systems and 2 sets of radiator tubes to meet a 2-1/2-yr system lifetime objective. Because the specified component lifetime for the baseline system is 1-1/4 yr, the installed power conversion system capacity essentially amounts to the provision of one redundant system to supplement the minimum installed system capacity required for a 2-1/2-yr lifetime.

The application of a single boiler was found to be insufficient in meeting reliability and lifetime objectives. Instead, three boilers in the shield gallery were required. However, installation of multiple boilers also requires the preclusion of mercury leakage into the primary NaK fluid. A means of immediately detecting and isolating the leakage must be provided for useful application of the redundant boilers. The development of such boiler modifications is implicit in the selected redundancy concept for the baseline SNAP-8 system design. This problem is avoided by application of an intermediate NaK loop in the modified SNAP-8 designs investigated. The use of an intermediate NaK loop provides various system advantages including: prevention of both direct leakeage of mercury into the primary NaK loop and primary NaK leakage into a shutdown mercury loop; reduced shield gallery height and shield weight; accessibility to the boilers for potential maintenance; and operation in the MORL artificial-g mode without additional valving.

The artificial-g mode has minimal effect on the operation of the alternate SNAP-8 system (with intermediate loop) because the liquid/vapor interfaces of the condenser and boiler are installed at the same elevation. However, for the baseline SNAP-8 system (boiler installed in shield gallery) the induced gravity field results in higher absolute pressure at the boiler inlet than for the zero-g case. The net result is overall reduction in boiler performance and the possibility of wet vapor at the turbine inlet, necessitating the addition of a pressure control valve in the boiler feedline.

The alternate 20- and 30-kWe system designs selected for cursory analysis during this study include consideration of a component lifetime potential of 2-1/2 yr and a corresponding system lifetime potential of 5 yr. This requires extrapolation of the present SNAP-8 program reliability goals which have established a 10,000-hr component lifetime. The alternate designs consider the application of an additional power conversion system, giving a maximum of four systems, as a practicable limit on the installed redundancy requirements to provide a potential for increased lifetime. Installation of more than four PCS's is considered to be undesirable in view of increased weight, comparative design complexity, and possible unreliability over the 2-1/2-yr component lifetime; a completely realistic appraisal of the redundancy requirements for this longer operating period cannot be made at this time. The final phase of the NASA/Lewis-Aerojet Performance Potential Program includes an evaluation of component lifetime capability for 20,000 hr of operation. This work provides a basis for confirming selected redundancy requirements.

Uprating the SNAP-8 system design to approximately 50-kWe net output power capability can be accomplished with various system and component modifications. However, a 4,200-lb system weight increase results, thereby requiring increased launch payload capability. An uprated version of the Saturn IB could accommodate the increase in payload; however, the 230-ft height limitation would be exceeded. Saturn V could readily accommodate this system configuration.

1.4.3 SNAP-2

The 20-kWe SNAP-2 mercury Rankine system configuration has the lowest weight and radiator surface area requirements of the systems investigated in this study. The selected SNAP-2 system uses multiple combined rotating units (CRU) of 5.6 kWe gross output power level. Two PCS modules, each containing five active and two redundant CRU loops, comprise the system. Each CRU consists of a turbine, pump and generator assembly, pressure regulator, four-way valve, boiler tube, and radiator condenser.

An alternate SNAP-2 system design using scaled-up turbomachinery, capable of delivery a net output of 10 kWe was given a preliminary investigation. In this design, two active and one standby CRU loops are provided for each of two PCS modules to meet the 20-kWe output power level, reliability, and system lifetime requirements. This design offers the ultimate potential of reducing the system weight and complexity because of the fewer CRU loops required. However, use of the existing turbomachinery (CRU-V) design, capable of producing a 5.6-kWe gross power, was adjudged to be more representative of present technology, because of the development, design, test, and operating experience accumulated on this unit. Therefore, the existing design was selected as the baseline design for this study.

The baseline design utilizing the CRU-V machinery has accumulated in excess of 20,000 hr of test, and a single unit has recently achieved over 4,700 hr of testing. The adopted multiloop integration scheme has the advantages of minimum system development and qualification test costs and a significant partial power reliability advantage. The basic system operational characteristics presented for this design have been verified by the mercury Rankine Power Development System testing program.

Provision of individual component redundancy was investigated; however because of the potential unreliability associated with a large number of valves, particularly high-temperature mercury vapor valves, a complete CRU loop redundancy approach has been adopted. This approach requires a 21% increase in radiator area and a corresponding weight increase relative to a minimum radiator area system. However, the resultant radiator area (757 sq ft) and system weight are well within launch capabilities of the selected vehicle.

Application of the system to both zero-g and artificial-g modes of operation requires installation of approximately half of the PCS modules at the forward end of the configuration. Although the potential for maintenance of PCS modules in this location is limited, the redundancy provided is sufficient to meet reliability and lifetime objectives without reliance on such maintenance.

1.4.4 Brayton Cycle

Application of the Brayton-cycle PCS results in the highest thermal performance (18% cycle efficiency) of all the designs investigated. The radiator surface area requirement of 1,150 sq ft for the 20-kWe system is within the limits which can be effectively integrated into the various launch vehicle payload assemblies.

The selected Brayton-cycle PCS utilizes high-frequency, single-shaft machinery. This design was selected over the low-frequency, two-shaft turbomachinery design concept on the basis of increased flexibility, reliability, and ease of system integration. An intermediate NaK loop between the primary and gas loops is included in the basic system design. The intermediate loop results in negligible performance penalty while allowing the placement of PCS modules in an accessible location behind the shield and results in smaller secondary shield penetrations, and a reduction in shield gallery height.

A total of 6 installed 10-kWe PCS modules, having an independent radiator loop associated with each PCS module, constitute the power conversion system.

Use of a single basic 10-kWe PCS module design over all system power levels investigated was predicated on increased partial power reliability and greater flexibility. The specified component lifetime of 1-1/4 yr dictates the selection of 6 modules based on operation of two units during the initial 1-1/4-yr period, and two for the remainder of the system lifetime (2-1/2 yr). The remaining two units are in standby to provide the required reliability.

A recuperated Brayton cycle using argon as the working fluid is contained in each PCS module. The CRU selected in this design consists of a single-stage centrifugal compressor, a single-stage radial inward flow turbine, and a high-frequency (850 Hz) Rice alternator mounted on a common shaft. The turbine operates at a nominal inlet temperature of 1,250°F, based on the specified 1,300°F reactor outlet temperature limitation. Based on an overall system weight/radiator area optimization, a 200°F compressor inlet temperature was selected. The high-frequency (850 Hz), three-phase power output of the alternators is rectified and paralled on the dc side of the power conditioning system. Excess power demand is absorbed with the parasitic load control, located in the EC/LS cooling system and dissipated to space by the EC/LS radiator.

The system design basis is considered to be conservative, based on exhibited Brayton-cycle component development; however, a significantly more conservative approach (compressor efficiency lowered from 83% to 80% and turbine efficiency reduced from 90.1% to 87%) indicates that the system can still be readily accommodated in an effective manner in the configuration design.

1.4.5 Electrical System

A dc-link system has been selected to convert high-frequency ac power to 400-Hz ac power for the SNAP-2 and Brayton-cycle systems. Single inverters supply the ac load buses with nonparalled standby inverters located for manual switching into service. Dc power is derived from alternator power through transformer-rectifier-regulators for all dynamic power systems (SNAP-2, SNAP-8, and Brayton cycle). The SNAP-8 system delivers 400-Hz power directly to the ac buses, with only such filtering and regulations as necessary to provide high quality power to the experimental ac bus. The thermoelectric system provide regulated power directly to the dc buses at 56 Vdc, 3 wire (±28 Vdc). Separate inverters supply quasi-square wave and sine wave power for housekeeping and experimental buses, respectively.

1.5 SYSTEM CAPABILITIES

On completion of the MORL/reactor power system design and integration, attributes of the designs evolved were related to the principal integration requirements and limitations of the ORL application (Task Area IV, Comparative Analysis). These requirements and limitations were, in turn, grouped into six integration criteria as follows: (1) reactor power system weight, (2) radiator area, (3) lifetime and reliability, (4) design integrity, (5) maintenance and replacement, and (6) performance and flexibility. The reactor power system effectiveness in meeting the requirements and limitations of these criteria, as well as the system sensitivity to changes which accommodate these limitations were investigated. Potential improvements, within the present technology, that enhance the particular reactor power system integration capability, reliability, and growth were also identified.

Examination of the reactor power system designs studied in depth in Task Area III, Design and Integration Analysis, indicated that all systems meet the integration requirements of the MORL. Weight of the baseline 30-kWe SNAP-8 system configuration exceeds the integral and replacement launch weight limitation. However, potential system changes, including the use of an intermediate loop, offer the prospect of a significant weight reduction. SNAP-8 system design integrity is affected by the boiler design and by the use of the lube-coolant fluid for primary pump cooling. Boiler redesign, intermediate loop application and/or positive leak detection, and isolation means would minimize possible overall system failure in the event of mercury leakage into the primary system. The radiation exposure of lube-coolant fluid is marginal and warrants consideration of an alternative pump cooling fluid to prevent a potentially serious source of systemic failure. The two-phase flow phenomena inherent in Rankine systems limits the installation flexibility of system components in the artificial-g mode.

The 20-kWe SNAP-2 system exhibits the lowest wieght and radiator surface area requirements of the systems investigated and is well within all launch vehicle limitations. However, the number of CRU's (14) required to attain output power level, lifetime, and reliability requirements imposes installation and operational complexity. Significantly reduced complexity can be attained by increasing CRU lifetime potential from 1-1/4 to 2-1/2 yr and/or by uprating CRU output power capability from the present 5.6-kWe gross output power rating. Both of these changes appear to be feasible extensions of present technology. As in the case of SNAP-8, the two-phase flow phenomena impose limitations in the component arrangement.

The 20-kWe Brayton-cycle system satisfactorily meets the specified integral and replacement launch requirements. A high degree of flexibility is provided by application of a common 10-kWe module design capable of satisfying a range of power requirements with multiple modules installed. Absence of indentifiable limiting wearout failure modes provide confidence in the ability to extend component lifetime capability to 2-1/2 yr based in a continuing development program. Potential system changes, including the use of a helium-xenon gas mixture and the attainment of increased compressor efficiency through continued development, offer the prospect of further weight and radiator surface area reductions.

Both the 10- and 20-kWe thermoelectric systems satisfactorily meet the MORL integration requirements, with the exception that replacement of the 20-kWe compact converter system exceeds the payload capability of the initial and replacement launch vehicles. The principal asset of these systems is their potential for an extended converter lifetime. Confirmation of converter reliability in the continuing development programs offers the prospect of a reduction in the installed redundancy and corresponding weight and radiator surface area reductions. The compact converter design provides the potential for module replacement; further consideration should be given to conceptual designs for simplifying the module replacement operation. A dynamic analysis of the direct radiating converter design, together with a structural design optimization may result in a significant weight reduction through more efficient utilization of converter structure.

Task Area IV included an analysis and integration of a 50-kWe SNAP-8 reactor power system with the MORL; a description of the ground support and launch requirements for a 30-kWe thermoelectric reactor power system utilizing a Saturn V launch vehicle; and an application of the Earth-orbital reactor power system design to a Mars Flyby mission. These latter studies were included to illustrate the design flexibility of the reactor power systems to applications other than the specific models used for integration purposes in this study.

1.6 TECHNOLOGY PLANNING

The activities required for the development of flight ready reactor power systems for manned Earth-orbital application were developed in Task Area V, Technology Planning, and divided into four major phases that culminate in a vehicle launch. These phases in chronological order are: (1) reactor power system technology readiness, (2) subsystem design and testing, (3) prototype testing, and (4) vehicle integration and testing. A realistic overall schedule for a MORL/reactor power system launch consists of a reactor power system technology readiness phase of at least 18 to 24 months followed by a 66-month phase for the reactor power system and vehicle development. The technology readiness phase, which precedes the authority to proceed (ATP) date of the mission vehicle, initiates power system research and technology efforts in critical areas, and carries these efforts to sufficient depth prior to ATP to provide an increased confidence in the design approach. Specific recommendations for the initiation of required reactor power system changes or potential system improvements, during the technology readiness phase, for the reactor and shield, as well as for the thermoelectric, SNAP-8, SNAP-2, and Brayton power conversion systems are presented in Table 1-7. Early implementation of items indicated as required system changes will help ensure availability of results in time to support early manned Earth-orbital applications.

It is expected that the results of this study will aid significantly in providing mission-oriented guidance for the nation's reactor power system development program in the key Earth-orbital area. Figure 1-2 presents a matrix of this and other future mission applications visualized through 1980 against the major mission-oriented requirements definition areas; it provides a tool for assessment of overall space reactor power system requirements definition.

In the Earth-orbital mission areas, the MORL reactor power study has defined the total problem and postulated solutions in most key areas for resuppliable, long-duration missions. It is felt that sufficient data have been developed during this study to allow extrapolation to cover the nonresuppliable short-/long-duration missions in these same areas. Major areas identified in this study which were not pursued in depth, and consequently for which solutions were not developed are indicated at the bottom of the figure. These areas are: (1) qualification/acceptance testing and facilities requirements at the factory, at the vehicle assembly area, and at the launch pad, and (2) reactor power system operational requirements for operation, repair, testing, and maintenance of these systems.

In the lunar missions area, it is expected that the on-going lunar reactor study by Lockheed will provide similar data for a lunar-based operation. It is expected that these data can be extrapolated to cover short-duration lunar orbiting missions and potential resuppliable missions.

It is suggested that a similar reactor application study is required in support of the on-going interplanetary mission study being conducted at Boeing for NASA, and that this study should be broad enough to consider both flyby and

Table 1-7

TECHNOLOGY READINESS

Required System Changes and Study Areas

Reactor and Shield	Thermoelectric	SNAP-8	SNAP-2	Brayton	Facilities	Aerospace Safety	Vehicle Requirements
Incorporate 349-element core Incorporate burnable poisons Increase number of active control drums Provide tapered reflector and drums Develop shield design suited for MORL application Develop means for decay heat removal	Continue development of converters to improve performance through minimization of parasitic losses, reduced degradation, segmentation of couples and alternate materials Maximize reliability and lifetime through identification and evaluation of failure and wearout modes	Redesign boiler to preclude tube leakage resulting in intermixture on Hg and NaK Study of boiling and condensing and fluid evacuation in zero-g environment Study of application of system for operation in artificial-g environment Develop multiple restart capability Develop redundant systems equipment for load transfer and malfunction detection Study of lube coolant fluid radiation tolerance Study of static deterioration for redundant system	Orbital testing of boiling and condensing in zero-g environment Further study of application of system for operation in artificial-g environment Develop redundant systems equipment for load transfer and malfunction detection Study of static deterioration for redundant system	Design and test of gas foil bearing design	Study of facilities requirements for: Integrated reactor power system development and Qualification Testing, Flight System Testing, and Prelaunch and Launch Facilities	Study of aerospace safety requirements including manufacture assembly, testing, transportation prelaunch, orbital operations, and disposal using MORL as model	Study of impact of on-board radiological control and decontamination facility for contaminated parts on vehicle design Further study of deployment concepts Study of leak detection, control and effects of fluid leakage on vehicle Study of radiator design and fabrication Study of emergency power system interface with primary power system Orbital test requirements

Potential System Improvements and Study Areas

Reactor and Shield	Thermoelectric	SNAP-8	SNAP-2	Brayton
Study of thermoelectric pumps Experimental confirmation of shield design	Consider reduced redundancy based on verification of converter reliability and lifetime goals Optimize direct radiating system structural support based on dynamic analysis Study of on-board maintenance Study of alternate means of maintenance of resident fluids for redundant systems	Provide intermediate loop Improve component and system lifetime Study of on-board maintenance Study of alternate means of maintenance of resident fluids for redundant system	Study of 10-kW module rating Improve boiler design Study of on-board maintenance Study of alternate means of maintenance of resident fluids for redundant systems	Design studies of Rice alternator Evaluation of Xe-He gas mixture Study of on-board maintenance Study of alternate means of maintenance of resident fluids for redundant systems

	MISSION DEFINITION / STUDY AREA	EARTH ORBITAL SHORT DURATION	EARTH ORBITAL LONG DURATION	EARTH ORBITAL RESUPPLY		LUNAR SHORT DURATION	LUNAR LONG DURATION	LUNAR RESUPPLY	INTERPLANETARY FLYBY/LANDER
MISSION ORIENTED REQUIREMENTS	OVERALL POWER SYSTEM			MORL REACTOR STUDY	RELIABILITY LIFETIME/REPLACEMENT POWER LEVEL WEIGHT, SIZE		LUNAR BASE STUDY		FUTURE STUDY REQUIRED
	REACTOR/SHIELD DESIGN				LIFETIME COMMON DESIGN FOR POWER RANGE RESTART PROVISION REACTOR SAFETY SHIELD CONCEPT				
	PCS DESIGN				REDUNDANCY LIFETIME/REPLACEMENT MAINTENANCE POTENTIAL POWER LEVEL PERFORMANCE				
	STANDBY/EMERGENCY POWER SYSTEM				PBC SYSTEM PROLONGED DURATION EC/LS THERMAL LOAD RELIABILITY/REPLACEMENT				
	CONFIGURATION/ INTEGRATION				DEPLOYMENT REQUIREMENTS SHADOW SHIELD PCS RADIATOR AREA EC/LS RADIATOR AREA LAUNCH REQUIREMENTS				
COMMON REQUIREMENT	QUALIFICATION/ACCEPTANCE TESTING AND FACILITIES				KSC TEST				
	SYSTEM OPERATIONAL DESIGN REQUIREMENTS				START-UP, SHUTDOWN, REPAIR, TEST, MAINTENANCE				

Figure 1-2. Potential Reactor Power System Applications

lander cases. Initiation of such a power system study would obviously depend on availability of preliminary mission requirements from the overall mission study.

In areas of qualification/acceptance testing and facilities, as well as system operational design requirements, it is expected that commonality will exist to a large degree for all of these missions; therefore, it is suggested that study efforts might be initiated in this area using the MORL reactor study as a base. Results of this study would be applicable to all of these major missions.

Section 2

CHARACTERISTICS AND REQUIREMENTS

Design and subsequent operation of a MORL/reactor power system is feasible and does not compromise the MORL mission. It enhances the MORL experimental program in the 20- and 30-kWe applications, and achieves the manned Earth-orbital requirement of long lifetime coupled with high reliability. The primary design problem was attenuation of the reactor source radiation dose to a level compatible with MORL personnel exposure limits with minimum weight penalty. This is accomplished through the use of shadow shielding and location of the reactor power system 125 ft from the MORL. Separation distance is the same for all reactor power systems based on an optimization typified in Figure 2-1. Reaction control system (RCS) propellant consumption, required for maintenance of the ±0.1° spacecraft attitude control accuracy, was considered in this optimization using the selected RCS design; i.e., one RCS aboard the MORL and one located on the reactor power system configuration.

2.1 CHARACTERISTICS

All MORL experimentation associated extravehicular activity (EVA) and orbital operations is accommodated by an 80-ft-diam dose plane at the aft end of the MORL. With separation distance optimized at 125 ft and an 80-ft dose plane diameter, a 35° shield cone angle results. All reactor power systems structure and/or pertuberances lie within this cone angle, thereby minimizing scatter radiation. Because deployable radiators were not adopted, all reactor power system configurations are of the same geometric shape (35° cones) with maximum diameters of 154 or 260 in. (compatible with the MORL and S-IVB), and where the external surface of the cone serves as both the principal structural support and the power conversion system radiator. When large radiator areas are required, the required length of 154- or 260-in.-diam cylindrical section is added to the conical section. The internal geometry of the reactor power systems are arranged to provide maximum accessibility for maintenance; for example, the power conversion system components are located as far from the reactor as possible to minimize the radiation dose to crewman performing maintenance. Figure 2-2 shows the MORL/reactor power system configuration and the defined radiation exclusion zone.

Launch of the MORL/reactor power systems into orbit also effects the reactor power system configuration. The reactor power system is stacked atop the MORL during initial unmanned launch into orbit with an upgraded Saturn IB launch vehicle. Subsequently, it is deployed to its operating position at the aft of the MORL by an articulating support boom. Because the dynamic conversion systems have a lifetime of only 2-1/2 yr, they must be replaced at least once during the 5-yr MORL mission. Consequently, the reactor power systems must also be compatible with the manned replacement launch vehicle. Figure 2-3 depicts a replacement reactor power system launch assembly with an

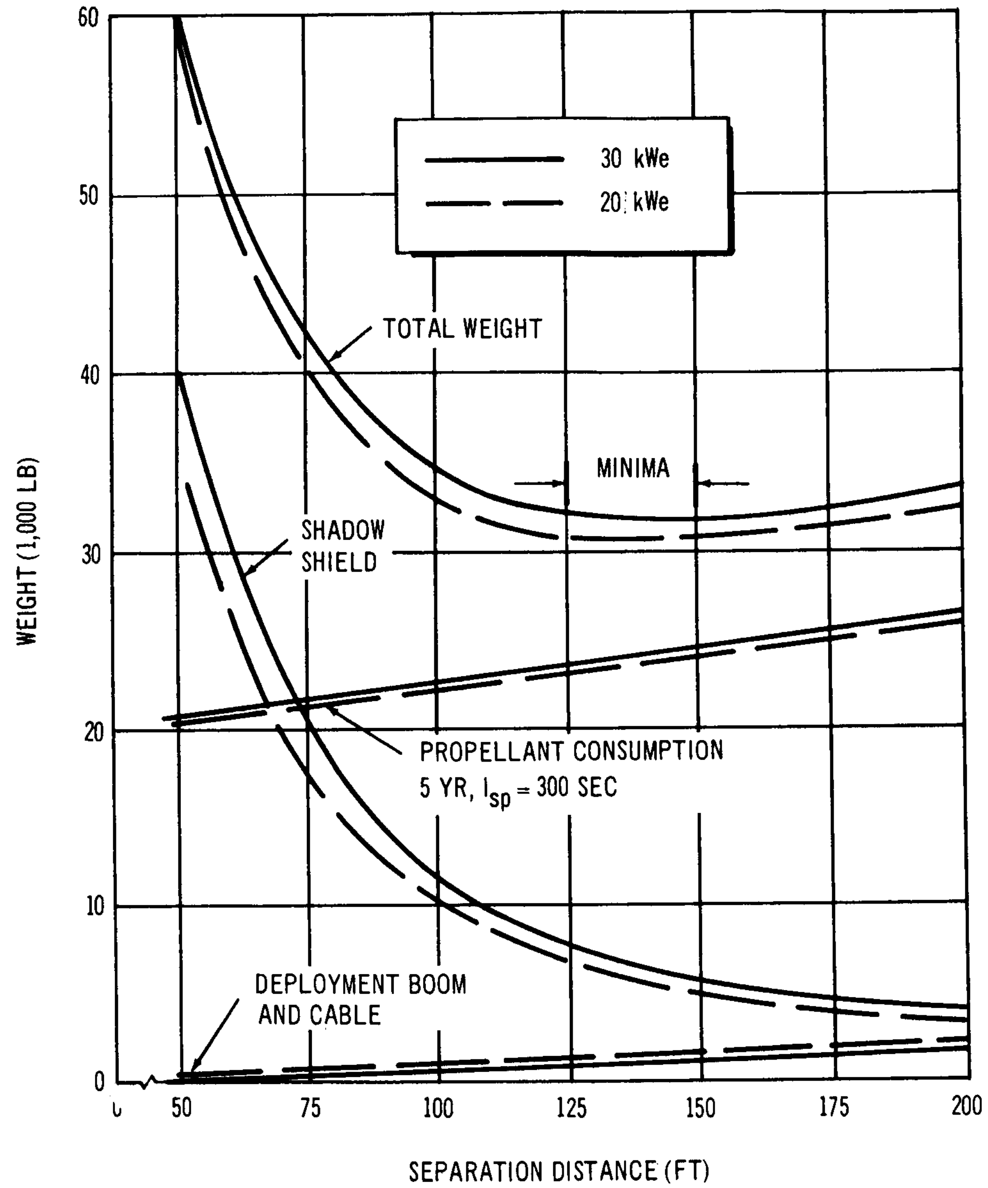


Figure 2-1. Separation Distance Optimization (Typical Case – SNAP-8)

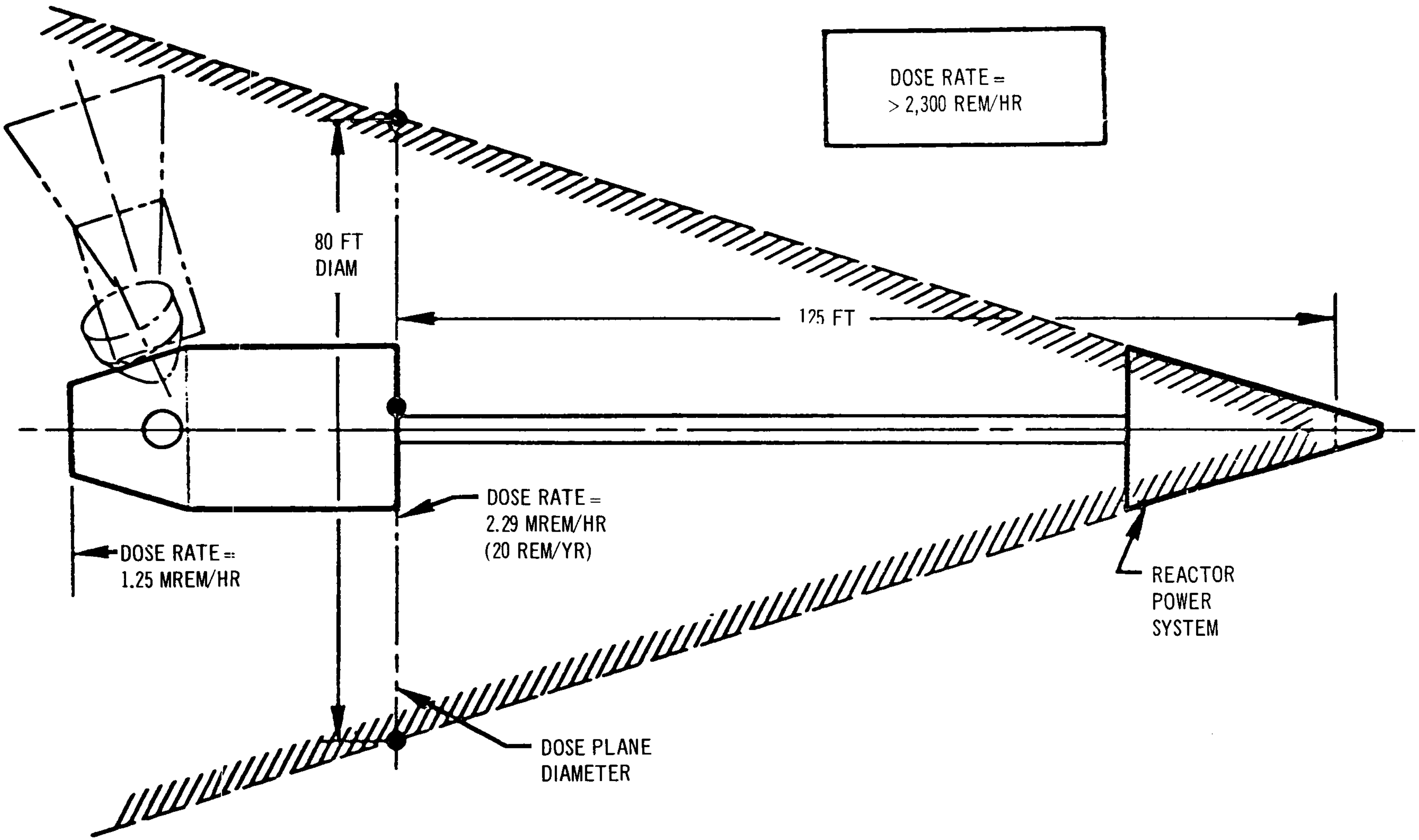


Figure 2-2. Radiation Exclusion Zone

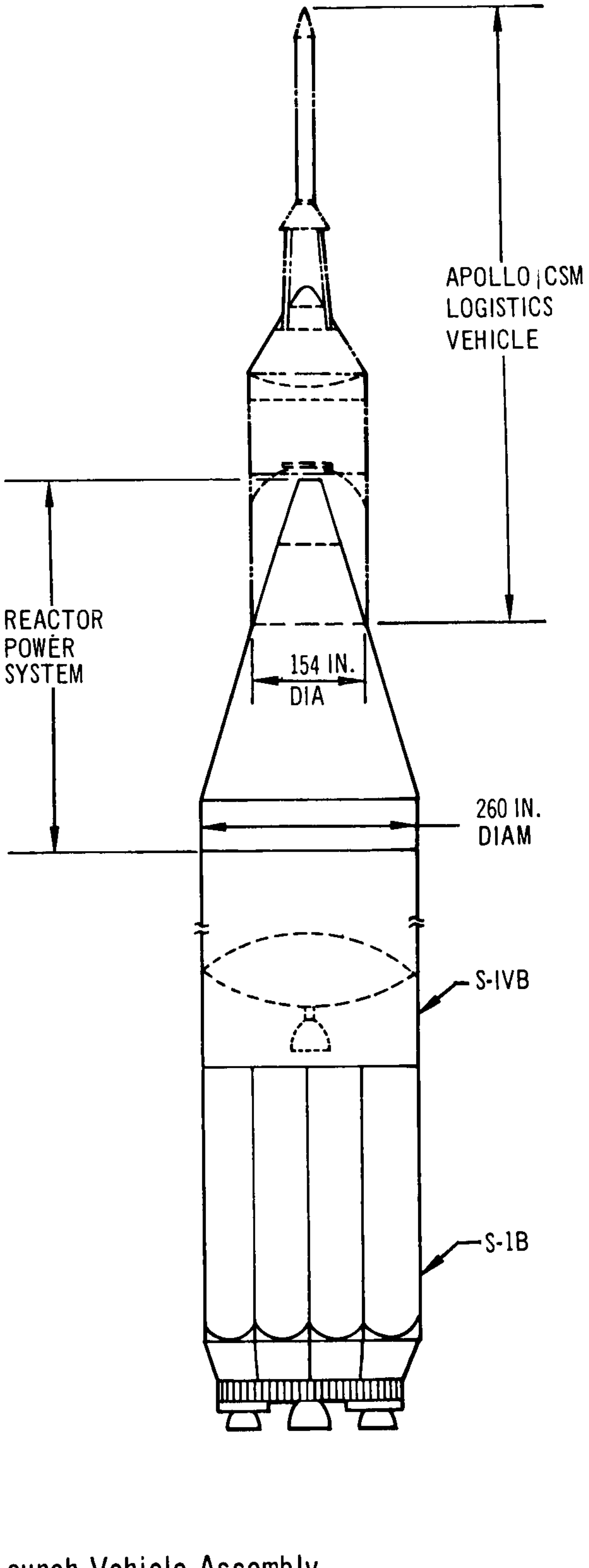


Figure 2-3. Replacement Launch Vehicle Assembly

Apollo command and service module (CSM) atop the power system. Inferred by this assembly is that the power conversion system radiators must support the load of Apollo CSM as well as the reactor. Because the configurations must exhibit commonality of design between the initial and replacement launch configurations for economy of design and fabrication, the replacement reactor power system, becomes the design condition. It is highly desirable, and almost economically mandatory, that the replacement power system utilize the same launch vehicle and launch complex as the MORL logistics program; hence a product-improved Saturn IB is used for replacement launches into the baseline, 50^{o}-inclination orbit. The overall height of the Saturn IB/power system/Apollo is constrained by the structural capability of the Saturn IB stage in the flight condition; consequently, the length of the reactor power system (hence, radiator area) is limited. The payload available to the replacement reactor power system is also limited by the Saturn IB payload capability; hence, the secondary shield is retained on the deployment boom during the replacement operation to minimize the replacement reactor power system weight. Initial launch of the MORL/reactor power system is accomplished with an upgraded Saturn IB launch vehicle (for example, the MLV SAT-IB-11. 5).

It has been assumed that a reactor power system would not be considered for a first-generation space station which might require approximately 10 kWe and that an isotope (Pu-238) Brayton cycle (PBC) system would be a prime candidate. However, if the PBC system is not available because of the unavailability of sufficient Pu-238, a 10-kWe reactor-direct radiating-thermoelectric system might be considered as an alternate. The 10-kWe power level is compatible only with a 6-man crew and an environmental control and life support system (EC/LS) with closed-cycle H_2O and open-cycle O_2 subsystems. A maximum crew size of 9 to 12 men is presently specified for MORL on the basis of volume and facilities available for reasonable living conditions consistent with obtaining maximum results of the experimental program. Consequently, a 9-man crew, 2 of whom are cross trained in reactor operations and an EC/LS with both H_2O and O_2 closed-cycle subsystems is assumed for the 20- and 30-kWe power levels. However, the EC/LS heat rejection requirements for the 30-kWe system exceed the area available on the MORL such that a 14-ft MORL extension is required. In addition, it appears that the 30-kWe power level cannot be utilized effectively unless growth in the experimental program is experienced. Therefore, it is concluded that the 30-kWe power level is best adopted to a growth version of the MORL, which could more usefully apply the higher power and more readily accommodate the associated power dissipation capabilities.

The MORL/reactor power system requirements of a 5-yr mission life with associated high confidence in attaining this lifetime can be met by application of the long lifetime and high reliability potential inherent in the reactor design. Attainment of these requirements in the power conversion system designs has been achieved solely through installed redundancy and, when required, complete reactor power system replacement. While it is realized that manned maintenance may also contribute to reactor power system reliability, the design approach provides capabilities for such maintenance in the system designs but does not rely on maintenance in determining the required redundancy. This approach is justified in that manned maintenance capabilities have yet to be demonstrated, and the benefits to be derived are uncertain when consideration is given to overall mission objectives as distinguished from a preoccupation with power system operations.

Based on component-system lifetimes of 1-1/4 to 2-1/2 yr for the dynamic conversion systems, the amount of redundancy required had to be determined considering that as redundancy increases, system design complexity also increases. Conventional reliability formulations do not reveal the optimum overall reliability because many failure modes are not amenable to quantitative analysis. Such failures as those resulting from excessive operational requirements, inadequate manual response, subsystem interactions, or inadequate inspection because of design complexity and compactness fall in this category. Therefore, the system design evolution involves the following steps:

1. Perform a preliminary design of the power conversion systems, including reliability cognizance of component lifetime goals and mission and/or system lifetime requirements, using a combination of design experience, judgment, and reliability goal allocation to ensure that the redundancy provided is within a reasonable range for the intended application.
2. Perform a failure mode and effects analysis on the preliminary design to identify the particular areas of system design most susceptible to failures which could seriously degrade system performance, thereby focusing further attention on such areas. By successive elimination of these failure modes, accomplished through system redesign, the reactor power system confidence factor gradually increases to a point where the initial estimate of redundancy is either verified or suitably adjusted.
3. Initiate the development phase of the power conversion system design, again with reliability cognizance, based on the redundancy assessment developed to date.
4. Conduct development tests to verify the design integrity of the power conversion system, eliminate or minimize failure effects where possible, and further confirm the system confidence factor developed to date.
5. Forward failure reports to design engineering for redesign if required. This is followed by retest, thereby further confirming the redundancy assessment and development of reactor power system confidence factor.
6. Conduct margin testing to verify the limit of design capability and to further confirm confidence factor.
7. Conduct MORL/reactor power systems tests (system integration and all-systems environmental test) to establish a satisfactory confidence level prior to launch.

2.2 REQUIREMENTS

Adequate assessment of the impact of MORL on the reactor power system and, conversely, the effects of the power system on MORL requires identification of the various mission and the power system requirements.

Table 2-1

MORL/REACTOR POWER SYSTEM MISSIONS

	Inclination (°)	Altitude (nmi)	Period (min.)	Lightside (min.)	Umbra (min.)	Launch Azimuth from ETR (°)
Low orbit (baseline)	50	218	94	57	37	44.5
Polar orbit	90	218	94	94(1)		146(2)
				57	37	44.5(3)
Synchronous	28.3	19,350	24 hr	24 hr		90

1. Design condition
2. Initial launch
3. Replacement launches, 44.5° launch azimuth followed by orbit rotation to polar orbit

2.2.1 MORL Requirements

The MORL/reactor power system is a concept for a semipermanent (5 yr) orbital facility capable of supporting a manned experimental program, designed for either zero-g or artificial-g operations with a postulated launch period of 1974 to 1977. The MORL diameter is compatible with the S-IVB (260 in. in diameter) while the length is a function of power level. The MORL/reactor power system possesses the capability for three missions, Table 2-1.

An upgraded Saturn IB launch vehicle is required for initial launch of the MORL/reactor power system into the 50° inclination which is 3-day subsynchronous. A product-improved Saturn IB is used for subsequent reactor power system replacement launches. All initial and replacement launches into polar and synchronous orbits require the use of the Saturn V. The reactor power system will experience a maximum of 6-g axial and 2-g lateral accelerations during these launches.

For the baseline mission, the following launch operations criteria are applicable:

1. Saturn Launch Complexes 34 and 37B at Kennedy Space Center (KSC) are available, but Launch Complex 37A will have to be activated for the MORL launch and Launch Complex 34 will have to be modified to accommodate an upgraded Saturn IB.
2. Launch pad turnaround times are as follows: normal, 6-1/2 weeks and emergency, 4-1/2 weeks.

3. The minimum launch-reaction time for a replacement reactor power system is 12 days, defined as the time required to launch and rendezvous the vehicle from an on-pad standby condition.

4. The hold-time characteristics of the Saturn IB launch vehicle are as follows: At T-3 days, 90 days; at T-6 hr, 30 days; and at T-10 min., 8 hr.

5. A replacement reactor power system must be available in a T-2 day ready condition at all times during the mission.

The Apollo/Gemini rendezvous mechanism is used for all logistic events. During the latter phases of this rendezvous, but before final approach and docking, the closest approach of the logistics vehicle to MORL, including error sources, is a 2-nmi radius (90^o below and 45^o above the local horizontal) referenced from the docking port station of the MORL. Therefore, the reactor power system with a shadow shield designed for only an 80-ft dose plane diameter at the aft end of MORL may be operated at full power during the rendezvous maneuver. The time to complete rendezvous for the 50^o-inclination mission, from liftoff to docking, is normally 6 hr with a maximum 2.75 days. An analysis of the complete rendezvous event is presented in Appendix B.

The long-term orientation for the MORL/reactor power system, when operated at zero-g, is bellydown; that is, the vehicle's longitudinal axis is aligned with the velocity vector. Orientation requirements are 4.5 hr/day in inertial orientation and 19.5 hr/day in bellydown orientation. An attitude control accuracy of $\pm 0.1^o$ will accomodate approximately 94% of the precise Earth-oriented and inertial experiments. The remaining experiments are gimbaled to obtain the desired accuracy. Orientation in the rotating mode is dictated by the experimental program requirements and is established during initial spin-up. The vehicle then remains inertially fixed, subject to gravity gradient and other disturbance torques, designated as spin stabilized. A range of 1 to 4 spinups will be accomplished within a 147-day period.

Initial MORL/reactor power system manning with a 3-man crew, who accomplish station activation and reactor power system deployment, occurs within 6 to 19 days and full manning within 45 days after vehicle launch. During the interval when the MORL is unmanned, all of the MORL fluid systems, other than the reactor power system fluid systems, are operating. The normal MORL/reactor power system resupply interval is 90 days, with all systems designed for a 147-day maximum.

The electrical power system control, conditioning, and distribution equipment supplies the load buses with electrical power of the required quality for loads of 28 Vdc, and 3-phase, 115/200 V, 400 cps ac, respectively. MIL-STD-704, Category B, is taken as the standard for steady state and transient operation of the 400 cps ac power; MIL-STD-704, Category A, is used for dc power. Representative load profiles for the 10- 20- and 30-kWe conditioned power output are shown in Figure 2-4. An automatic load following capability is provided by the electrical power conditioning and control systems to meet the variations in real MORL loads within specified power quality requirements. At 20 kWe, the division between ac and dc loads is approximately 60% ac and 40% dc.

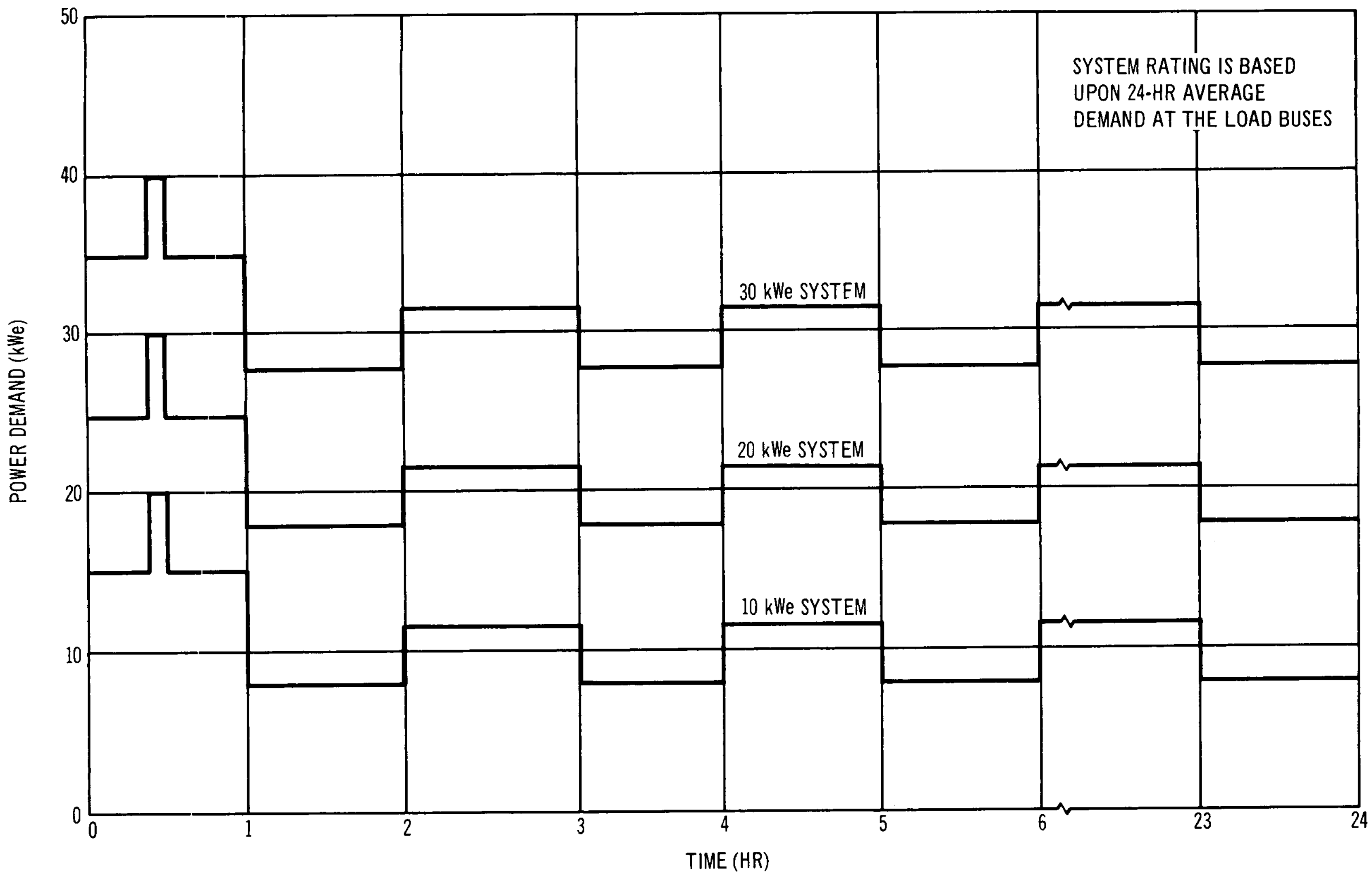


Figure 2-4. Electrical Power Load Profile

Mission survival reliability dictates that a standby power system augment the reactor power system. The standby power source must operate during launch, in orbit prior to MORL manning, and during periods when the reactor power system is inoperative. It must be capable of at least 42 days of continuous operation at a gross output of 5. 5 kWe, providing MORL with only sufficient power to satisfy minimum station- and orbit-keeping requirements.

The EC/LS thermal power requirements for a 6-man crew (open oxygen cycle), 10-kWe system are 2. 27 kW at 250°F compared to 5. 99 kW at 360°F for 9-man crew (closed oxygen cycle) 20- and 30-kWe systems. EC/LS radiator fluid temperature is 115°F inlet and 35°F outlet. The EC/LS radiator must be capable of rejecting the entire power load.

2. 2. 2 Environmental Conditions

The artificial-g spin system, using the spent Saturn S-IVB and reactor power system as a counterweight, produces a maximum of 0. 6 g at the MORL center, corresponding to 2 g's at the reactor power system. Deployment of this counterweight is accomplished at a spin rate of 0. 11 rad/sec and a separation rate of 0. 1 fps.

The maximum permissible personnel exposure levels (Rem) are shown in Table 2-2. The dose plane (located at the aft end of the MORL) dose rate from the reactor is 20 Rem/yr, while the fast neutron relative biological equivalent (RBE) is 6.

Maintenance of the power conversion systems can be performed while the reactor is at 5% to 10% power, limited to 60 hr/yr per crewman (3 Rem/yr dose).

The heat influx to the MORL outer surface is obtained based on a radiator emissivity of 0. 9 and an absorptivity-to-emissivity ratio (α/ϵ) of 0. 25. The average heat sink temperatures for the baseline and polar orbits are -20° and -28°F, respectively, and a minimum of -110°F for the synchronous orbit. The reliability of the heat rejection system to operate successfully for 5 yr (not considering system replacement), and to withstand possible meteoroid penetration is a minimum of 0. 99. During periods when the reactor power

Table 2-2

ALLOWABLE PERSONNEL EXPOSURE LIMITS
MAXIMUM EXPOSURE (REM)

Critical Organ	90 Days	180 Days	365 Days	Single Exposure
Eyes	225	240	270	100
Skin	300	350	400	100
Blood forming organs	50	80	150	25

system is inoperative, thermal protection must be provided to maintain the radiator and system fluids in a liquid state and at a suitable viscosity.

The following correlation is used to determine meteoroid armor equivalent thickness requirements:

$$\psi = 4 \times 10^{-10} \, t^{-3} \qquad (2\text{-}1)$$

where

ψ = penetrations/sq ft - day

t = equivalent thickness of single-sheet aluminum (in.)

For a truss core sandwich structure typified by MORL, the total required sheet thickness is equal to 0.27 t, where t is determined from Equation 2-1 when the actual sheet thickness is divided equally among the three sheets. For application of aluminum armor only, the required thickness is corrected according to the average radiating temperature as follows: 300°F = 1.0 t; 600°F = 1.14 t. Linear interpolation between these temperature limits is allowable. The vulnerable area is taken as the projected outside tube diameter. For finned-tube or bumpered-tube configurations with only one side exposed to the outside environment, the meteoroid protection on the tube sidewall and back side may be reduced to 0.25 times frontal-armor requirements.

2.2.3 Reactor Power System Requirements

The reactor power system consists of the reactor, shield, primary system, power conversion system, and radiator. The reactor power system configuration length is determined by the required radiator area but is limited by the maximum height of the replacement launch vehicle. Maximum allowable radiator area dictated by this vehicle height limitation, precluding Saturn IB stage interstage structural stiffening, is approximately 1,900 sq ft. If the Saturn V is considered for replacement launch, maximum allowable radiator area is approximately 3,300 sq ft precluding launch-umbilical-tower (LUT) modification. Other applicable criteria are as follows:

1. Initial and replacement reactor power system configurations should be identical (except for secondary shield retention capability).
2. The reactor power system configuration is dictated by the requirements of replacement launch, which nominally occurs at 2-1/2 yr.
3. Radiators must be designed as load-carrying structures.
4. Power conversion systems preferably should be located at the aft end of the configuration such that maintenance can be conducted in a reduced radiation environment.
5. The primary system components shall be located in a shield gallery, thereby reducing the radiation dose from activated NaK to crewman performing maintenance on the power conversion system.

6. The electrical power conditioning and control components should be located on the MORL.

7. The reactor power systems shall be designed for both zero-g and artificial-g.

8. Reactor power systems shall be designed for zero uncontrolled leakage of hazardous fluids.

9. On-board fluid leak detection and means of control shall be provided.

10. The reactor power system shall be designed to sustain a minimum of six shutdown and subsequent restart operations per year.

11. System temperature levels shall be maintained within safe limits throughout the shutdown period by provisions for removal of reactor decay heat, thermal protection of the radiators to prevent fluid freezing, and the supply of power from the standby source to make up system heat losses and for necessary pump operation.

12. System restart shall be accomplished in a minimum period consistent with component limitations, in no case longer than 10 hr.

13. Instrumentation shall be provided to monitor the status and verify the integrity of the shutdown system.

14. The SNAP-8-type uranium-zirconium-hydride reactor with a maximum reactor outlet coolant temperature of 1, 300°F is used.

15. The selected fuel form, moderator, materials, fuel rod diameter, metallurgical limits, and fabrication requirements embodied by the existing SNAP-8 core design, developed by Atomics International under AEC cognizance, remain fixed.

16. The dynamic power conversion system lifetimes shall be 2-1/2 yr with corresponding component lifetimes of at least 1-1/4 yr.

17. The thermoelectric power conversion system and components shall be designed for a 5-yr potential lifetime.

18. Attainment of MORL reliability requirements shall be achieved in power conversion system design solely through installed redundancy and, when required, complete reactor power system replacement.

19. The power conversion systems shall be designed to permit manned maintenance, however, in developing system and reliability lifetime criteria, reliance should not be placed on ability to perform maintenance beyond minimal preventive maintenance such as inspection and instrument replacement, and diagnosis and minimal corrective mainte nance such as minor structure repairs, isolation of faulty components, and electrical component replacement.

20. Operating and redundant power conversion systems shall be designed for multiple restarts and malfunction detection and shall incorporate load transfer capability.

Section 3

REACTOR POWER SYSTEMS

This section presents the resultant design concepts obtained from this study for the reactor, primary system, and shielding; SNAP-8, SNAP-2, Brayton, and thermoelectric power conversion systems; and the MORL electrical subsystem. Also summarized are the parametric studies and design rationale utilized in arriving at the specific design decisions.

3.1 REACTOR, PRIMARY SYSTEM, AND SHIELDING

Five baseline reactor power system configurations were selected for detailed analysis; four alternate system configurations were chosen for cursory study. Each configuration uses shadow shielding and a reactor assembly equipped with tapered reflectors to minimize the shadow-cone envelope. A common reactor design, sized to obtain minimum combined reactor and shield weight at the maximum required nominal output power level of 600 kWt for a 5-yr lifetime and a 1, 300°F reactor coolant outlet temperature, was selected as the power source for all systems studied.

3.1.1 Design and Performance Characteristics

The design data common to each system configuration are presented in Table 3-1. The design and performance data unique to each power conversion system application are presented in Figures 3-1 and 3-2. The two 30-kWe SNAP-8 power conversion systems (Configurations 4 and 8 of Figures 3-1 and 3-2) are distinguished by the application of an intermediate NaK loop between the primary coolant and power conversion systems and by the use of thermo-electromagnetic primary and intermediate loop pumps in Configuration 8. The two SNAP-2 power conversion system configurations are differentiated by the rating and number of individual combined rotating units (CRU); Configuration 3 contains a CRU-V design of 5.6-kWe nominal rating, and Configuration 6 exhibits an uprated CRU capable of 10-kWe nominal conditioned output.

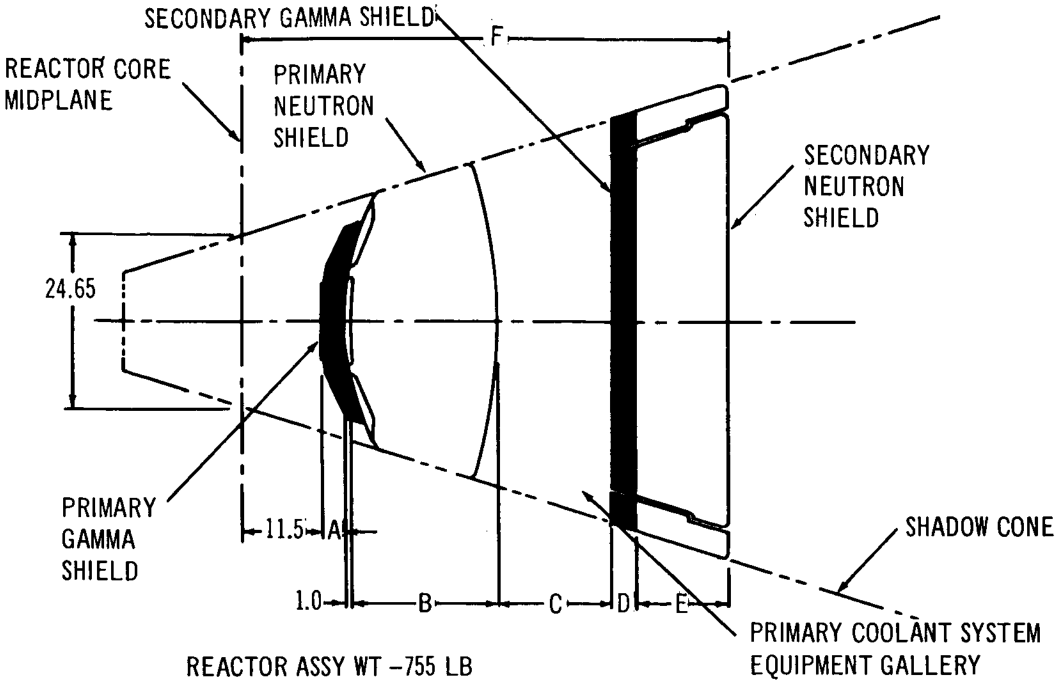
3.1.2 Design Arrangement

The design arrangement shown in Figure 3-3 was selected because parametric studies established the adequacy of this lower-weight, shadow-shielded concept, in comparison with a 4π shield design, to satisfy all presently identified MORL operations. The use of a dual shield facilitates attenuation of radiation from both the reactor and the primary coolant system and reduces secondary activity to a negligible level. The primary coolant system pumps, heat transfer components, and expansion compensators are located in the gallery between the two shield assemblies. Consequently, the more intense reactor radiations are attenuated by two gamma and neutron shield assemblies; the less intense primary coolant emissions are attenuated by a single gamma and neutron shield assembly.

Table 3-1

BASIC DESIGN AND PERFORMANCE DATA

Reactor	
Rated output, nominal maximum, kWt	600
Rated reactor coolant outlet temperature, °F	1, 300
Rated lifetime, yr	5
Fuel element design	SNAP-8 type
Number of fuel elements	349
Fuel element diam, in.	0. 560
Fuel element length, in.	17. 0
Min. clearance between fuel elements, in.	0. 020
Core vessel material	Type 316 Stainless steel
Core vessel wall thickness, in.	0. 215
Core vessel outside diam, in.	12. 197
Primary coolant	NaK-78
Primary coolant system nominal operating pressure, psia	33
Reflector material	Beryllium
Reflector thickness at reactor core midplane, in.	3. 5
Control drum radius-to-thickness ratio	0. 833
Number of active control drums	8
Envelope diam at reactor core midplane, in.	24. 65
Weight, lb	755
Shielding	
Gamma shield material	Depleted U, 8 $^{w}/o$ Mo
Neutron shield material	Natural lithium hydride
Neutron shield containment material	Type 347 Stainless steel
Neutron shield containment and structural mass fraction	0. 28
Integration constraints	
Separation distance, ft	125
Dose-plane diam, ft	80
Dose-plane dose rate, Rem/yr	20
Fast neutron relative biological effectiveness (RBE)	6



	CONFIG NO.	POWER CONVERSION SYSTEM TYPE	NOMINAL ELECTRICAL OUTPUT (kWe)	PCS POWER REQM'TS (kWt)	PRIMARY LOOP REQM'TS (kWt)	REACTOR THERMAL OUTPUT (kWt)	SHIELD WT (LB)	PRIMARY LOOP WT* (LB)	TOTAL WT (LB)
BASELINE CANDIDATE CONFIG.	1	BRAYTON	20	140	12	152	7064	157	7976
	2	T/E	10	408	14	422	8083	270	9108
	3	SNAP 2	20	299	14	313	7509	270	8534
	4	SNAP 8	30	404	10	414	11591	978	13,324
	5	T/E	20	604	18	622	9315	503	10573
ALTERNATE CONFIG.	6	SNAP 2	20	251	14	265	7233	270	8258
	7	SNAP 8	20	333	14	347	8255	270	9280
	8	SNAP 8	30	404	15	419	8654	447	9856

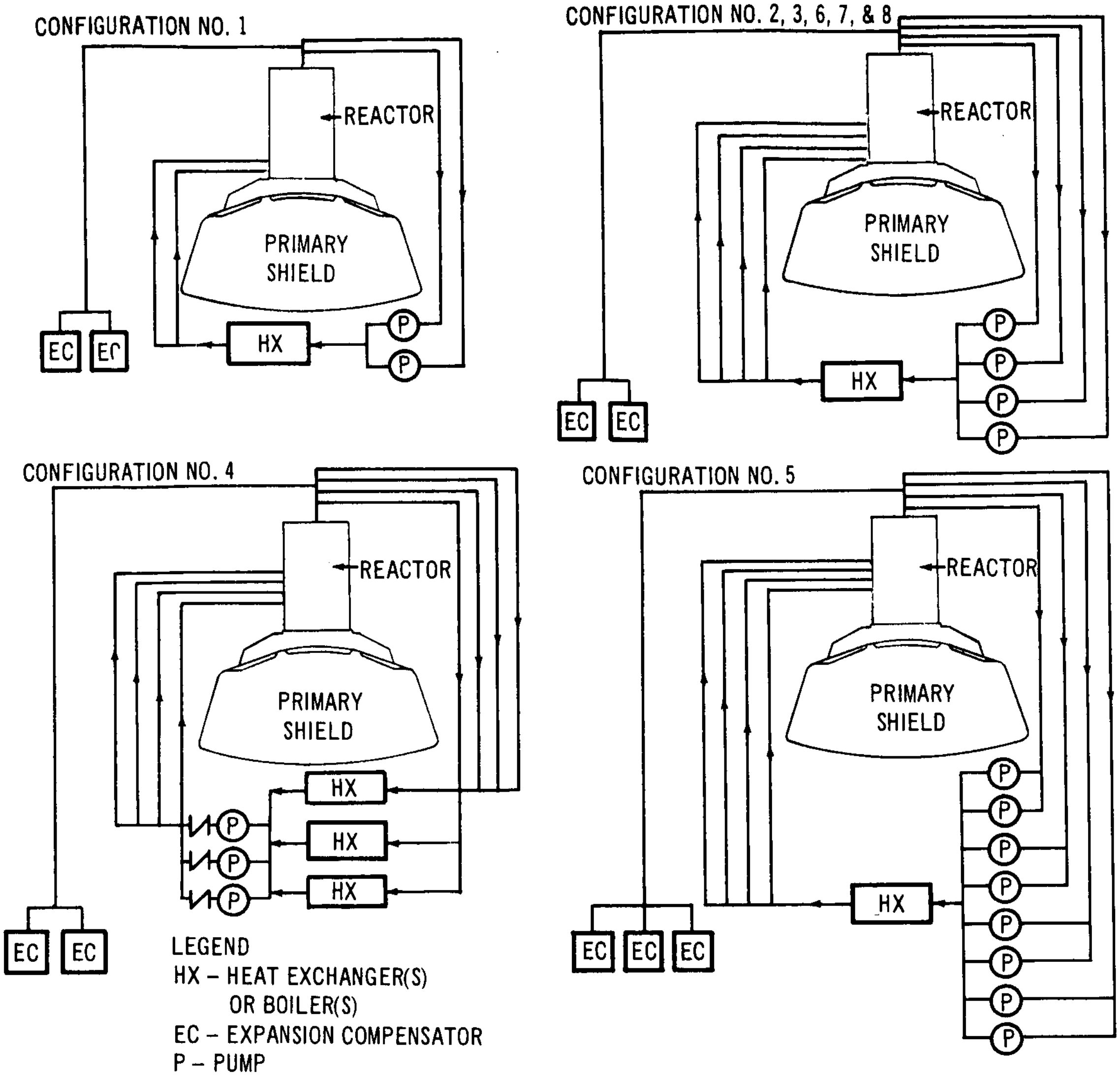
	CONFIG NO.	APPROXIMATE DIMENSIONS (IN.)					
		A	B	C**	D	E	F
BASELINE CANDIDATE CONFIG.	1	2.59	19.9	15.5	3.06	12.7	66.25
	2	2.63	20.3	15.5	3.40	13.0	67.33
	3	2.64	20.4	14.5	3.41	13.0	66.45
	4	3.16	20.7	39.5***	3.45	13.0	92.31
	5	3.01	20.8	21.5	3.68	13.1	74.59
ALTERNATE CONFIG.	6	2.63	20.3	12.0	3.34	13.0	63.77
	7	2.65	20.4	18.5	3.46	13.0	70.51
	8	2.72	20.5	19.5	3.54	13.1	71.86

* WEIGHT OF NaK COOLANT, PIPING, EXPANSION COMPENSATORS & PUMPS

** ALLOWANCE OF 1.5 IN. FOR INSULATION INCLUDED IN THIS VALUE.

*** ALLOWANCE OF 6 IN. OVER MINIMUM SPECIFIED VALUE TO ACCOMMODATE GROWTH

Figure 3-1. MORL Reactor, Shielding, and Primary Coolant System Data



	CONFIG. NO.	MASS FLOW RATE (LB/HR)	REACTOR ΔP (PSI)	PRIMARY LOOP ΔP* (PSI)	REACTOR INLET TEMP. (°F)	REACTOR OUTLET TEMP. (°F)	PUMP TYPE	POWER CONVERSION SYSTEM TYPE	NOMINAL OUTPUT (kWe)
CANDIDATE CONFIG.	1	17000	0.10	0.64	1150	1300	A	BRAYTON	20
	2	35000	0.41	0.94	1100	1300	A	T/E	10
	3	33000	0.37	0.85	1050	1200	A	SNAP-2	20
	4	34000	0.39	0.89	1100	1300	B	SNAP-8	30
	5	51200	0.89	1.61	1100	1300	A	T/E	20
ALTERNATE CONFIG.	6	29000	0.29	0.68	1050	1200	A	SNAP-2	20
	7	28200	0.27	0.64	1100	1300	A	SNAP-8	20
	8	34000	0.39	0.89	1100	1300	A	SNAP-8	30

*TOTAL INCLUDES REACTOR AND INCLUDES 0.1 PSI HEAT EXCHANGER PRESSURE DROP ALLOWANCE.

TYPE "A" PUMP IS A DIRECT RADIATING THERMO-ELECTRO-MAGNETIC PUMP WITH A 1" x 0.4" x 3" THROAT

TYPE "B" PUMP IS THE SNAP 8 CENTRIFUGAL PUMP MOTOR ASSEMBLY

Figure 3-2. Primary Coolant System Data

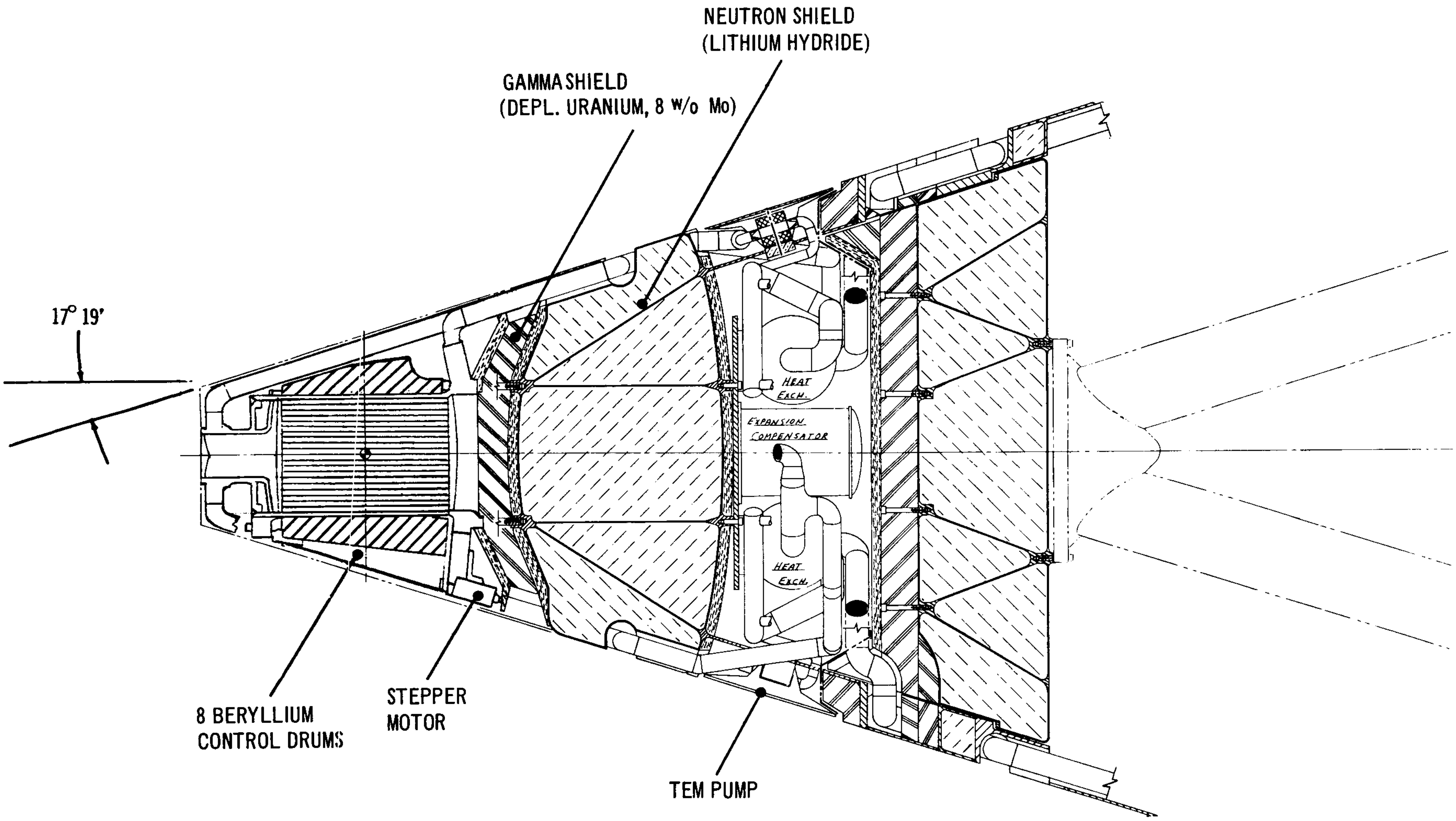


Figure 3-3. Shield and Gallery Equipment

3. 1. 2. 1 Reactor

The selected reactor design shown in Figure 3-3 utilizes current SNAP-8 reactor technology but incorporates those modifications in the necessary configuration to achieve the MORL mission requirements. The reactor assembly consists of two fundamental subassemblies: core and reflector. The core subassembly consists of a core vessel, grid plates, baffle plate, internal reflectors, and fuel elements. Attached to the outside of the core vessel are supports that hold and position the reflector assembly.

The core vessel is a right circular cylinder, composed of 316 stainless steel, which has side-inlet NaK coolant nozzles at the bottom and a central outlet in the top head that connects to side-exit nozzles. Internal grid plates position and support the fuel elements; a flow baffle provides proper coolant flow distribution to minimize average fuel element maximum temperature. The grid plates are contoured to minimize vessel height.

The core consists of a cluster of 349 SNAP-8-type uranium-zirconium-hydride fuel elements and clad beryllium oxide internal reflectors. Fuel elements are arranged in a triangular array with a 0. 020-in. gap separating adjacent fuel elements. The space between the fuel element array and the wall of the cylindrical core vessel is filled with the internal reflectors.

The reflector subassembly is made from a series of neutron-reflecting components and drive mechanisms. Eight rotatable control drums, tapered and shaped as shown in Figure 3-3 to minimize the shadow-cone envelope, are used to adjust the reactivity of the reactor by neutron leakage control. The control drums are supported by bearings incorporated in the core vessel structure to utilize core vessel thermal expansion, thus enhancing the absolute value of the core negative-temperature coefficient. Fixed cusp-type external reflectors are installed in the unoccupied space between the control drums to provide additional reactivity.

Each control drum is driven through a bevel gear drive train (2:1 ratio) by an electrically operated half-degree step actuator, which is positioned in the available space between the control drums and the primary gamma shield to minimize the shadow-cone envelope. The control-drum actuator is a bidirectional stepper motor which rotates the control drum through a nominal 1/4° angle upon command. The actuator is a fail-as-is device designed to maximize reactor life and minimize inadvertent shutdown. No scram circuits are provided. Shutdown is accomplished by driving the control drums to their least reactive position. No provisions are included to eject the reflector, because the possibility of an accidental reflector ejection appears significantly greater than the increment in safety achieved by this capability.

3. 1. 2. 2 Primary Coolant System

In each instance, except for the Brayton system application (Configuration 1 of Figures 3-1 and 3-2), four NaK primary coolant loops are employed. In these loops, the coolant supply and return pipes pass around the primary shield in equally spaced, stepped longitudinal depressions in the neutron shield. In the low power reactor Brayton application (Configuration 1), two parallel loops are adequate.

Expansion compensators in each primary coolant system accommodate NaK volumetric changes during heatup from ambient conditions and maintain sufficient coolant system pressure during normal operation to ensure compressive fuel element cladding stresses throughout the system lifetime. The tap to the expansion compensator is made at the high point in the coolant system to limit the amount of coolant supported by the expansion compensator during launch acceleration periods.

Primary coolant circulation in all cases except for the baseline SNAP-8 system (Configuration 4) is accomplished by direct radiating, thermoelectromagnetic pumps similar to those used for SNAP-10A. These pumps are installed in the system hot leg to make coolant flow virtually independent of power demand. The high inherent reliability of these pumps and their ability to restrict back flow when operating above 2% of rated capacity make it feasible to operate pump sets in parallel without additional flow control. Each pump is active during the entire reactor operating lifetime. To ensure adequate flow during this period, a degradation factor of 10% has been factored into the performance assessment of each pump. Throat efficiencies of about 1% can be expected.

The baseline SNAP-8 system utilizes the canned rotor centrifugal pump developed for the SNAP-8 power conversion system. One active and two standby pumps are provided to attain the required primary coolant system reliability. Check valves are installed in the pump discharge lines to prevent recirculation through the idle pumps.

3.1.2.3 Shielding

A typical dual shadow shield arrangement proposed for the MORL/reactor power source is also presented in Figure 3-3. The complete shield assembly consists of two depleted uranium alloy gamma shields and two natural lithium hydride shields enclosed in stainless steel casings. The first neutron shield serves as the basic structural component for assembly of the reactor, the primary gamma shield, and the primary coolant system components installed in the gallery. To obtain the highest structural efficiency, internal load-carrying members are provided to keep the load paths simple and direct. The second neutron shield is divided into two basic components to provide a capability for permanently attaching the major portion of the second shadow shield to the deployment boom to reduce the replacement power system weight. The reactor, primary shield, and primary coolant system loads are transmitted through a structure spanning the gallery to the outer ring portion of this second shadow shield which serves as a load-carrying member. During launch, these loads are transmitted directly to the radiator structure attached to this ring shield. An independent structural path from the base of the reactor power system configuration is provided to attach the inner plug shield to the deployment boom.

3.1.3 Design Analyses

The most significant parametric studies and design analyses performed to develop and characterize the selected reactor and shield designs are summarized below.

3.1.3.1 Reactor Analyses

To evolve the selected reactor design, parametric studies were conducted to determine the weight, size, and other characteristics of SNAP-8 reactors over a range of power levels, operating temperatures, and lifetimes. The range of the operating parameters investigated was as follows:

1. Thermal power--50 to 1,200 kWt.
2. Maximum coolant temperature--1,000° to 1,300°F.
3. Design lifetime--up to 5 yr.

Variations in the fuel element length (12 to 24 in.), reflector thickness (3 to 5 in.), and number of fuel elements (211, 241, 349, and 499) were considered to achieve these required performance levels. Performance limits for reactivity, phase change, fuel swelling, and vessel creep were established. The reactivity requirements included power, temperature, equilibrium xenon, and hydrogen redistribution short-term effects as well as fuel depletion, fission product poisons, and hydrogen loss long-term effects and reactivity margin.

The significant conclusions of these analyses are as follows:

1. The capabilities of the SNAP-8 technology can be extended to cover the complete parameter range of interest for the MORL application by varying the number and length of fuel-moderator elements.
2. The total reactor plus shield weight penalty caused by increasing the core size to achieve the 5-yr lifetime objective is relatively small compared with that associated with replacement at shorter intervals.
3. If thermal power levels above approximately 870 kWt (30-kWe thermoelectric system requirement) are eliminated, the reactor designs using 349 elements are optimum over most of the remaining power range (for 5-yr operation at 1,300°F). The optimum core lengths vary from 12 to 24 in. for minimum weight systems down to approximately 150 kWt.

Figure 3-4 shows the minimum combined weight of the optimized reactors and shields for 5-yr lifetime and 1,300°F coolant outlet temperature at power levels up to 600 kWt. The weight penalties associated with particular reactor and shield combinations for use over a range of power levels are also shown. The weight penalty associated with the 349-fuel-element reactor with 17-in. fuel elements is under 500 lb for application at any power level up to 600 kWt.

Because of the comparatively small weight penalty and because of the advantages in design and development which result from adopting a common reactor design over the full power range up to 600 kWt, the 349-fuel-element reactor with a fuel element length of approximately 17 in. was applied for all systems in this study. For the 30-kWe thermoelectric system application, the use of a unique 349-fuel-element reactor, and possibly a 499-fuel-element reactor, would be necessary, depending on the ultimate thermal power requirements, operating temperature, and lifetime.

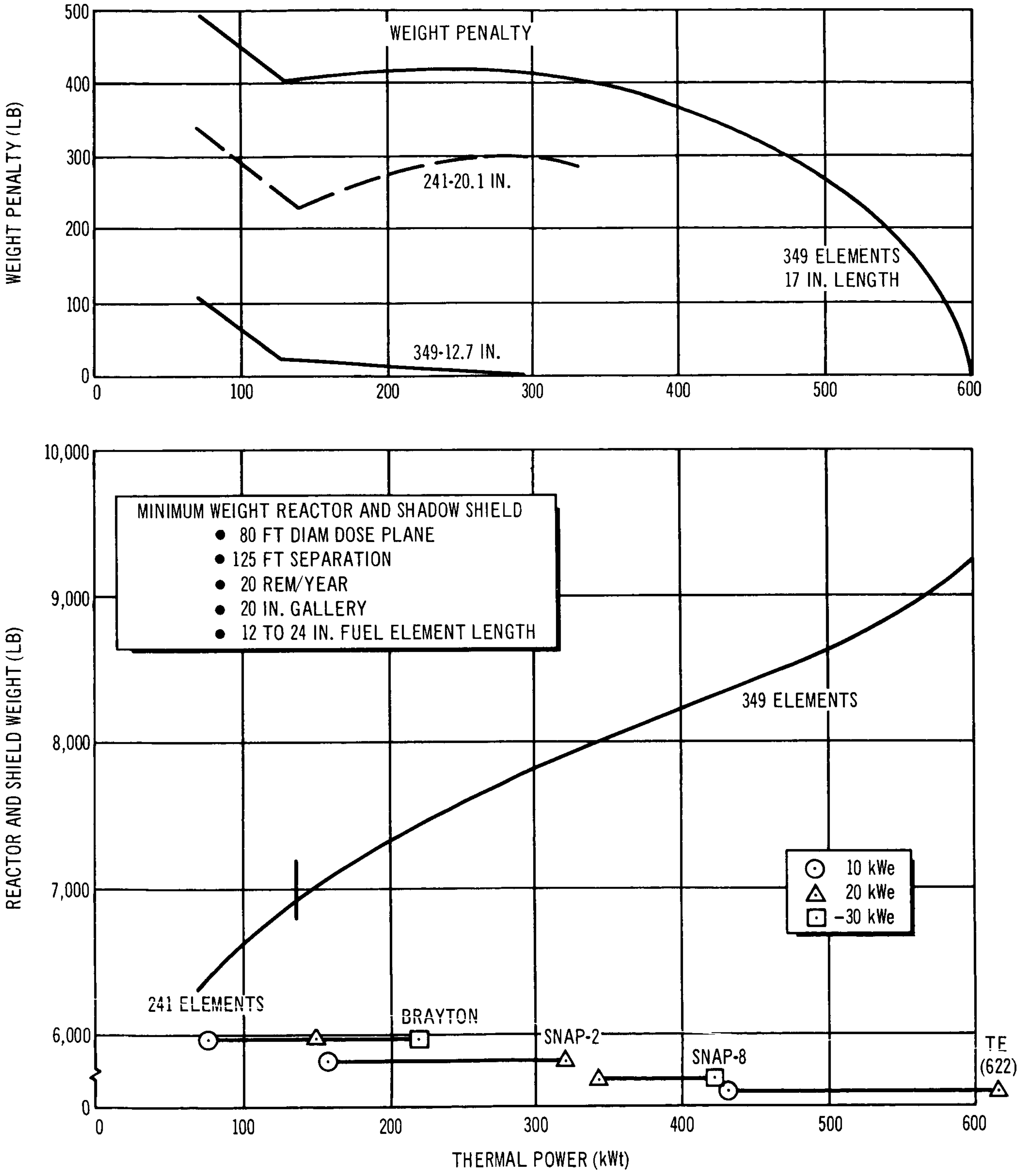


Figure 3-4. Reactor and Shield Weights (5-Year, 1,300°F Design)

Initial parametric studies were premised on the availability of suitable burnable poisons and sufficient control reactivity in 3-in. -thick tapered reflectors to control reactors with operating lifetimes as long as 5 yr. Subsequently, nuclear control analyses were performed to clarify this premise, using the selected 349-fuel-element reactor. A 3-in. -thick reflector was used as the basis for this analysis rather than the proposed 3-1/2-in.-thick design to ensure that the range of interest was fully covered. Study results indicate that nuclear control of this design for a 5-yr operating lifetime is feasible. The candidate burnable poisons include Sm-152, Dy-162, In-115, Eu-151, Ir-191, and Hf-177. All of these except Ir-191 are readily available in oxide form, which is the same physical state used in the SNAP-8 experimental reactor. None of these should produce appreciable gas. The best poison for this configuration appears to be In-115, which is readily available, inexpensive, and has well-known cross-sections. The isotopes Gd-155, Cd-113, Sm-149, and Gd-157 could also be used as the burnable poison if the unpoisoned excess reactivity is reduced somewhat or if the control drum worth is increased by a like amount.

3. 1. 3. 2 Shielding Analyses

Parametric shadow and 4 π shield weights were determined as a function of the following parameters to provide a basis for design selection:

1. Envelope diameter at the reactor core midplane.
2. Reactor fuel element length.
3. Reactor core/assembly diameter.
4. Shield gallery height.
5. Reactor thermal output.
6. Reactor-dose plane separation distance.
7. Dose-plane diameter.
8. Dose rate at the dose plane.
9. Rendezvous zone dose rate (4 π shield only).

The resultant nomographs of shield weight are presented in Figures 4-8 to 4-11 of Task Area II, Douglas Report No. DAC-59213. Based on overall design optimization studies, a reactor-MORL separation distance of 125 ft and a shadow shield were selected to satisfy the integration requirements.

Shield component thicknesses for the dual-shadow shield were determined for each candidate and alternative configuration selected, using the geometric relationships and dosage limits given in Table 3-1, experimentally determined radiation attenuation characteristics for each material, and suitable material thickness apportionments to obtain the minimum weight shield. The resultant basic shield dimensions are presented in Figure 3-1.

The average relative contribution of the 5 radiation sources to the total MORL dose for a minimum weight design are as follows: reactor neutrons, 12%; reactor gammas, 8%; capture gammas in the primary shield, 49%; capture gammas in the secondary shield, 22%; and NaK gammas, 9%. For a 600-kWt power level, the fast neutron flux is approximately 2 x 10^{14}nvt/yr, and the gamma intensity is approximately 1 x 10^{9} R/yr in the gallery. Gallery dose rates at other power levels are approximately proportional to reactor output.

In the primary gamma shield, four significant heating sources have been considered: (1) core gamma ray absorption, (2) absorption of gamma rays resulting from neutron capture, (3) fission of U-238, and (4) fission of residual U-235 (0. 2w/o). In the primary neutron shield, there are three significant sources of heating: (1) absorption of gamma rays, (2) energy from the moderation of fast neutrons, and (3) absorption of energetic alpha and tritium particles resulting from capture by the lithium-6 nuclei. In the secondary gamma and neutron shields, the absorption of gamma rays is the only significant heat source. For a 600-kWt reactor thermal power level, the heat generation rates in each shield region, considered in the same order, are 7. 6 kW, 2. 2 kW, 0. 05 kW, and essentially zero.

By exposing the outer circumference of the primary gamma shield to permit radiation cooling, the peak temperature is maintained at less than 1,225°F. Insulation of the primary neturon shield from the gamma shield and the gallery prevents a lithium hydride temperature greater than 1,000°F, although the insulation on the gallery side must be tailored to maintain a temperature greater than 600°F to avoid excessive radiation-induced swelling in this high-flux region. The secondary shield temperatures are not limiting and can be adjusted to a uniform temperature up to approximately 600°F by application of tailored insulation and/or low emissivity coating on the shield circumference.

The fission product radioactivity levels resulting from defected fuel elements were determined in the primary coolant and at the MORL dose plane. Because a part of the fission product inventory will be released to the circulating coolant and carried to the primary coolant system components located in the gallery, the secondary gamma shield would be the only effective shield for the MORL. The fission product concentration in the primary coolant system resulting from fuel element defects is a function of power level, operating time, number of defected fuel elements, fraction of the inventory released from the defected elements, and nuclear characteristics of the fission products. The major unknown and controlling parameter is the fraction of the fission product inventory released from the fuel elements. However, extensive study of SNAP-8 experimental reactor data indicates that less than 0. 17% of the gross fission product inventory in a defected fuel element will be released to the primary coolant system. On this basis, the net increase in radiation dose that would result from as much as 10% defected elements would be only approximately 2. 4%.

An analysis was conducted to establish the radiation environment after reactor shutdown at a point normal to the reactor (outside the shielded zone) and at a point directly behind the second shadow shield. The radiation dose rate behind the shadow shield at a point 10 ft from the primary coolant system equipment in the gallery is mainly from the primary NaK in the gallery region. The dose rate immediately after reactor shutdown is about 117 mRem/hr and is essentially independent of reactor power. Because the principal activity emanates from Na^{24}, the dose rate decays exponentially, based on a half-life of 15 hr. By comparison, the unshielded dose 100 ft from a reactor which has operated at 400 kWt for a prolonged period is approximately 90 Rem/hr immediately after shutdown. At other power levels, the dosage is directly proportional to the power level ratio.

The lithium-hydride neutron shields must be contained to prevent loss of hydrogen. This containment barrier must provide protection against puncture caused by meteoroid impact. Because the shield face surfaces are largely protected by components, the conical surfaces of both neutron shields are the principal surfaces vulnerable to meteoroid puncture. For a nonpuncture probability of 0.999, a stainless steel casing thickness of 0.150 in. is required. This casing has negligible effect on shield weight. Because this thickness is only 40% greater than the current SNAP-8 shield casing thickness, achievement of adequate meteoroid protection is not a problem.

3.1.4 Control and Instrumentation

Various power system and reactor control modes were evaluated. The principal alternatives considered were the use of parasitic load control rather than load-following control for the power system and flux or temperature control for the reactor.

Although the load-following mode has the potential advantage of conserving reactor reactivity and burnup during part-load operation, the required power level and flow control is relatively complex. The selected parasitic load control provides control simplicity and avoids undesirable fluctuations in fuel element operating temperature by maintaining the power system continuously at rated load. With this control mode, the reactor control system must only be sufficiently fast to permit startup in a reasonably short period, adjust reactor power to account for changes in parasitic load, maintain reactor transients within allowable limits during power conversion system startup and compensate for degradation during long-term operation. Previous analyses of SNAP reactors indicate these requirements can be satisfied without either coolant flow control or rapid control drum movement.

The selected control system utilizes reactor coolant outlet temperature for reactor power output regulation and a neutron flux measurement primarily for diagnostic purposes. Reactor coolant outlet temperature was selected as the principal control variable because (1) high temperatures damage the fuel element hydrogen barrier, (2) large temperature differentials penalize power conversion system performance, and (3) temperature sensors are more reliable than flux instruments. Essentially, the system provides a reactor coolant temperature deadband control system similar to that developed for the SNAP-8. The system includes a means for automatic deadband temperature adjustment and limited manual control.

The reference temperature setpoint is automatically adjusted to compensate for system degradation by cascade compensation. The principal power conversion system parameters are monitored and compared with the desired value; the primary coolant temperature required to maintain the desired value is then computed. The reference temperature setpoint is then adjusted accordingly. The recommended power conversion system control variables for modifying the reactor coolant temperature setpoint are as follows for the individual systems studied:

1.	Brayton	Reactor outlet temperature[*].
2.	SNAP-8	Boiler NaK inlet temperature.
3.	SNAP-2	Boiler NaK outlet temperature.
4.	Thermoelectric	Converter current.

Provisions are also incorporated in the recommended control system for both automatic and manual startup. The normal startup mode is an automatic procedure regulated by reactor coolant temperature and a preprogrammed control drum stepping rate. Manual startup is accomplished with the aid of the three levels of nuclear instrumentation provided for this purpose.

The instrumentation and data display requirements are based on the assumption that limited diagnostic instrumentation is required for an operational mission. In general, only instrumentation affecting safety or parameters subject to operator control have been selected for display. Therefore, a data display panel requiring approximately 3.5 sq ft of MORL console space is provided with the following meter displays:

1. Reactor outlet temperature (narrow range).
2. Reactor outlet temperature (wide range).
3. Reactor inlet temperature.
4. Primary coolant flow rate.
5. NaK expansion compensator position.
6. Control drum position.
7. Neutron level (startup range).
8. Neutron level (intermediate range).
9. Reactor power.
10. Reactor period.
11. Control power supply voltages.
12. Power conversion system parameter.

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[*] No special modification of reactor controller.

Indicator lights are used to indicate the status of the following:

1. Control drum limit switches.
2. Setback status.
3. High or low reactor coolant temperature alarms.

Audible alarms are also provided for high or low reactor outlet temperatures.

3.1.5 Operating Requirements

The operating requirements include initial reactor startup, reactor restart, reactor control during power conversion system startup, shutdown, failure, and temperature control during nonoperating periods.

3.1.5.1 Initial Reactor Startup

Two startup options have been considered, representing the upper and lower time limits for reactor startup. The minimum startup period is obtained with the use of a startup programmer similar to that used on the SNAP-8 to change the control drum stepping rate during the three startup phases to the maximum rate consistent with reactor limitations and safety requirements. The required startup period from the cold subcritical state to hot full-power operation is approximately 1-1/2 to 2 hr. The longest practical startup period is obtained by starting the reactor at the slow, long-term control drum stepping rate; the time required would be approximately 10 hr.

The obvious advantage to be gained from the slow control drum stepping rate is system simplicity by eliminating the startup programmer. However, the high potential reliability of solid-state programmers located in low-radiation fields, coupled with a significantly shorter startup period, resulted in selection of the programmer-regulated, minimum startup period.

3.1.5.2 Reactor Restart

The principal difference between initial startup and restart is that a greater degree of uncertainty will exist during restart in the control drum position at criticality, which will vary as a function of reactor output prior to shutdown, burnable poison depletion, shutdown interval, and reactor temperature at restart.

The reactor may be more reactive partially through its operating lifetime because of a higher consumption of burnable poison than U-235 fuel. However, a change to the slower control drum stepping rate at the appropriate control drum position (50-cent subcritical position when reactor is at its most reactive state in life), together with judicious selection of burnable poison(s) should facilitate a minimal reactor startup interval within acceptable limits.

The reactor temperature can be expected to remain high during a brief reactor shutdown. To overcome the core temperature coefficient reactivity loss, the change to the slower control drum stepping rate would occur substantially below the actual 50-cent subcritical state suggested above. When criticality is attained, the control drums will be in more reactive positions and the originally established reactivity rate (3-cent/min.) for this startup phase would increase (approaching a 5-cent/min. rate). However, no insoluble problems are foreseen from these circumstances. The higher primary coolant flow rates present at this time because of the larger temperature differential across the direct radiating pumps reduce the reactor temperature transient at the attainment of sensible heat. In the baseline 30-kWe SNAP-8 system (Configuration 4 of Figure 3-1 and 3-2), higher pump speeds than those used for the initial startup would be necessary. Moreover the neutron source at this time is substantially greater than the original Po-Be source. In such instances, the reduced excess reactivity at attainment of sensible heat reduces the resultant reactor power and temperature transient.

3.1.5.3 Reactor Transient Performance

Detailed studies of reactor and primary coolant system performance during startup of both mercury Rankine and thermoelectric power conversion systems have been conducted previously. In addition to these analytical studies, injection startup experiments have been repeated many times using a complete SNAP-2 mercury Rankine system with an electrical heat source. The response of the SNAP-8 experimental reactor to step changes in primary loop temperature has also been studied experimentally. The complete SNAP-10A reactor-thermoelectric system, of course, was started many times both in ground tests and in space operation. Although the Brayton cycle has not been studied to the same degree as the other systems, the gas-working fluid has far less ability to induce a thermal shock in the primary loop during system startup than does mercury; therefore the startup transients with the Brayton cycle should be less severe. An evaluation of these previous studies and operating experience indicates that the reactor transients will not be excessive during startup of any power conversion system under consideration.

Reactor performance was studied under the conditions of partial and total power conversion system (PCS) shutdown, as well as partial and total PCS failure. The 0.21-cent/°F negative-temperature coefficient ensures that reactor output will follow the load demand and no special reactor control action will be necessary during these events. However, the normal action during total system shutdown would be to step the control drums out to their least reactive position at the fast stepping rate.

A sudden or instantaneous loss of the total PCS heat load could cause some fuel element damage; the reactor might thus lose some of its normal power producing capability. However, the probability of suffering complete and instantaneous loss of heat removal capability is extremely low, particularly when redundant power conversion loops are used. Moreover, the possibility of this highly unlikely situation may be further reduced by the use of additional control parameter signals to step out the control drums in the event of an extreme accident condition.

No problems are envisioned from sudden fractional changes in the PCS demand.

3.1.5.4 Temperature Control During Shutdown

During the period before initial reactor startup and during standby periods following reactor shutdown, the possibility of primary coolant freezing exists. Moreover, the possibility of fuel element damage caused by failure to dissipate fission product decay heat immediately following reactor shutdown is also presented.

The heat input necessary to maintain primary coolant system temperature above 60°F amounts to only 0.12 to 0.17 kWt, depending on the rated thermal power level. With the use of thermoelectromagnetic pumps, a simpler system is obtained if the coolant is maintained at 200°F, with a nominal increase in heat losses (0.33 to 0.44 kWt, total). At 200°F, a coolant flow rate of at least 5% rated flow, which is considered adequate to distribute heat sufficiently to prevent freezing, is automatically furnished by the pumps. Allowance has been made in the design of the standby power source to provide this power requirement.

Immediately following reactor shutdown, a substantial heat rejection capability must be provided to remove fission product decay heat and thereby prevent excessive fuel element temperatures that could cause hydrogen barrier and cladding failures. When the normal thermal coupling between the reactor and PCS radiators remains intact, the heat rejection capability is greatly in excess of the decay heat generation rate, and a rapid cooldown to temperatures below the freezing point of most liquid metals can be expected unless control (such as thermal shields) is provided.

For reactor power systems in which thermal coupling to the PCS is interrupted at shutdown, radiation from the primary coolant system components is the principal decay heat rejection mode. The decay heat generation rate exceeds the primary coolant system heat rejection capability for a brief time interval in most of the systems studied. The heat rejection rate of a 150-kWt configuration always exceeds the decay heat generation rate, whereas at 300 kWt and 600 kWt, excessive heating rate periods of about 15 and 200 sec, respectively, would occur. Two possible methods of providing the necessary heat rejection capability include an increase in thermal radiation losses of the primary coolant system (such as provided by the direct radiating thermoelectromagnetic pumps), or the use of an additional heat removal device in the primary coolant system. However, the development of individual PCS requirements for startup indicates that the application of an auxiliary heat exchanger in the primary system is desirable. Heat transferred directly from the primary system to the radiator by this means would also be used in the interval between thermal shield removal from the radiator and power conversion system startup to maintain radiator coolant temperatures within allowable limits.

3.1.6 Aerospace Safety

Aerospace safety requires a review of the radiological hazards associated with the use of SNAP reactors for space power systems and appropriate safety measures to control these hazards sufficiently so that no undue hazards to the public, the launch support team, or the MORL crew exist. Accordingly, the following phases, representing the history of the reactor from fabrication to disposal, have been evaluated:

1. Fuel fabrication, assembly, and testing.
2. Shipment.
3. Launch site checkout and prelaunch activities.
4. Launch and boost-to-orbit injection.
5. Reactor startup and orbital operation.
6. Reactor shutdown and disposal.

The available information dealing with these individual phases is extensive. Section 3. 6 of the Task Area III report summarizes an evaluation of these phases specifically for the MORL application and concludes that the entire sequence can be safely accomplished within limits which represent an acceptable level of risk. The following discussion covers the reactor shutdown and disposal phase, which is generally considered to be the most critical phase.

After the useful service life of the reactor, several disposal methods or combinations of methods are possible, including injection of the system into long-life orbit, an orbital fuel element release and subsequent fuel element entry burnup, or reactor entry. Injection of the reactor power system into a long-life orbit allows the fission product inventory to decay to an acceptable level prior to atmospheric entry. The simplest sequence for insertion into a high orbit is through a bitangential orbit transfer and subsequent separation of the reactor and shield from the remainder of the contiguration. The impulsive velocity to transfer from a 219-nmi orbit to orbital altitudes appropriate for adequate fission product decay ranges from 500 to 800 fps. Separation of the reactor and shield from the power conversion system configuration increases the orbital lifetime by a factor of approximately six.

Another disposal mode is to deorbit the reactor configuration so that intact entry occurs in a preselected position on the surface of the Earth. Such an event could be programmed for either ocean burial or recovery. The impact point is affected by the deorbit velocity, position errors, and atmospheric variations. Estimates of the influence of velocity error on the impact accuracy indicate that impact errors on the order of 1 nmi/fps velocity error will occur in deorbits from a 218-nmi orbit having range angles less than 90°. This is an indication that impact areas can be selected within reasonable limits to make ocean burial feasible. A transponder attached to the entering unit should reduce impact uncertainties sufficiently to permit postimpact recovery.

A still simpler and more easily implemented disposal method is orbital fuel element release with subsequent fuel element entry burnup. Extensive study indicates that the most practical approach is to separate the spent reactor from the MORL and then rupture the core vessel to disperse the fuel elements. It has been demonstrated conclusively that the release of fuel elements from the reactor vessel at sufficient altitude will result in burnup. Disposal in this manner will present no significant hazard to the MORL crew or to the public.

Improper ejection of the reactor could add to the crewman's exposure, but the doses would not be unacceptably high because the reactor is shut down prior to ejection. If the reactor were separated from the MORL very slowly (about 1 fps) and the astronauts were exposed to the unshielded reactor from the moment of release, the total dose received would be less than 0.4 rad for a 300-kWt unit, which is an acceptable emergency exposure level.

A SNAP reactor can pose a hazard to the general public only as a result of a series of improbable events, which taken together are considered to be implausible. First, a catastrophic failure of MORL must occur in which the reactor is not ejected and caused to burn up. Furthermore, it must be a situation in which the astronauts are unable to take any corrective action. Finally, during entry, some unexplained circumstance is necessary to cause associated equipment to protect the reactor from aerodynamic heating, thus preventing complete reactor burn up. All these events must take place for this improbable event. However, if these events did occur, the release of a fairly strong radiation source to the biosphere could take place and a hazard could result. It should be noted that the reactor would most probably land in the ocean, or in an unpopulated area, thus eliminating radiological hazard. The public can be endangered only if the reactor survives re-entry and lands in a populated area. In addition to the low probability of occurrence of a hazard to the public, the tracking of MORL operations from Earth would facilitate action to minimize radiological hazards in this eventuality.

It may be concluded that a SNAP reactor can be used as a power source for the MORL without undue hazard to the public.

3.2 SNAP-8 MERCURY RANKINE POWER CONVERSION SYSTEM

The baseline SNAP-8 system design consists of three independent power conversion systems, coupled to three boilers installed within the shield gallery, and two sets of radiator tubes to meet a 2-1/2-yr system lifetime objective. Because the specified component lifetime for the baseline system is 1-1/4 yr, the installed power conversion system capacity essentially amounts to the provision of one redundant system to supplement the minimum installed system capacity required for a 2-1/2-yr lifetime. The most significant factors leading to the selection of this design and leading to the integration concepts presented are the following:

1. Relationships of reliability and lifetime objectives for the SNAP-8 components relative to mission lifetime requirements.
2. Relationships of possible power system failure modes (in particular, the possibility of a boiler tube leak) on the integrated system design and means of minimizing the adverse effects of possible malfunctions.
3. Installation concepts based on providing accessibility for maintenance and for accommodation of both zero-g and artificial-g space stations.
4. Application of the SNAP-8 system defined as EGS-2 (reference the Performance Potential Study), for the principal evaluation and to establish the integrated configurations.

Although the effects of increased component lifetime (20, 000 hr) were considered, the selected design is based on a 11, 000-hr component lifetime in consonance with SNAP-8 program objectives, because operating capabilities beyond this period cannot be confidently predicted until greater operating experience is accumulated. Consequently, a system lifetime of 2-1/2 yr was selected to minimize excessive installed redundancy. Investigation of an intermediate loop between the reactor and boiler loop indicated potential advantages in providing access to the boiler and associated power conversion components for inspection, maintenance and isolation, and in minimizing the possibility of activated primary NaK leakage behind the reactor shielding. Moreover, with application of an intermediate loop, redundancy is more readily accommodated with a smaller effect on shield weight, and reduced valving requirements. These and other significant aspects of the SNAP-8 system analyses are summarized herein for application of the system with a long-duration, manned Earth-orbital application.

3. 2. 1 System Design Description

The SNAP-8 mercury Rankine reactor power system configuration, assembled atop the MORL for the initial launch, is shown in Figure 3-5. The required radiator area is provided on two sections of the surface. The larger section contains the heat rejection loop (HRL) requiring 827 sq ft of area and is located at the forward end of the conical configuration. The lubrication cooling (L/C) loop requiring 238 sq ft of area, is located at the aft end of the configuration. The adapter between the MORL and the power system configuration is required for this initial launch but is not necessary for the replacement launch. The attach section at the base of the configuration provides a rigid support for the truss section. Three SNAP-8 power conversion systems (PCS) are located symmetrically around the periphery of the configuration; the arrangement of one typical PCS is shown. The PCS components are easily accessible because the components are all located at the aft end of the configuration.

The zero- and artificial-g modes can both be accommodated with the SNAP-8 installation shown because the condenser is installed so that the direction of condensation is toward the apex of the cone. Rotation of the MORL has essentially no effect on the operation of the modified SNAP-8 system because the liquid-vapor interfaces of the condenser and boiler can be installed at the same elevation. However, this is not the case for the baseline SNAP-8 system because the boilers are installed within the shield gallery and, with respect to the local gravity, are considerably below the condenser. This results in higher absolute pressures at the boiler inlet than the zero-g case. For example, a 20-ft separation distance between the mercury pump and boiler, and a 2-g,artificial-g acceleration load results in a mercury pressure increase at the boiler inlet compared with the zero-g. This, in turn, causes a displacement of the liquid-vapor interface within the boiler, in the downstream direction, with an accompanying overall reduction in boiler performance and the possibility of wet vapor at the turbine inlet. One method of correcting this problem involves the addition of a pressure valve in the boiler feedline.

In the case of a local-g environment, it is necessary to locate the mercury pump below the condenser to avoid loss of NPSH because of the hydrostatic head. The L/C loop must also be considered in the case of a local-g environment because the L/C fluid dynamic slingers are designed to operate against a fixed back pressure which must be maintained within ±0. 5 psi to obtain proper

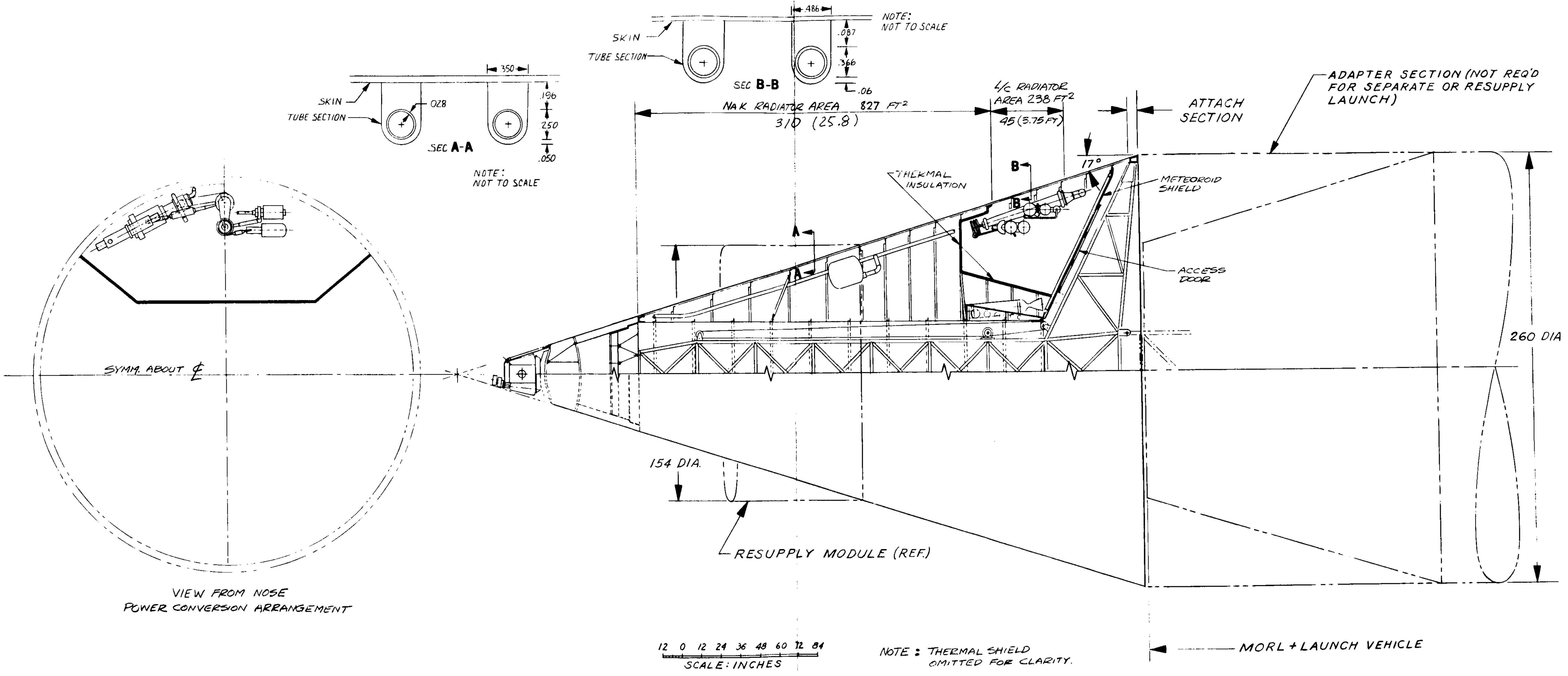


Figure 3-5. 30 kWe SNAP-8 Mercury Rankine Nuclear Power System

coolant flow rates. Excessive back pressure will cause flooding of the mercury motor and alternator cavities. The L/C pump motor assembly (PMA) must, therefore, be located below both the turbine alternator assembly (TAA) and the mercury pump motor assembly (Hg PMA) when local-g operation is encountered.

The installation of three boilers in the shield gallery is considered necessary to meet reliability and lifetime objectives. The use of one or even two boilers of the current SNAP-8 design is not sufficient to meet the required system reliability. Because it is assumed that mercury leakage into the primary NaK fluid is unacceptable, modification to the boiler design to incorporate double containment of fluids is required to preclude such leakage.

The development of such boiler modifications is implicit in the selected redundancy concept for the baseline SNAP-8 system design. This problem is avoided by application of an intermediate NaK loop for the modified SNAP-8 system designs investigated. The modified system design includes the use of thermoelectromagnetic pumps connected in parallel to three series-connected, NAK-to-NaK heat exchangers installed in the shield gallery. The use of NaK-to-NaK heat exchangers prevents the direct leakage of mercury into the primary coolant or the leakage of radioactive NaK into a shutdown power conversion system. Moreover, primary side isolation valves are not required; the overall reliability is thereby improved. The design of the modified system requires a boiler inlet temperature 10°F lower than that of the baseline system design to accommodate the temperature difference in the NaK-to-NaK heat exchanger. However, this slight reduction in temperature has a negligible effect on the performance of the modified system.

The alternate 20- and 30-kWe system designs selected for cursory analysis include consideration of a component lifetime potential of 2-1/2 yr and a corresponding system lifetime potential of 5 yr. This requires extrapolation of the present SNAP-8 program reliability goals which have an established 10,000-hr component lifetime. Assuming a constant failure rate, the extension of these goals to a significantly longer component operating period results in lower component reliability values and increased redundancy requirements. The alternate designs considered the application of one additional power system to make a total of four systems. In view of the uncertainties involved in further extension of the available reliability goals to cover the 2-1/2-yr component lifetime, a realistic appraisal of the redundancy requirements for this longer operating period cannot be made at this time; however, based on subjective reasoning, a maximum of four or perhaps five SNAP-8 systems appears to be a reasonable upper limit for the total number of systems.

Table 3-2 summarizes the reactor power system weights for the 30-kWe baseline system and includes weight penalities for the control moment gyro, shield retention and deployment boom, standby power system, electrical system, reaction control system, and MORL extension and fairings. The components that are installed on the MORL are tabulated separately from those installed on the power system structural assembly. Table 3-3 shows a more detailed weight breakdown of the PCS and the electrical systems.

3.2.2 System Operational Requirements

Preoperational thermal requirements and crew activities during startup, normal operation, load control, system shutdown, standby operation, and restart are discussed below.

Table 3-2

REACTOR-SNAP-8 POWER SYSTEM WEIGHT SUMMARY

Parameter	Weight (lb)		
Reactor power system weight:			
Reactor and primary system		1,733	
Shield		11,591	
PCS and electrical components installed on power system structural assembly		6,499	
Structure		2,042	
Thermal shields and reactor disposal system		1,209	
Thermal shields	(698)		
Reactor disposal	(511)		
Subtotal			23,074
Associated reactor system weight (1):			
Control moment gyro penalty		1,560	
Shield retention and deployment boom		2,350	
Structure	(1,619)		
Tension cables	(131)		
Electrical transmission cables	(600)		
Standby power		1,676	
Electrical system on MORL		4,493	
Alternator load control	(370)		
Control and conditioning	(1,698)		
Bus and distribution	(1,500)		
Standby source electrical	(925)		
RCS penalty (2)		1,289	
Tanks and supports	(304)		
Propellant	(985)		
MORL extension (3)		354	
Fairing		30	
Subtotal			11,752
Reactor power system configuration total weight			34,826
Integral launch adapter			1,020
Integral launch weight (4) (with 20% contingency)			63,846 (71,016)
Replacement launch weight with shield retention (with 20% contingency)			17,509 (21,011)
Replacement launch weight with fixed shield (with 20% contingency)			23,074 (27,688)

Notes:

1. Components and structure which are retained by or are a part of the MORL and are not resupplied with the replacement power system.
2. RCS weight penalty is that weight in excess of the baseline MORL RCS weight (880 lb of propellant and 426 lb of tanks and supports) for a 218-nmi, 50°-inclination orbit over a 147-day duration.
3. 5.2-ft extension over baseline MORL length for EC/LS and standby power system radiator.
4. Includes 28,000 lb for the MORL less Pu 238 Brayton Power System.

Table 3-3

SNAP-8 PCS AND ELECTRICAL SYSTEM WEIGHTS

POWER CONVERSION SYSTEM	Unit Wt (lb)	Number Required	Weight (lb)
Primary coolant system			
NaK PMA	178	3	534
NaK coolant and piping			99
Expansion compensators	94	3	282
Auxiliary heat exchangers	21	3	63
(Note PLR installed on MORL)			
Subtotal			978
Mercury Rankine loop			
Boiler	331	3	
Turbine alternator assembly	603	3	
Turbine exhaust bellows	23	3	
Condenser	141	3	
Mercury pump motor assembly	85	3	
Mercury injection system	144	3	
Valves, piping, miscellaneous	179	3	
Subtotal	1,506		4,518
Heat rejection components			
NaK PMA	178	3	534
Expansion reservoir	39	3	117
Valves, piping, miscellaneous	66	1	66
Subtotal			717
Lube coolant components			
L/C PMA	20	3	60
Expansion reservoir	36	3	108
Valves, piping, miscellaneous	127	1	127
Insulation			171
Subtotal			466
HRL radiator and 2 sets of tubes			1,431
L/C radiator and 2 sets of tubes			399
Radiator structural support and frames			790
Thermal shields and reactor disposal system			1,209
Subtotal			10,508
Nonelectrical associated reactor power system weights: (Retained on MORL during replacement)			
CMG penalty			1,560
Shield retention and deployment boom			
Structure	1,619		
Tension cables	131		
Electrical transmission cables	600		
Subtotal			2,350
Standby power			1,676
RCS penalty*			
Tanks and supports	304		
Propellant	985		
Subtotal			1,289
MORL extension**			354
Fairing			30
Subtotal			7,259

ELECTRICAL SYSTEM	Unit Wt (lb)	Number Required	Weight (lb)
Electrical components installed on power system structural assembly			
PCS control cable harness	60	2	
Power lines	50	2	
Electrical equipment on power system configuration, subtotal	110		220
Electrical components installed on MORL			
Alternator load control system			
Parasitic load control assembly (solid state)	90		
Parasitic load resistors	89		
Generator load control breakers	6		
Subtotal	185		370
Control and conditioning system			
Dc system			
Transformer rectifier	60	2	
Main dc voltage regulator	35	2	
Subtotal	95		190
Ac system			
Sine wave regulator filter	30	2	
Emergency inverter (400 Hz only)	50	2	
Subtotal	80		160
Load control system	10	2	
Switches, circuit breakers, relays		37	
Subtotal			192
Bus and distribution system			
Subtotal			1,500
PBC standby system (electrical equipment including batteries)			925
Low temperature control assembly	209	2	
Start programmer	15	2	
Rotary inverter	316	2	
Power factor capacitor	25	2	
Thermal insulation	13	2	
Subtotal	578		1,156
Electrical components installed on MORL subtotal			4,493

SUMMARY	Integral Launch	Replacement Launch
Power system subtotal	10,508	10,508
Reactor	755	755
Shield	11,591	6,026
Total reactor, shield, and power conversion system	22,854	17,289
Electrical components installed on power system configuration	220	220
Associated weights:		
Electrical components installed on MORL	4,493	---
Nonelectrical reactor system weights	7,259	---
Total weight	34,826	17,509

Notes:

*The RCS weight penalty is defined as that RCS weight required over and above the baseline MORL RCS weight. Total RCS weight is 2,595 lb; 1,078 lb installed on MORL and 1,517 lb installed on the reactor power system.

**5.2-ft extension required for EC/LS and standby power system radiator.

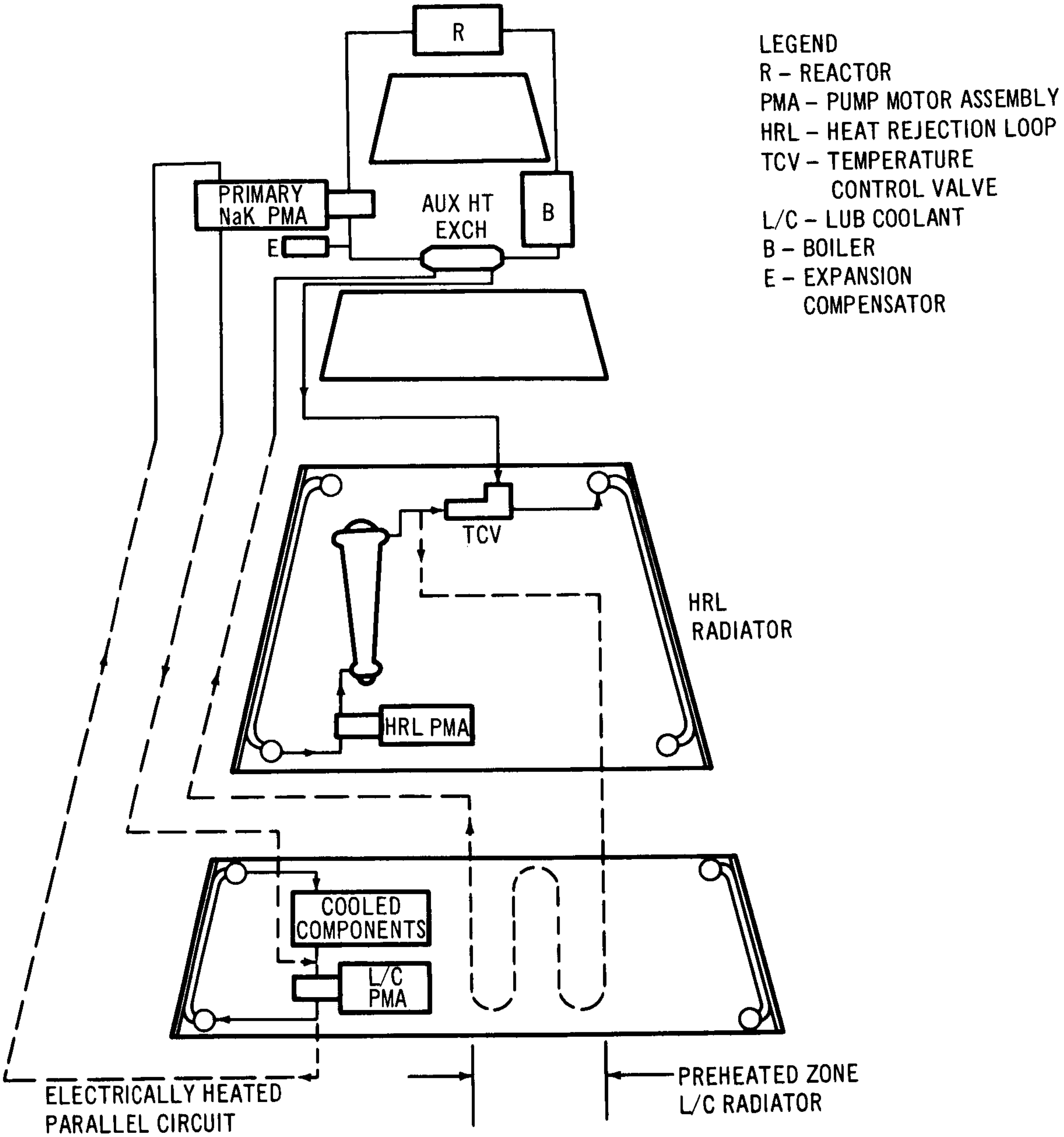


Figure 3-6. Preheating Lube Coolant Radiator

3.2.2.1 Preoperational Heating

Thermal shields are provided to maintain all heat-rejection fluids at 100°F. Prior to the selection of thermal shields, consideration was given to the use of the SNAP-8 auxiliary heat exchanger to raise the L/C fluid to a temperature of 100°F before startup. Although the use of thermal shields eliminates the need to raise the L/C fluid to 100°F, it is still necessary to maintain the fluid temperature at 100°F during the startup procedure inasmuch as the thermal shields are removed during the startup sequence prior to initiating reactor criticality. Once the shields are removed, a 2- to 5-hr interval is required before the reactor power system is self-sustaining.

For a portion of this period, the L/C and radiator fluids require additional thermal energy to preclude fluid freezing. Therefore, the concept developed for L/C fluid warmup is now basically applicable to preventing fluid freezing during startup.

The heat transport loop for providing thermal energy to the L/C radiator during startup of the primary NaK loop is shown in Figure 3-6. Primary loop reactor heat is transferred to one of 16 parallel loops in the L/C radiator by routing the auxiliary heat exchanger lines to a particular circuit. This will heat or maintain 1/16 of the L/C radiator at the 100°F level required for satisfactory functioning. The preheated section of the L/C radiator will subsequently warm adjacent sections until the radiator is operational. To ensure passage of coolant through the primary NaK PMA during warmup of the L/C radiator, the NaK PMA is connected in a loop parallel to the radiator. This loop may initially be heated to 100°F by means of electrical heaters, thereby permitting the L/C pump to supply coolant to the NaK PMA even before warmup of the L/C radiator. With proper operation of the primary NaK PMA ensured, the rerouted auxiliary heat exchanger line preheats one of the L/C radiator flow loops to make it operational. Thus, with the procedures discussed above, approximately 200 W of electrical heating is sufficient to guarantee satisfactory warmup of the L/C radiator.

3.2.2.2 Startup and Normal Operation

Because the development of the SNAP-8 system is based on specifications for unmanned applications, the SNAP-8 startup procedure, as presently defined, is entirely automatic. A more expeditious startup of the PCS may be possible by providing manual override for some of the startup timers. Monitoring of the PCS state point parameters during startup can also be of diagnostic value, should any component malfunction.

During normal operation, the crew will switch loads on and off the load bus, as required, and perform PCS monitoring functions for identification of performance deterioration. The crew must decide when performance of a PCS has deteriorated sufficiently to retire it from service. For such a case, or in the event of a PCS failure, the crew executes the switching necessary to connect a standby PCS to the reactor. The new PCS is then started and brought to a normal operational condition.

3.2.2.3 Shutdown, Standby, and Restart

Diagnostic procedures will, if warranted, signal the need for a system shutdown. The shutdown procedure depends on the nature of the fault. For both an emergency reactor shutdown situation and a normal shutdown, power is required to sustain operation of both primary and HRL NaK pumps to provide reactor cooling and to maintain radiator fluid temperatures within acceptable limits during the shutdown interval. Further study is required to establish a division between those faults which demand an immediate, automatic shutdown and those faults which may be corrected by manned action while the system remains in operation. Faults that require crew participation include those which can be tolerated by reductions in system power output.

In the present SNAP-8 system program, a detailed shutdown and restart procedure has not been developed; however, a general method considered feasible for the MORL application was presented during the course of this study.

It may be desirable to shut down one PCS and start the redundant PCS without a complete interruption of output power capability. This may be accomplished by a system modification and by reducing the net power to the laboratory to approximately 10 kWe prior to switchover. The NaK radiator manifold must be modified to allow step changes in radiating area, or other means for reduced cooling may be developed. This is necessary to avoid an excessive reduction in turbine back pressure which causes cavitation in the mercury pump and subsequent reductions in mercury flow rate. Incorporation of means of reducing the effective radiator area permits a reduction in mercury flow rate to a point where two PCS systems can be operated simultaneously. Therefore, a continuous, though reduced, net power output may be maintained while switching from one PCS to another. For any given time during the switchover procedure, the laboratory will draw its power from only one PCS. Thus, the problems of alternator paralleling are avoided.

3.2.3 System Maintenance Requirements

The following list includes several maintenance functions that can be performed without necessitating the breaking and rewelding of liquid lines.

1. Repair of electrical wiring, connections, switches, and inverters.
2. Repair of electrical, hydraulic, and mechanical valve control systems.
3. Repair of instrumentation lines and warning and readout systems.
4. Repair of structure and component mountings.
5. Repair of thermal insulation for pipes and components.
6. Methods of cleaning fluid line traps and filters may be designed to permit their removal and replacement.

Additional maintenance operations for the inoperative power systems include periodic startup and checkout to verify standby system integrity. Periodic checkout is required to evaluate the effects of static deterioration and thermal cycling.

The present SNAP-8 PCS includes rotating inverters for converting from dc to ac current for startup requirements. However, the use of static inverters is possible. For either type of inverter, replacement can be accomplished simply by disconnecting and reconnecting electrical lines.

The alternator and the L/C pump assembly may only be replaced by cutting and reconnecting lubricant lines. Decoupling of the alternator does not require decoupling mercury lines.

Because the parasitic load resistor is installed in the MORL, replacement is relatively simple. In the same manner, with appropriate safety measures, all electrical and control components, wiring, and monitoring equipment are replaceable. In addition, valve actuators and linkages are also replaceable.

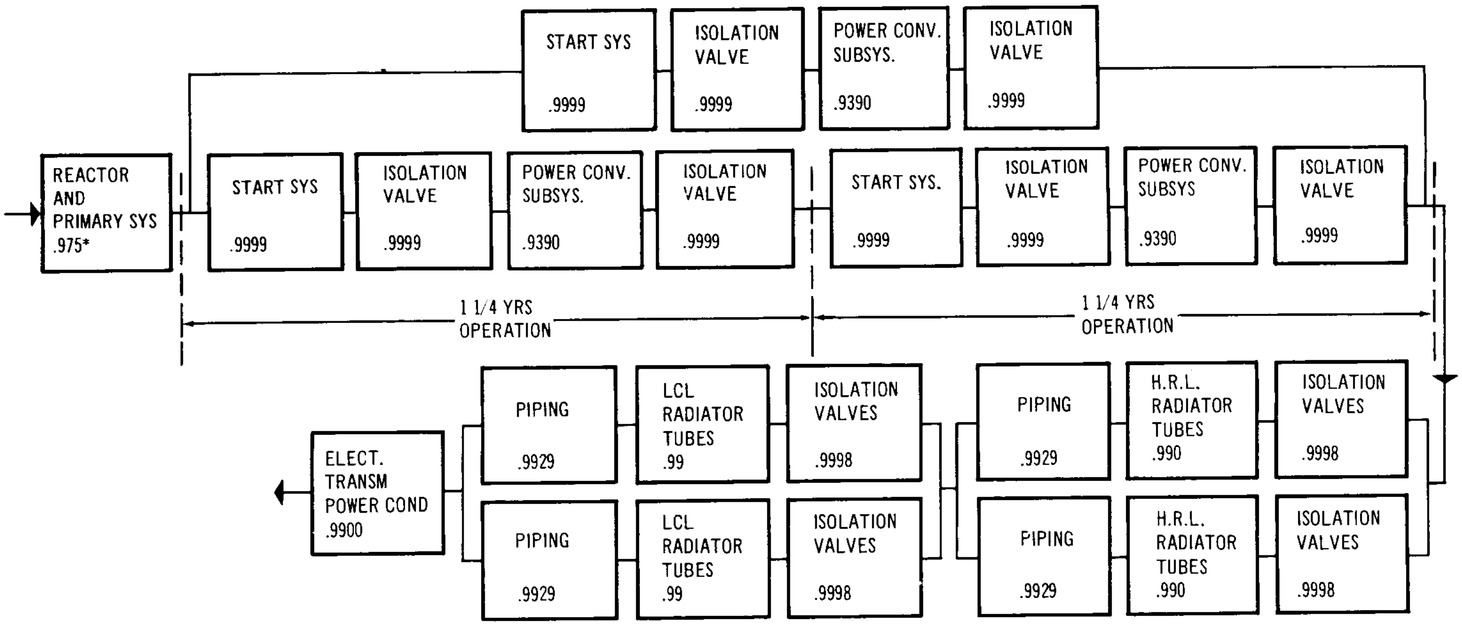
3.2.4 Reliability

The SNAP-8 reliability model and computations are shown in Figure 3-7 for three power conversion subsystems with a lifetime goal of 1-1/4 yr for each subsystem and 2-1/2 yr for the system. The reliabilities of the power conversion subsystem components are as stipulated by the subcontractor except for the addition of isolation valves. The reactor and primary system reliability is reduced from 0.98 to 0.975 to account for the application of centrifugal pumps in the primary system as opposed to thermoelectric pumps as used in all the other system designs. The calculated reactor power system reliability is 0.959 based on 3 subsystems and the subcontractor component reliability goals. Therefore, it is concluded that the use of a fourth subsystem is unnecessary to meet the overall reliability objective if these component reliability goals are realized. However, these goals are considered to be relatively optimistic with respect to expected performance of currently available equipment.

3.2.5 Performance Analysis

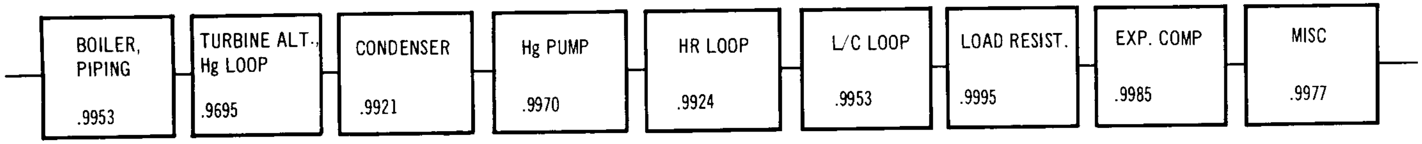
A total of 7 SNAP-8 configurations, shown in Table 3-4, were considered during the course of this study. At the conclusion of the Task Area II study phase, three SNAP-8 power conversion systems, each containing redundant components and the necessary switching valves, were selected for further analysis as shown in the table. Although component redundancy was investigated in detail, the Task Area III study results indicate that selection of complete PCS redundancy without internal component redundancy is a more desirable concept. The principal reason for this choice is the unreliability associated with the numerous component switching functions that offset the gain in reliability associated with redundant components.

The PCS component design bases employed for the selected baseline and modified systems are shown in Table 3-5. The baseline SNAP-8 system design evolved at the conclusion of Task Area III includes application of three independent SNAP-8 PCS's coupled with three boilers installed within the shield gallery and a total of two sets of radiator tubes for the HRL and L/C loop. The primary difference between the baseline SNAP-8 systems are that (1) the boiler is installed within the shield gallery for the baseline system and (2) an intermediate NaK-to-NaK loop is provided within the shield gallery for the modified designs. The use of an intermediate loop minimizes the leakage problem, reduces system weight, and provides accessibility to the boilers for isolation and potential maintenance, because the boilers can be installed behind the secondary shield.



(*ALLOWANCE FOR NaK CENTRIFUGAL PUMPS INCLUDED)

POWER CONVERSION SUBSYSTEM (R = 0.9390)



RELIABILITY CALCULATION:

R (POWER CONV. SUBSYS, 1 1/4 YRS) = (.9953) (.9695) (.9921) (.9970) (.9924) (.9953) (.9995) (.9985) (.9977) = 0.9390

R (EACH POWER CONV. SYS, 1 1/4 YRS) = $(.9999)^3$ (.9390) = 0.9387, AND $\lambda t = 0.0633$

R (POWER CONV SYS, 3 FOR 2 1/2 YRS) = $e^{-2\lambda t}\left[1 + 2\lambda t + \frac{(2\lambda t)^2}{8}\right] = 0.9947$

R (RADIATOR TUBES, 1 OF 2 SETS EACH, 2 1/2 YRS) = $[1 - (1 - .982)^2]^2 = 0.999$

R (REACTOR POWER SYSTEM, 2 1/2 YRS) = (.975) (.9947) (.999) (.990) = 0.959

RELIABILITY VALUES BASED UPON SNAP-8 POWER CONVERSION COMPONENT RELIABILITY GOALS

Figure 3-7. 30 kWe SNAP-8 Power System Reliability Diagram

Table 3-4

ALTERNATIVE SNAP-8 SYSTEMS CONSIDERED FOR MORL

Nominal Power Level (kWe)	30	30	30	30	30	20	20
Designation	Baseline design	Baseline design	Baseline design	Modified design	Modified design	Modified design	Modified design
Configuration	3 boilers installed within shield gallery 4 conversion systems	3 boilers installed within shield gallery 3 conversion systems	4 boilers installed within shield gallery 4 conversion systems	Intermediate loop 4 conversion systems	Intermediate loop 3 conversion systems	Intermediate loop 4 conversion systems	Intermediate loop 3 conversion systems

Selected for further analysis: based on system weight, component and system life, system complexity, and design integrity.

Final Recommendations:
Baseline design, 3 boilers installed within shield gallery, 3 conversion systems, redesign of boiler. Further study and development effort recommendations included in Technology Readiness section.

Table 3-5

SNAP-8 SYSTEM COMPONENT DESIGN BASIS

Baseline/Reference Design	Modified Design
Boilers installed within shield gallery, no intermediate loop.	Boilers installed behind secondary shield. Intermediate loop employed.

Rankine cycle state points constant.

Component life, 1-1/4 yr; system life, 2-1/2 yr.

Turbine Modifications:

- The use of opposed visco pumps mounted between the turbine bearings to facilitate removal of the thrust balance piston, and the elimination of mercury vapor leakage through the clearance annulus.
- Improved design and fabrication techniques to eliminate the small clearance spaces between the tips of the nozzle vanes and adjacent structure.
- Reduction in the trailing edge thickness of the rotor blades, accompanied by a reduction in pitch-to-chord ratio.
- Turbine flow areas sized for required system power level.

These modification result in a 7. 4 point improvement in efficiency, giving a turbine design efficiency of 64. 4%, based on 2 w/o liquid carryover.

Speed Control System:

- Substitution of silicon-controlled rectifiers for the magnetic amplifiers to reduce component losses in the low temperature control assembly and eliminate 1. 5 kWe load associated with the off mode of the saturable reactor.
- Addition of compensating capacitors to correct system power factor to 0. 9 lagging.

NaK Pump Motor Modifications:

- Reduced speed (4, 700 to 4, 800 rpm range) to reduce hydraulic losses.
- Induction motors employed.

The weight breakdown for the baseline SNAP-8 PCS is shown in Table 3-3. The comparative PCS weights for the modified 20-kWe and 30-kWe systems are shown in Table 3-6.

The location of the boilers significantly affects the performance of the SNAP-8 system. Location of the boiler in the shield gallery for the baseline system results in the possibility of introducing activated primary NaK into the PCS or mercury into the primary coolant system in the event of boiler tube leakage. Four possible methods of reducing the adverse effects or eliminating this potential failure mode are the following:

1. Install redundant boilers and associated NaK isolating valves in parallel primary loops within the shield gallery and provide a suitable mercury leak detection sensor and remote operators for the NaK shutoff valves.

2. Install redundant boilers in series within the shield gallery and provide a mercury leak detection sensor and remotely operated mercury vapor and liquid valves behind the secondary shield.

3. Provide a boiler design that precludes the intermixture of mercury and NaK in the event of tube leakage.

4. Provide an intermediate NaK loop to prevent both direct leakage of mercury into the primary system and primary NaK into a shutdown mercury loop.

The first two methods require the development of leak-detection and sensing systems. The development of leak-tight mercury vapor valves for the series boiler design appears to be an especially difficult task. Moreover, both of these methods rely on rapid response to failure to limit the amount of fluid leakage. The amount of mercury leakage which can be tolerated is not known at this time.

A redesign of the boiler represents a more positive means of preventing intermixture of mercury and NaK. However, this redesign requires an increase in boiler size and weight because of reduced heat transfer effectiveness. A complete redesign of the boiler to eliminate both the leakage problem and minimize the boiler size, thereby reducing the shield gallery height, would be the optimum solution.

The performance of the system is affected by the radiation tolerance of the lube-coolant fluid used to cool the primary NaK pump motor assembly installed in the shield gallery. The radiation dose level within the shield gallery is estimated to be approximately 1 x 10^9 rad/yr. The average radiation level to which the lube-coolant is exposed for 1 yr is 1 x 10^8 rad. In general, organic fluids have a threshold dose level between 1 x 10^8 and 1 x 10^9 rad prior to initiation of fluid breakdown. Although the radiation dose levels within the gallery are estimates subject to considerable variation, it is clear that the use of lube-coolant fluid within the shield gallery requires further analysis.

Table 3-6

MODIFIED SNAP-8 SYSTEM WEIGHT SUMMARY
(With Intermediate Loop)

Component	30 kWe 3 Boilers 3 Hg Loops 3 HRL Loops 3 L/C Loops (lb)	20 kWe 3 Boilers 3 Hg Loops 3 HRL Loops 3 L/C Loops (lb)
Boiler NaK loop	1,500	1,338
Mercury loop	3,918	3,513
HRL loop and pumps	828	819
L/C loop and pumps	519	495
Intermediate NaK loop	540	460
2 electrical systems (not including alternator and motor)	2,078	1,840
HRL radiator and 2 sets of tubes	1,472	1,271
L/C radiator and 2 sets of tubes	435	394
Total weight, power conversion system	11,290	10,130
Reactor weight	755	755
Shield weight	8,654	8,255
Total	20,699	19,140

If the NaK pump motor assembly is used in the primary coolant system, three alternate methods of providing coolant fluid are possible: (1) use of an additional NaK to lube-coolant fluid heat exchanger, located behind the secondary shield to cool a fraction of the heat rejection loop NaK flow, which in turn is used to cool the pumps; (2) use of heat rejection loop NaK at 500°F to cool the pumps directly, inasmuch as the NaK pumps include inorganic insulation capable of high temperature operation; and (3) location of the primary pumps below the secondary shield with local shielding around each pump. The third alternate reduces, but does not eliminate, exposure of the lube coolant to primary NaK and, consequently, does not appear to provide the ultimate solution. Moreover, additional fluid line shield penetrations and increased shielding weight would be required.

3.2.6 Radiator Design

The HRL and L/C radiators have been designed for heat rejection rates associated with 30-and 20-kWe systems. The HRL radiator is located immediately behind the reactor secondary shield, and the L/C radiator is located near the base of the conical frustrum adjacent to the HRL radiator.

Both radiator designs are based on the Langley Research Center meteoroid armor criteria for a 0.995 probability of no puncture during a 2-1/2-yr lifetime. This value is for a radiator with a single set of tubes. The redundancy schemes further reduce the probability of failure by making use of dual sets of tubes on the HRL and L/C radiators. A complete list of radiator parameters is presented in Table 3-7. The HRL radiator has 136 tubes arranged in parallel along elements of the cone. The HRL flow enters the inlet manifold at the small diameter of the radiator and then passes through the parallel radiator passages into the exit manifold at the base. The L/C radiator has 144 tubes arranged in 16 parallel circuits of 9 tubes each; each circuit is connected in series by U-shaped tubes. Inlet tube sections of parallel circuit panels are adjacent to each other to minimize circumferential thermal gradients at the circuit panel boundaries. The arrangement of parallel circuits satisfies the pressure flow requirements of all L/C loops and simultaneously maintains an acceptable film coefficient within the radiator tubes. Integration of the low-temperature control assembly (LCA) cooling requirements into the lube-coolant loop has not been considered in this study. However, current efforts are underway by the SNAP-8 system contractor to investigate the feasibility of raising the allowable LCA temperature to permit use of the lube-coolant fluid for cooling. For the purposes of this study, dissipation of the LCA cooling load of approximately 0.3 kW at 150°F is considered feasible by either passive cooling at the aft end of the power system structure or through integration with the EC/LS heat rejection system.

3.3 SNAP-2 MERCURY RANKINE POWER CONVERSION SYSTEM

The selected SNAP-2 system uses multiple combined rotating units (CRU) of 5.6 kWe gross output power to obtain the required system output power level of 20 kWe. The system consists of two PCS modules, each containing five active and two redundant CRU loops. Each CRU consists of a turbine, pump and generator assembly, pressure regulator, four-way valve, boiler tube, and radiator condenser. A total of 14 CRU are required for the specified

Table 3-7

SNAP-8 RADIATOR PARAMETERS

	HRL Radiator Design		L/C Radiator Parameters	
PCS power output, kWe	30	20	30	20
Heat rejection, kWt	338	287	18.5	16.5
Number of parallel loops*			16	16
Tubes per circuit			9	9
Number of tubes for 1 set of tubes	136	136		
Flow rate, lb/hr	31,800	27,000	4,970	4,430
Inlet temperature, °F	660	660	210	210
Exit temperature, °F	490	490	243	243
Dimensions				
Area, sq ft	827	698	238	212
Axial length, in.	239	213	45	40
Slant length, in.	250	222	47	42
Diameter--small end, in.	78.5	78.5	215.5	215.5
Diameter--large end, in.	227.5	210.5	243.5	240.5
Tube diameter (OD), in.	0.250	0.250	0.366	0.366
Tube wall thickness, in.	0.020	0.020	0.020	0.020
Armor thickness, in.	0.198	0.191	0.127	0.124
Fin thickness, in.	0.040	0.040	0.040	0.040
Weight, single radiator				
Manifolds, lb	27	26	23	23
Manifold armor, lb	15	14	13	12
Tubes, lb	200	178	50	44
Tube armor, lb	282	251	63	55
Fins, lb	425	378	137	122
Total, lb	949	847	286	256
Weight with addition set of armored tubes, lb	1,431	1,276	399	355

---

*Parallel loops provided to minimize pressure drop.

2-1/2-yr system life. The most significant factors leading to the selection of this design and leading to the integration concepts presented are the following:

1. High reliability with respect to full power capabilities as well as partial power in the event of a CRU failure.
2. Installation concepts based on providing accessibility for maintenance and for accommodation of both zero-g and artificial-g space stations.
3. Application of the existing turbomachinery for the principal evaluation and for the establishment of integrated configurations.
4. Relationships of possible power system failure modes (in particular the effects of corrosion products) on the overall system life and on the integrated system design.

Although the effects of increased component lifetime (20, 000 hr) were considered, the selected design is based on a 10, 000-hr component lifetime compatible with SNAP-2 program objectives because operating capabilities beyond this period cannot be confidently predicted until greater operating experience is accumulated. Consequently, a system lifetime of 2-1/2 yr was selected to minimize excessive installed redundancy. These and other significant aspects of the SNAP-2 system analyses are summarized in this section for application of the system with a long-duration, manned Earth-orbital application.

3. 3. 1 System Design Description

The SNAP-2 mercury Rankine system configuration developed for the zero-g MORL design is shown in Figure 3-8. This system requires the least radiator area (625 sq ft) of the reactor power systems investigated; therefore, the required surface can be readily accommodated by an extension of the 154-in.-diam cylindrical section of the configuration. The adapter section shown between the 154- and 260-in. diam cylindrical sections is not required for the initial launch, but it is required for a resupply launch. The attachment structure for the deployment boom is modified to fit the required 154-in. diam; the secondary shield retention mechanism, if provided, is modified for the shorter length of the configuration (shield retention is not essential).

A total of 14 CRU loops are installed on the periphery of the configuration, at the juncture of the conical section and the 154-in.-diam cylindrical section. These loops are so stationed as to provide accessibility to the components for maintenance. The location of the CRU is interrelated with the arrangement of radiator-condenser tubes because the length of condensate piping to the CRU should be relatively short to avoid a cycle performance penalty. Location of all CRU at the base of the conical section precludes application of this arrangement to the artificial-g (rotating) mode of station operation because the radiator-condenser tubes on the conical surface are oriented 180^{o} from the desired position.

To accommodate the artificial-g mode of operation, as well as the zero-g mode, the system arrangement shown in Figure 3-9 was developed. A total of six CRU are installed at the forward end of the conical section, and eight CRU are retained at the forward end of the cylindrical section. This revised

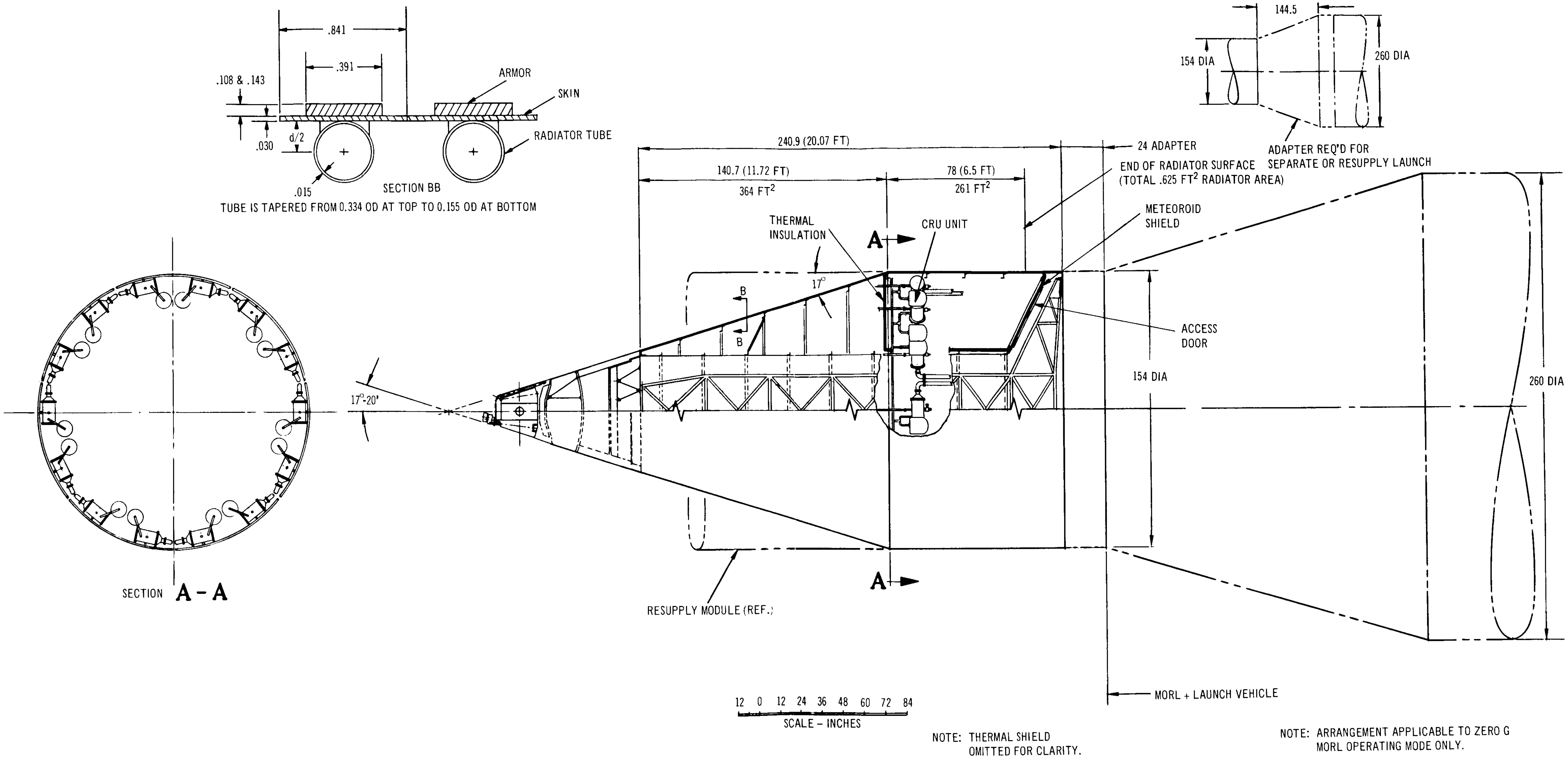


Figure 3-8. 20 kWe SNAP-2 Mercury Rankine Nuclear Power System

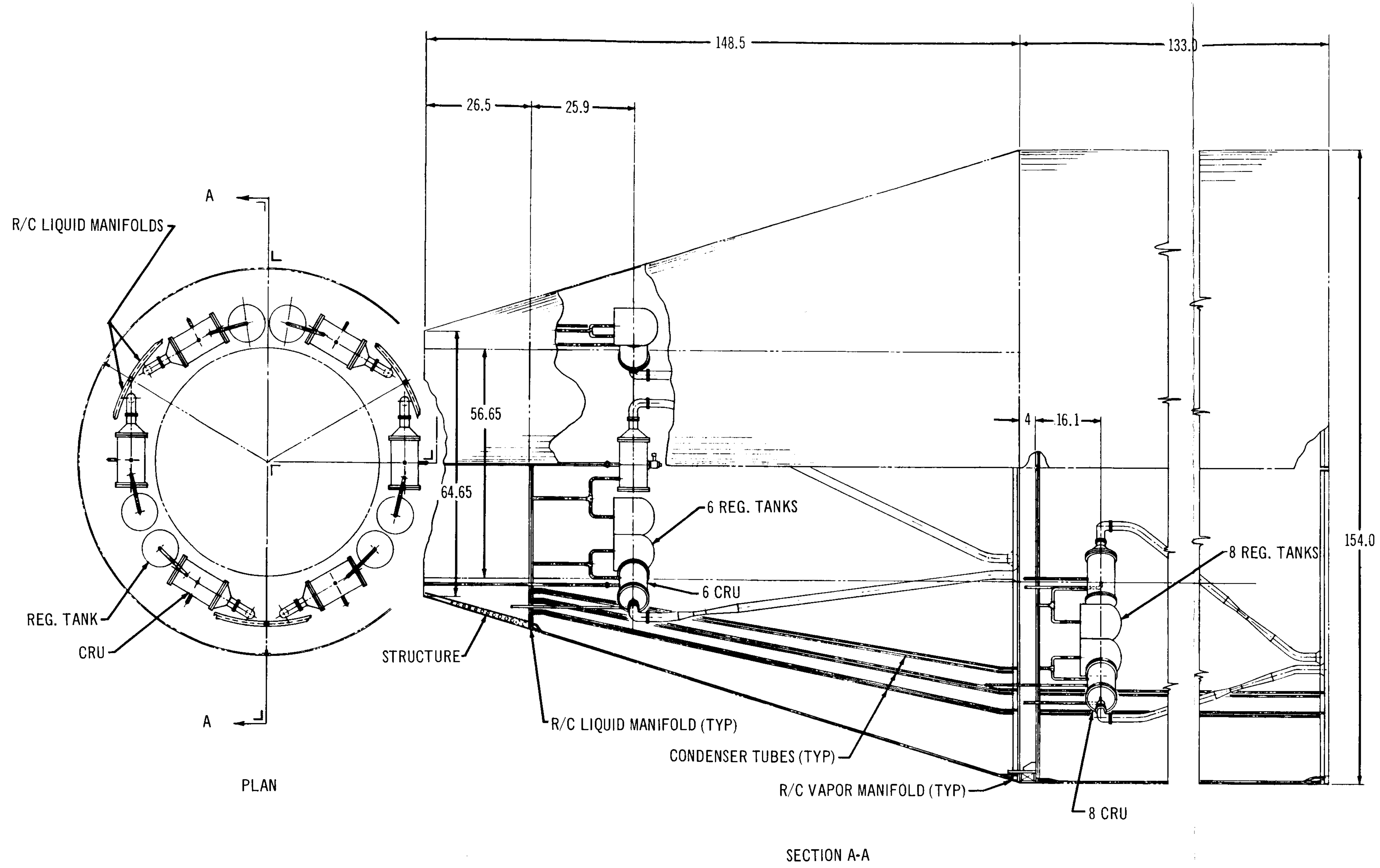


Figure 3-9. System PCS Integration Scheme (SNAP-2)

arrangement, coupled with a revision in system redundancy, requires an increase in the total radiator surface area from 625 to 757 sq ft and a reorientation of radiator-condenser tubing. However, the increase in surface area is relatively insignificant with respect to design integration because both values are comparatively low. The location of CRU and regulator tanks at the subcooler and vapor interface of associated radiator-condensers permits system operation under 1 g for ground tests and under both zero-g and artifical-g (about 2 g at the PCS) modes of operation. The potential for maintenance of the six CRU located at the forward end of the conical structure is limited. However, extensive maintenance of the SNAP-2 mercury Rankine system is not considered necessary in view of the installed redundancy provided. The configuration shown in Figure 3-9 is selected as the reference design basis.

Because of the potential unreliability associated with a large number of valves, particularly high-temperature mercury vapor valves, a complete CRU loop redundancy approach has been adopted in preference to individual component redundancy. This approach necessitated an increase in radiator area by about 21% and an attendant weight increase relative to a minimum radiator area system. However, the resultant radiator area (757 sq ft) and system weight are well within launch capabilities of the selected vehicle.

The CRU V machinery utilized in the baseline design has accumulated in excess of 20, 000 hr of testing, and a single unit has recently achieved more than 4, 700 hr of testing. The adopted multiloop integration scheme has the advantages of minimum system development and qualification test costs and provides a significant partial power reliability advantage. The basic system operational characteristics presented for this design have been verified by the mercury-Rankine power development system testing program.

The alternate system design applies uprated turbomachinery, capable of delivering a net output of 10 kWe. In this design, two active and one standby CRU loops are provided in each of two PCS modules to meet the 20-kWe output power level, reliability, and system lifetime requirements. This design offers the ultimate potential of reducing the system weight and complexity because of the fewer number of CRU loops required.

The reactor power system weights for the reference design are summarized in Table 3-8. Table 3-9 presents a more detailed breakdown of the PCS and electrical system weights. The mercury inventory includes seven steady-state inventories and two excess startup inventories per PCS. The extra startup inventory is provided in case of a failure during startup of one of the CRU loops. The radiator-condenser weight includes structure and meteoroid armor. The miscellaneous items include valves and a NaK freezing protection loop. The associated reactor power system weights include the weight penalties for the control moment gyro, shield retention and deployment boom, standby power system, reaction control system, MORL extension and fairings, and electrical conditioning equipment.

The electrical cable and component weights installed on the power system structural assembly are negligible because system startup is accomplished with the self-contained mercury injection system. Therefore, all electrical components are installed on the MORL as indicated in Table 3-8.

Table 3-8

REACTOR-SNAP-2 POWER SYSTEM WEIGHT SUMMARY

Parameter		Weight (lb)	
Reactor power system weight:			
Reactor and primary system		1,025	
Shield		7,509	
PCS		3,875	
Structure		1,000	
Thermal shields and reactor disposal system		1,081	
Thermal shields	(570)		
Reactor disposal	(511)		
Subtotal			14,490
Associated reactor system weight (1):			
Control moment gyro penalty		1,452	
Shield retention and deployment boom		2,254	
Structure	(1,673)		
Tension cables	(131)		
Electrical transmission cables	(450)		
Standby power		1,676	
Electrical system on MORL		3,500	
Alternator load control	(465)		
Control and conditioning	(1,180)		
Bus and distribution	(1,000)		
Standby source electrical	(855)		
RCS penalty (2)		943	
Tanks and supports	(252)		
Propellant	(691)		
MORL extension (3)		354	
Fairing		30	
Subtotal			10,209
Reactor power system configuration total weight			24,699
Integral launch adapter			120
Integral launch weight (4) (with 20% contingency)			52,819 (57,783)
Replacement launch adapter			1,030
Replacement launch weight with shield retention (with 20% contingency)			12,275 (14,730)
Replacement launch weight with fixed shield (with 20% contingency)			15,520 (18,624)

Notes:

1. Components and structure which are retained by or are a part of the MORL and are not resupplied with the replacement power system.
2. RCS weight penalty is that weight in excess of the baseline MORL RCS weight (880 lb of propellant and 426 lb of tanks and supports) for a 218-nmi, 50°-inclination orbit over a 147-day duration.
3. 5.2-ft extension over baseline MORL length for EC/LS and standby power system radiator.
4. Includes 28,000 lb for the MORL less Pu 238 Brayton Power System.

Table 3-9

SNAP-2 PCS AND ELECTRICAL SYSTEM WEIGHTS

POWER CONVERSION SYSTEM

Component	Weight (lb)
CRU's (14)	1, 120
Piping	140
Mercury Inventory	810
Mercury components (injection and regulator tanks)	560
Boiler (dry)	480
Miscellaneous	280
Radiator-condenser (dry, tubes and frame	1, 485
Thermal shield and reactor disposal system	1, 081
Power system subtotal	5, 956

Nonelectrical Associated Reactor Power System Weights:
(Retained on MORL during replacement)

Control moment gyro penalty		1, 452
Shield retention and deployment boom		
Structure	1, 673	
Tension cables	131	
Electrical transmission cables	450	
		2, 254
Standby power		1, 676
RCS penalty(1)		
Tanks and supports	252	
Propellant	691	
		943
MORL extension(2)		354
Fairing		30
Subtotal (lb)		6, 709

ELECTRICAL SYSTEM

Electrical Components Installed on MORL	Quantity	Weight (lb)
Alternator load control system		
Parasitic load control assembly	(5)	300
Parasitic load resistors	(5)	150
Generator load control breakers	(5)	15
Subtotal		465
Control and conditioning system		
Dc system		
TR unit	(5)	225
Main dc voltage regulator	(5)	125
AC system		
High volt rectifier	(5)	200
Square wave inverter	(2)	168
Sine wave inverter	(1)	102
Emergency inverter	(2)	120
Load control system	(5)	50
Switches, circuit, breakers, relays	(57)	190
Subtotal		1, 180
Bus and distribution system		
Subtotal		1, 000
PBC standby system (electrical equipment)		855
Electrical equipment on MORL, subtotal		3, 500

SUMMARY

	Integral Launch		Replacement Launch	
Power conversion system subtotal	5, 956		5, 956	
Reactor and primary loop	1, 025		1, 025	
Shield	7, 509		4, 264	
Total reactor, shield and power conversion system		14, 490		11, 245
Associated weights:				
Electrical components installed on MORL		3, 500		
Nonelectrical reactor system weights		6, 709		
Replacement launch adapter		---		1, 030
Total Weight		24, 699		12, 275

Notes:

1. The RCS weight penalty is defined as that RCS weight required over and above the baseline MORL RCS weight. Total RCS weight is 2, 249 lb; 1, 009 lb installed on MORL, 1, 240 lb installed on reactor power system.
2. 5. 2 ft extension required for EC/LS and standby power system radiator.

3.3.2 System Operational Requirements

Preoperational thermal requirements, startup, shutdown, restart, and system maintenance are discussed in this section.

3.3.2.1 Preoperational Heating

After the MORL launching an inactive period occurs prior to system startup. During this time, the system is subject to the temperature extremes of space but must be in an operative condition on MORL manning. All of the components are capable of withstanding this temperature range in a standby mode with the single exception of the mercury inventory. However, the inventory is stored in two insulated injection tanks and requires only a small amount of electrical heating (30 W) from the standby power source to maintain temperatures above the mercury freezing point of -40°F. Thermal shields are provided to maintain all heat rejection fluids in a liquid state for those systems that have previously been operational. Installation of an auxiliary NaK loop in the PCS area to radiate reactor decay heat to the PCS components was also considered to maintain all heat rejection fluids in a liquid state and to prevent freezing after the thermal shrouds are removed during the startup sequence. A schematic diagram of the auxiliary NaK loop is shown in Figure 3-10. One tube is added to the boiler and NaK is pumped through the boiler and then routed to the PCS area through a finned tube dissipating thermal energy to the PCS.

3.3.2.2 Startup, Shutdown, and Restart

The startup, shutdown, and restart methods employed are direct outgrowths of the successful system developed for the SNAP-2 and mercury Rankine programs. The employed method uses the injection of high-pressure liquid mercury into the CRU bearings and the preheated boiler. The mercury vapor generated in the boiler causes CRU spinup. The turbine exhaust vapor is condensed and collected in the radiator-condenser along with the bearing drain stream. Thus, radiator-condenser preheat is affected by the combination of vapor condensation and by a reduction of the radiating area and effective heat capacity. When the pressure in the radiator-condenser reaches 4.0 to 6.0 psia, the CRU mercury pump is primed and begins pumping. While the excess radiator-condenser startup inventory is draining into the pressure regulator tank, the CRU pump is supplying the entire system flow. In addition, because the injection pressure is below that of the CRU pump discharge, refill of the injection tank begins as soon as the pump is primed; and the system is ready for restart in a very short time (10 to 15 min). This type of startup system has been successfully demonstrated with a full-scale, mercury Rankine system enploying a horizontal radiator-condenser to simulate a zero-g environment.

The PCS is shut down simply by closing the inlet valve to the boiler, thus starving the turbine. The CRU decelerate as the boiler inventory is depleted and the pumps supply the bearing flow during spindown. After shutdown is complete, the system steady-state inventory is distributed in the plumbing and radiator-condenser tubes, while the startup inventory is in the unpressurized injection tank.

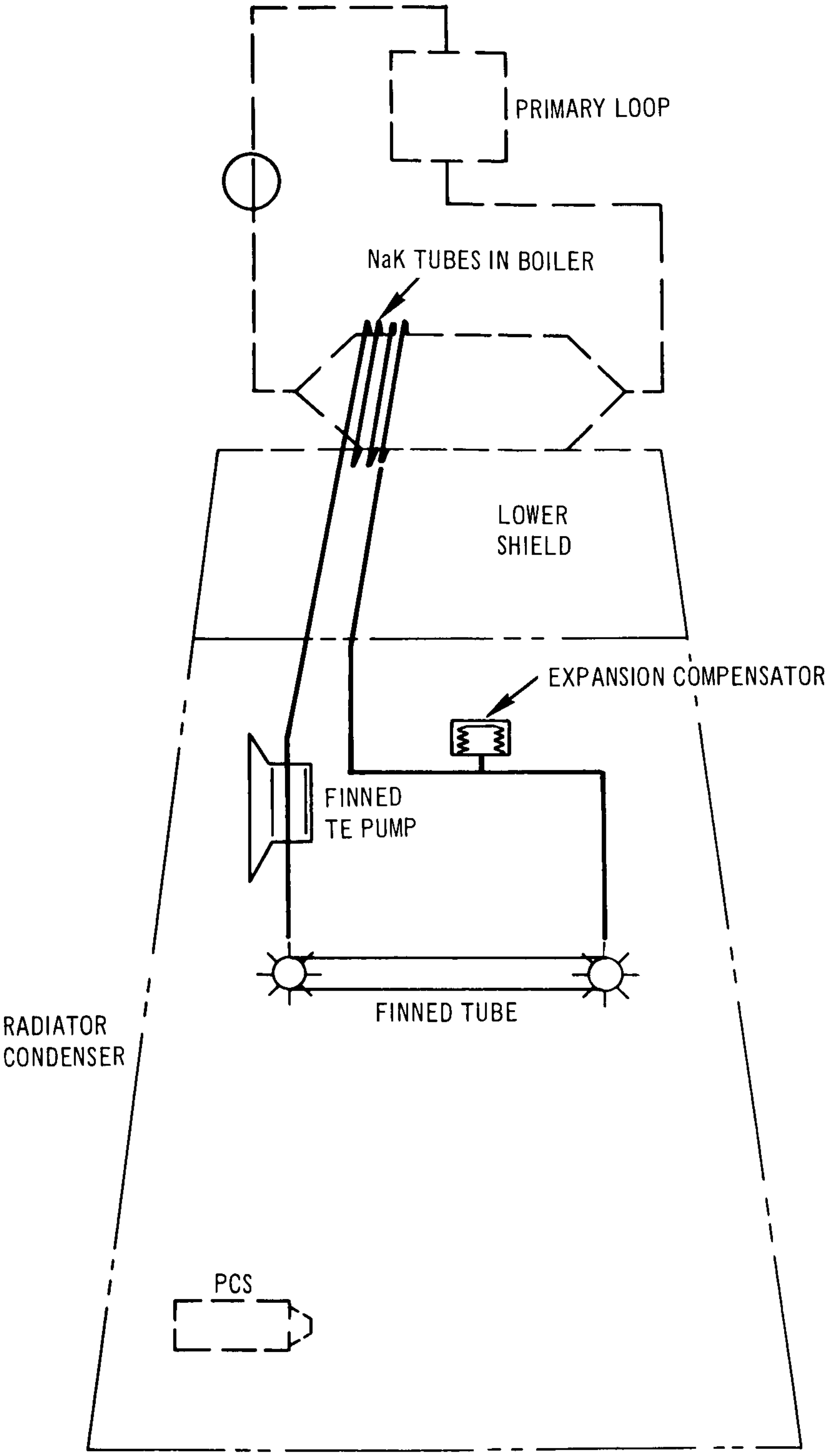


Figure 3-10. Hg Freezing Prevention Loop

3.3.3 System Maintenance Requirements

If a CRU loop component fails, the loop is shut down and one of the standby redundant loops is simply switched in from the control console located in the laboratory. Although no maintenance should be required, access to the PCS is provided in the design for possible manual backup of the few valve functions involved in startup, shutdown, and restart of loops.

This approach was taken for the following reasons:

1. The desirability for all-welded construction.
2. Elimination of a complex network of failure detection instrumentation and logic equipment required to pinpoint the failed component.
3. Minimization of operator and technician participation required for power system maintenance.

Except for electronic components, the practicability of servicing and repair is a function of the feasibility of decoupling the working fluid loop lines. The toxicity and corrosive nature of mercury and the demand for inventory control and low impurity content within the system loop dictates hermetic sealing throughout the system. Hermetically sealed systems operating with large thermal gradients and for long durations, in turn, dictate welded joints. The breaking of welded joints may contaminate the system, thus greatly reducing the performance reliability.

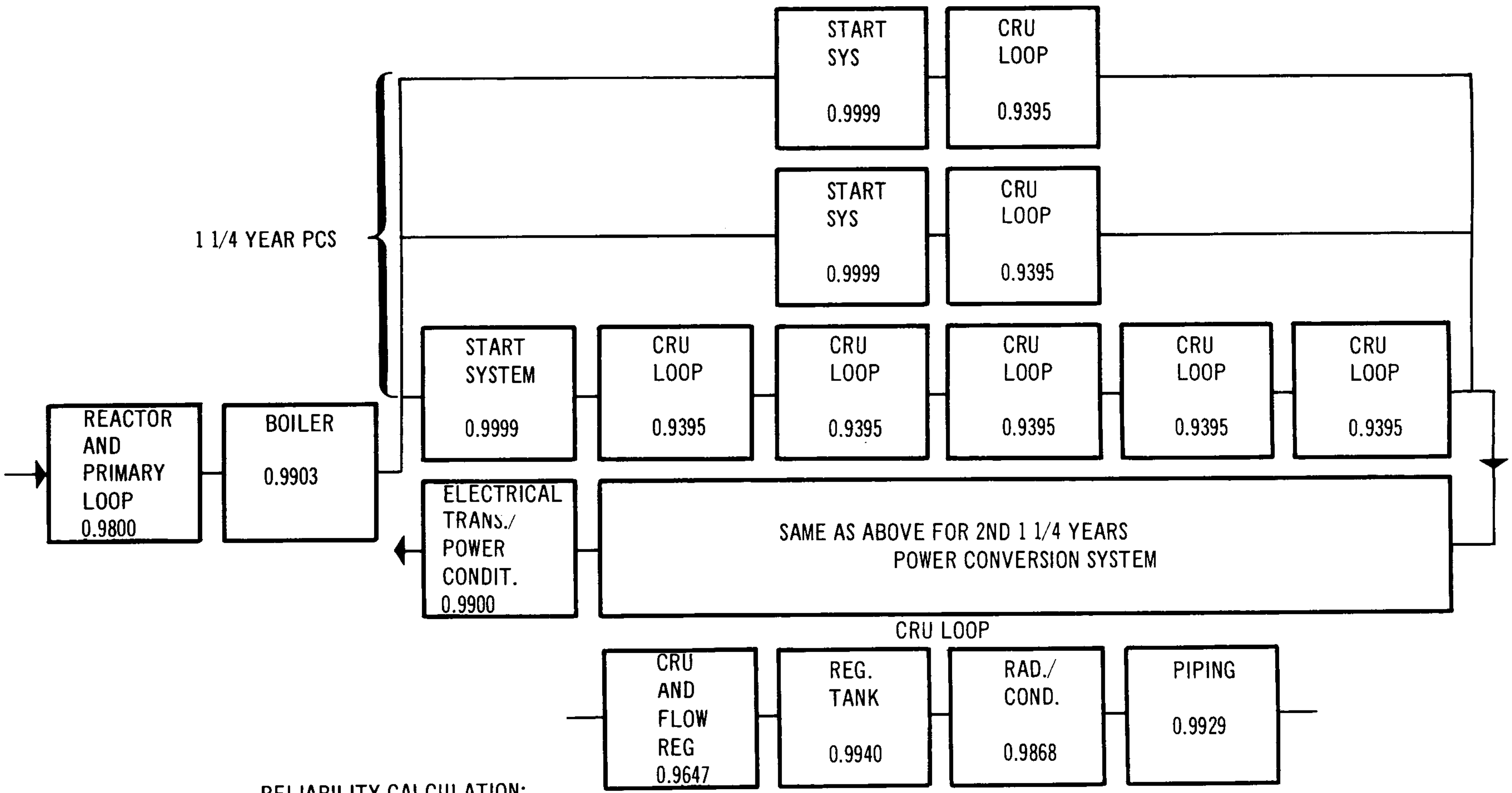
3.3.4 Reliability

The SNAP-2 reliability model and computations are shown in Figure 3-11 for two power conversion subsystems with lifetime goals of 1-1/4 yr for each subsystem and 2-1/2 yr for the system. Each subsystem contains five active and two standby CRU loops. For this case, the reliability equation is applied separately to each subsystem, using five operating and two standby units. In the calculations, the total SNAP-2 power conversion system failure rate was reduced to approximately 42% of the original SNAP-2 estimate. This conforms with SNAP-8 reliability goals and facilitates system comparisons on an equivalent reliability basis. The apportionment of total failure rate among SNAP-2 subsystem components was not altered. The calculated reactor power system reliability is 0.9531.

3.3.5 Performance Analysis

A total of 12 SNAP-2 configurations, shown in Table 3-10 were considered during the Task Area II study phase using 5- and 10-kWe PCS nominal module sizes for system power requirements of 10 and 20 kWe. The CRU was considered to have a maximum 2-1/2-yr life. The 5-yr system lifetime shown in the table assumes replacement of rotating machinery at intervals of 1-1/4 to 2-1/2 yr. The varying reliability values are the result of discrete additions of redundant modules; one less module would not meet the minimum specification of 0.95.

The lifetime criterion led to a more detailed examination of Systems E, F, and K during the initial phase of the study. However, there are inherent uncertainties associated with projecting lifetime capabilities from the available



RELIABILITY CALCULATION:

R (CRU LOOP FOR 1-1/4 YEARS) = (.9647) (.9940) (.9868) (.9929) (.9999) (.9999) = 0.9395 AND ($\lambda t = 0.0624$)

$$R\,(\text{PCS FOR 1-1/4 YEARS}) = \left[e^{-N\lambda t} + R_{ss}\, e^{-N\lambda t} \left(N\lambda t + \ldots + \frac{(N\lambda t)^n}{n!} \right) \right] =$$

$$\left[e^{-5\lambda t} + R_{ss}\, e^{-5\lambda t} \left(5\lambda t + \frac{(5\lambda t)^2}{2} \right) \right] = 0.73199 + (0.9999)(0.73199)(0.3120 + .0487) = 0.9960$$

WHERE N = OPERATING UNITS
n = STANDBY UNITS
Rss = START SYSTEM RELIABILITY (0.9999)

R (REACTOR POWER SYSTEM FOR 2-1/2 YRS) = (.9800) (.9903) $(.9960)^2$ (.9900) = 0.9531

Figure 3-11. 20 kWe SNAP-2 Power System Reliability Diagram

Table 3-10

RELIABILITY EVALUATION

PCS Module Case Power (kWe)		PCS Life (yr)	System Life (yr)	Initial Number Active Modules	Number of Standby Modules	System Reliability
			10-kWe System Power			
A	5	1	1	3	1	0.960
B	10	1	1	1	1	0.960
C	5	2-1/2	2-1/2	3	4	0.962
D	10	2-1/2	2-1/2	1	2	0.960
E	5	2-1/2	5	3	9	0.965
F	10	2-1/2	5	1	4	0.965
G	5	5	5	3	5	0.970
H	10	5	5	1	2	0.965
			20-kWe System Power			
I	10	1	1	2	1	0.965
J	10	2-1/2	2-1/2	2	3	0.960
K	10	2-1/2	5	2	6	0.954
L	10	5	5	2	3	0.960

analytical and test data until greater operating experience and a more conclusive demonstration of lifetime capability have been obtained. Therefore, the designs selected for further detailed study during Task Area III were based on the more conservative component lifetime objective of 11,000 hr nominal (interpreted as 1-1/4 yr for purposes of reliability analysis). To maintain power conversion module redundancy within reasonable limits, a corresponding overall system lifetime of 2-1/2 yr was used.

The reference system design selected for the Task Area III study phase uses multiple CRU for 5.6 kWe gross output power to obtain the required system output power level of 20 kWe. An alternate design using combined rotating units of 10-kWe net capacity was also considered for comparative purposes. The selected reference system consists of two PCS modules with each module containing five active and two redundant CRU loops. A total of 14 CRU are required for the specified 2-1/2-yr system life. Although internal CRU loop redundancy was investigated, the study results indicate that selection of independent CRU without internal redundant components is a more desirable concept. The use of independent CRU requires one four-way valve for each CRU in contrast to numerous other switching valves that would be required to accommodate internal component redundancy. Each CRU consists of a turbine, pump and generator assembly, pressure regulator, four-way valve, boiler tube, and radiator condenser.

The design point for the alternate system, at a nominal CRU rating of 10 kW, is based on the same packaging and configuration concepts used in the reference design, except fewer machines are required. In this case, two active CRU loops are required for each 1-1/4-yr period; two redundant CRU loops are also provided. This results in a total of 6 CRU loops to produce a rated system power level of 20 kWe for a 2-1/2-yr system life.

System power levels of 10 kWe were not considered for the SNAP-2 system during the Task Area III study phase.

Table 3-11 lists the important characteristics and the operating conditions of the radiator-condenser. The radiator consists of steel tubes and manifolds with aluminum fins and armor, plus the necessary structure to support launch and spin mode loads. Each radiator-condenser segment contains 108 tubes (2 sets of 54 tubes). The tubes are round, have a 0.015-in. wall thickness, and have a linear taper both to minimize liquid mercury startup inventory and to provide stable operation. The wall thickness is 0.020 in. One-half of the tubes and manifolds carry armor for a 1-1/4-yr operation; the remainder are protected for 2-1/2 yr of operation. No armor credit has been taken for the steel tubes and the aluminum armor thickness is that required for operation at 600°F.

The segmented design of the radiator-condenser imposes a small area penalty. At least two of the radiator units may be required to operate in full sunlight when the vehicle is on the sun side of the orbit. Because each CRU is provided with a separate radiator-condenser and because no mixing of mercury streams from sun and shade sides of the vehicle is employed, each radiator-condenser must be capable of achieving the necessary subcooling in full sunlight. The effective sink temperatures are estimated to be 2°F for a radiator-condenser unit installed on the conical structure and 31°F for a unit installed on the cylindrical structure. The different values result from the differing ratios of surface area to projected area for 1/3 of the conical surface and for 1/4 of the cylindrical portion of the power system structure. As previously mentioned, the sink temperature effect is small for the relatively high-temperature mercury Rankine radiator-condenser. The thermoelectric pumps, installed within the shield gallery, require 8 sq ft of radiating surface for cooling. The gallery height of 14 in. provides sufficient surface area around the periphery of the gallery for installation of the pump radiating surfaces that are an integral part of the thermoelectric pump design. There are no low temperature cooling requirements for the SNAP-2 system. The parasitic load control dissipates the excess electrical energy that results from load variations of up to 5 kW through heaters cooled by the EC/LS system radiator.

Table 3-11

RADIATOR-CONDENSER DESIGN

	Parameters
Number of redundant CRU per 1-1/2-yr period	2
Mercury flow per CRU loop, lb/min.	23
Vapor-liquid interface pressure, psia	6.1
Condensing pressure drop, psi	2.25
Vapor inlet quality	0.976
Mercury outlet temperature, °F	352
Condensing heat load per radiator-condenser unit, kW	257
Subcooling heat load per radiator-condenser unit, kW	16
Emissivity	0.90
Solar absorptivity/emissivity	0.25
Effective sink temperature--conical segment, °F	2
Effective sink temperature--cylindrical segment, °F	31

	Conical	Cylindrical
Number of radiator-condenser units	3	4
Condensing area per unit, sq ft	92.5	93.8
Subcooling area per unit, sq ft	11.5	11.7
Manifold area per unit, sq ft	3	3.5
Total area per unit, sq ft	107	109
Total area, sq ft	321	436
Tube length, in.	123.7	125
Total length, in.	127.5	129
Tube wall thickness (steel), in.	0.015	0.015
Tube top ID, in.	0.326	0.332
Tube bottom ID, in.	0.125	0.125
Number of active tubes per unit	54	54
Total number of tubes per unit	108	108
Vapor manifold height and width (nominal), in.	1.0	1.0
Liquid manifold height and width (nominal), in.	0.3	0.3
Vapor manifold wall thickness (steel), in.	0.030	0.030
Liquid manifold wall thickness (steel), in.	0.020	0.020
Number of vapor manifolds per unit	2	2
Number of liquid manifolds per unit	2	2
Fin thickness (aluminum), in.	0.020	0.020
Armor thickness (aluminum), in. (1-1/4 to 2-1/2 yr)	0.119/0.149	0.119/0.149
Nonpuncture probability	0.99	0.99
Cone half-angle, degree	17.5	0

3.4 BRAYTON-CYCLE POWER CONVERSION SYSTEM

The selected 20-kWe Brayton-cycle power conversion system (PCS) design consists of multiple 10-kW, single-shaft modules using argon as the working fluid and including an intermediate, high-temperature NaK loop between the primary and gas loops and an NaK-cooled segregated radiator. The most significant factors leading to the selection of this design are as follows:

1. High reliability with respect to partial power capabilities as well as full power in the event of module failure.
2. High performance for the power level selected at low system weight, and radiator surface requirements that are well within configuration limits.
3. Maximum use of basically developed components for all power-level requirements.
4. Minimum development cost and time to produce power systems capable of meeting a range of power level requirements.
5. Compact PCS modules adaptable to replacement.
6. Minimum size and number of reactor shield penetrations.

3.4.1 System Design Description

The system arrangement is shown in Figure 3-12. Six completely self-contained and packaged PCS modules are arranged around the periphery of the conical configuration near the base. Each package contains the NaK-to-gas heat exchanger, combined rotating unit (CRU), recuperator, and heat-sink heat exchanger in a compact arrangement. The modules are supported by mounting lugs attached to a stiffening ring of the radiator structure. The CRU is oriented such that its axis is parallel to the longitudinal centerline of the configuration to minimize the effects of launch acceleration and shock. The compact module design provides the potential for replacement by diconnecting four fluid lines and the electrical connection. The secondary shield retention structure on the deployment boom is not shown because the weight of the Brayton-cycle system configuration is within the replacement launch load capability. However, with 20% contingency added to the Brayton-cycle replacement launch weight, this launch weight limitation is exceeded and secondary shield retention is required. The reactor/Brayton-cycle power system weight summary is given in Table 3-12.

The selected PCS, including state point data for normal operation, is shown schematically in Figure 3-13. The PCS includes a primary NaK-to-NaK heat exchanger located in the gallery between the primary and secondary shield. The intermediate-loop NaK lines penetrate the secondary shield and connect to six separate NaK-to-gas heat exchangers which are arranged in parallel and are individually connected to a closed, recuperated gas loop. Direct radiating thermoelectromagnetic (TEM) pumps are used in the intermediate loop and TEM pumps are the tentative choice for the radiator loops. Argon is the reference working fluid. Each gas loop contains a gas-to-NaK heat-sink heat exchanger

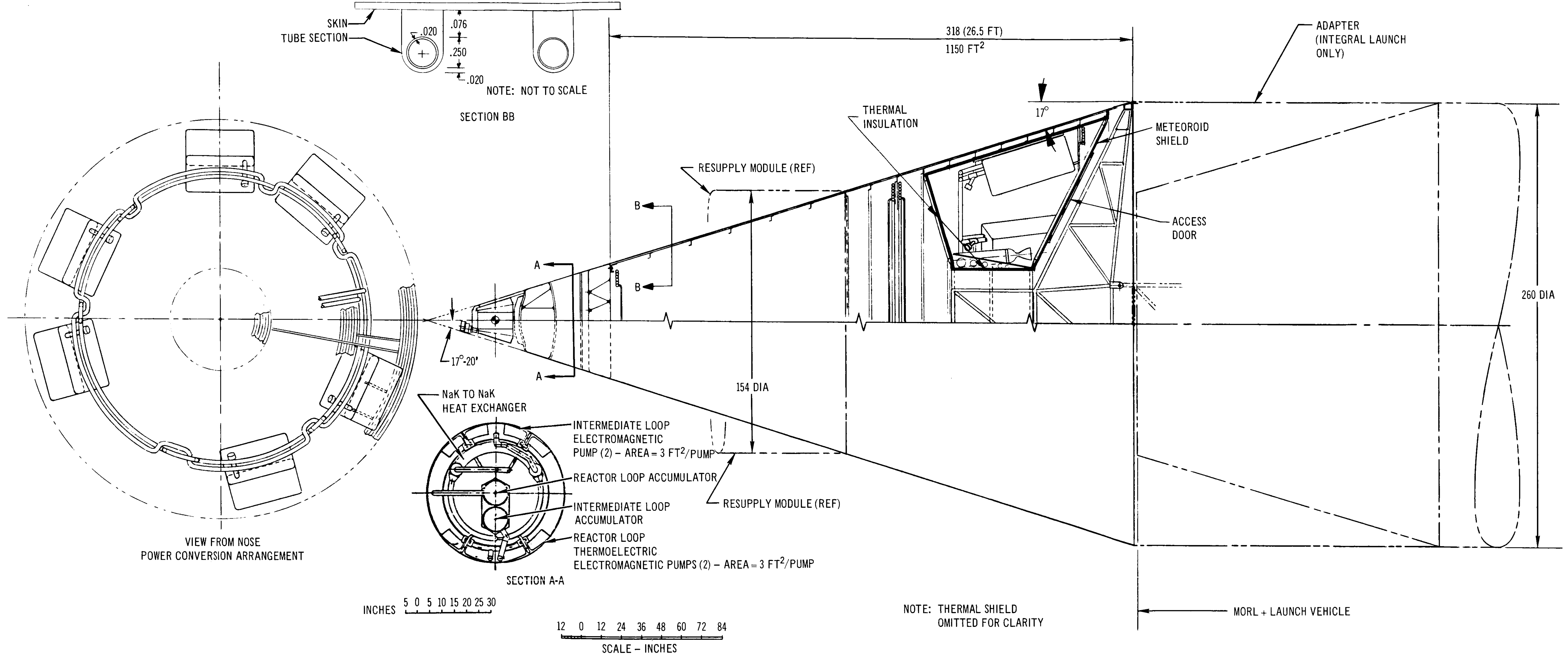


Figure 3-12. 20 kWe Brayton Cycle Nuclear Power System

Table 3-12

REACTOR-BRAYTON-CYCLE POWER SYSTEM WEIGHT SUMMARY

Parameter		Weight (lb)	
Reactor power system weight:			
Reactor and primary system		912	
Shield		7,064	
PCS		5,800	
Structure		1,617	
Thermal shields and reactor disposal system		1,355	
Thermal shields	(844)		
Reactor disposal	(511)		
Subtotal			16,748
Associated reactor system weight (1):			
Control moment gyro penalty		1,190	
Shield retention and deployment boom		2,150	
Structure (2)	(1,619)		
Tension cables	(131)		
Electrical transmission cables	(400)		
Standby power		1,676	
Electrical system on MORL		2,950	
Alternator load control	(186)		
Control and conditioning	(909)		
Bus and distribution	(1,000)		
Standby source electrical	(855)		
RCS penalty (3)		885	
Tanks and supports	(245)		
Propellant	(640)		
MORL extension (4)		354	
Fairing		30	
Subtotal			9,235
Reactor power system configuration total weight			25,983
Integral launch adapter			1,020
Integral launch weight (5) (with 20% contingency)			55,003 (60,405)
Replacement launch weight with shield retention (with 20% contingency)			13,698 (16,438)
Replacement launch weight with fixed shield (with 20% contingency)			16,748 (20,098)

Notes:

1. Components and structure which are retained by or are a part of the MORL and are not resupplied with the replacement power system.
2. Subtract 200 lb for fixed shield design.
3. RCS weight penalty is that weight in excess of the baseline MORL RCS weight (880 lb of propellant and 426 lb of tanks and supports) for a 218-nmi, 50°-inclination orbit over a 147-day duration.
4. 5.2-ft extension over baseline MORL length for EC/LS and standby power system radiator.
5. Includes 28,000 lb for the MORL less Pu 238 Brayton Power System.

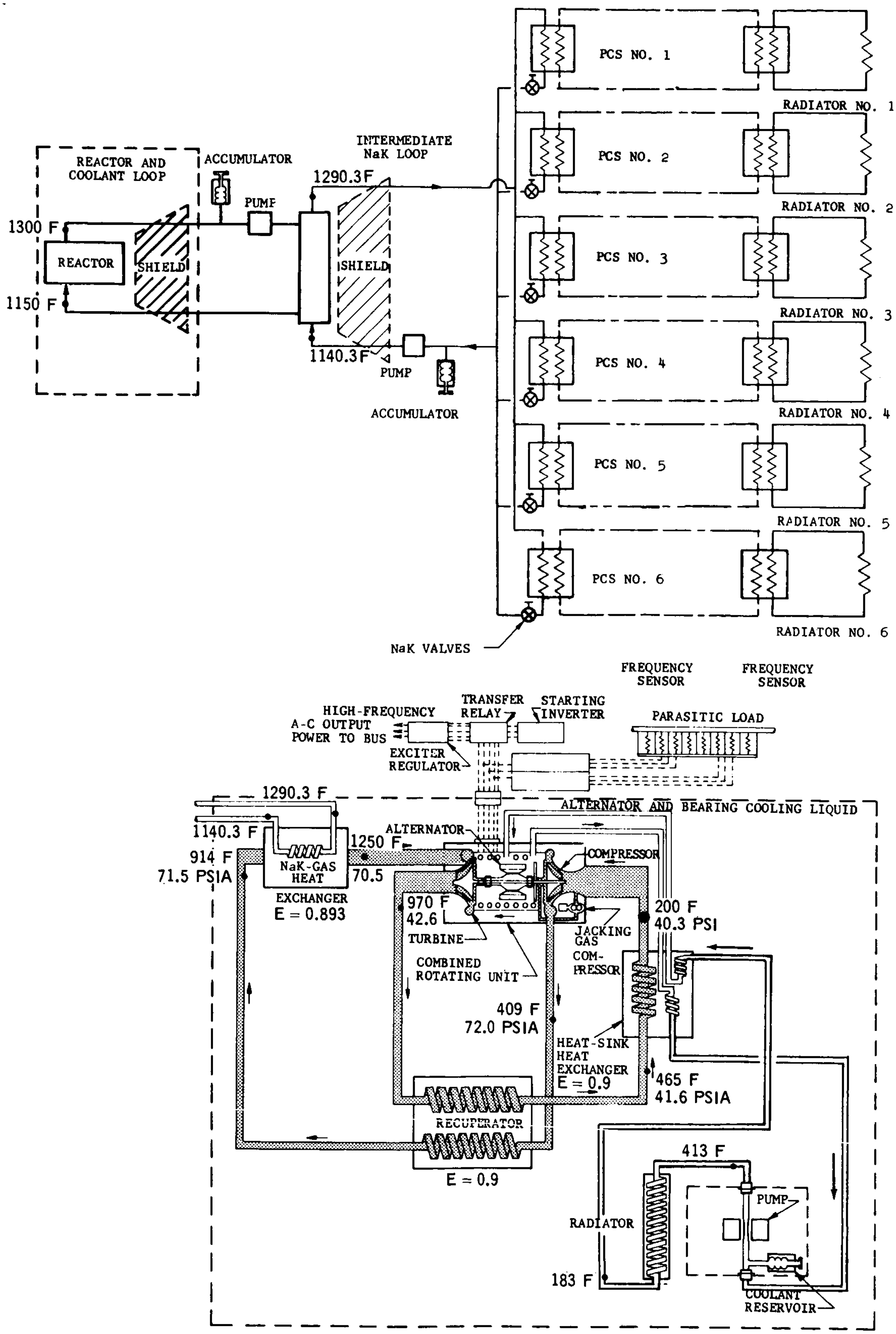


Figure 3-13. Brayton Power Conversion System

associated with a NaK radiator loop. Two of the six PCS modules are continuously operated to produce 20-kWe net output power; the remaining four modules are in standby.

The CRU consists of a single-stage centrifugal compressor, a single-stage radial inward flow turbine, and a high-frequency Rice alternator, all mounted on a common shaft. The high-frequency (850Hz), three-phase power output of the alternators is rectified and paralleled on the dc side by the power conditioning system. Excess power demand is absorbed in the parasitic load control, located in the EC/LS-cooling system on the MORL, and is dissipated to space by the EC/LS radiator.

The radiator design consists of a tube and fin structure. The radiation shell is a cone with top and bottom diameters of 62 and 256 in., respectively. Each of six separate radiator loops consists of a series of straight radiator tubes which make a single pass along the inside of the radiator shell between inlet and outlet manifolds. Aluminum is used as both tube and shell material in all designs. Stainless steel liners are bonded to the inside of the aluminum tube to provide containment of the liquid metal.

Table 3-13 summarizes the design and operating parameters of the reference system at rated design conditions. The PCS and electrical component weights are itemized in Tables 3-14 and 3-15, respectively.

3.4.2 System Performance and Operational Requirements

The normal mode of system operation produces a constant 850-Hz, 3-phase power supply rectified by the power-conditioning system. Individual rotating assemblies are controlled by a frequency-sensitive bridge that gates excess power to parasitic load resistors. When the power demand is lower than the constant system output, the parasitic load control absorbs the excess power, thereby maintaining constant CRU speed. Mild fluctuations in system capability, resulting from heat-sink variations and reactor operation in the temperature dead band, are compensated for by this parasitic load-control system. The only other control for the PCS is the valve in the NaK line. This valve isolates individual NaK-to-gas heat exchangers in the event of overspeed or by operator command.

Transient operation resulting from off-design turbine inlet temperature variations indicates that, within a normal reactor dead band of ±20°F, a turbine inlet temperature decrease of 20°F results in an alternator output power reduction from 12.6 to 11.9 kW.

3.4.2.1 Startup

The reactor power system is not started until after the MORL is in orbit and manned and until the power system is fully deployed behind the vehicle. The power system is inactive during the reactor startup period except for the NaK radiator loop, in which circulation is maintained.

After the initiation of the reactor startup procedure, but before criticality is attained, the thermal shields around the radiator are removed. To maintain the radiator in a liquid state after the thermal shields are removed, an auxiliary heat exchanger in the primary loop is used to transfer a portion of the heat generated during reactor startup to the radiator loop.

Table 3-13

SYSTEM DESIGN AND OPERATING PARAMETERS

Reactor Power System	
Conditioned output power, kWe	20
Reactor thermal power, kW	152
PCS module rating, kWe	10
Number of active/total installed modules	2/6
Overall system efficiency (based on conditioned power)	0.132
Radiator surface area, sq ft	1,150
Reference 10 kWe PCS Module	
Working fluid	Argon
Turbine inlet temperature, °F	1,250
Compressor inlet temperature, °F	200
Shaft speed, rpm	51,000
Compressor specific speed	0.11
Recuperator effectiveness	0.90
Pressure-loss factor, β	0.92
Compressor inlet pressure, psia	40.3
Compressor pressure ratio	1.795
Compressor rotor diameter, in.	4.50
Compressor efficiency	0.83
Turbine inlet pressure, psia	70.5
Turbine pressure ratio	1.652
Turbine rotor diameter, in.	4.42
Turbine efficiency	0.901
Power conditioning efficiency	0.834
Type of generator	Rice
Generator diameter, in.	2.69
Generator efficiency	0.951*
Generator output, kW	12.59
Windage and bearing losses, kW	1.02
Gross shaft power output, kW	14.26
Gas flow rate, lb/sec	1.537
Cycle heat input rate, kW	67.72
Cycle efficiency	0.18

---

*A generator efficiency of 0.90 was used in system design calculations.

Table 3-14

ESTIMATED SYSTEM WEIGHTS--PCS PLUS ENCLOSURE

Parameter	Unit	Weight (lb)
Power Conversion System (Gas Loop)		394
NaK-to-gas heat exchanger (wet)	18	
CRU (including jacking gas compressor)	90	
Recuperator	186	
Heat-sink heat exchanger (wet)	45	
Interconnecting ducting	50	
Insulation	5	
Intermediate NaK Loop		20
NaK-to-NaK heat exchanger (wet)*		
TEM pumps*		
NaK valves	20	
Radiator Loop Components**		90
Pump	60	
NaK expansion compensator	30	
Miscellaneous		205
Enclosure support structure	47	
Enclosure side panels	8	
Enclosure insulation	150	
Total PCS System Weight		709
6 PCS System Packages		4,254
6 Loop Radiator System		805
Tubes	454	
Manifolds	174	
Miscellaneous Structure	50	
Liquid Inventory	127	
6 Control Systems		66
Alternator exciter--regulator (6)	66	
Starting inverter regulator (2)***	---	
Insulated NaK lines		300
Miscellaneous valves and piping		100
Intermediate NaK-to-NaK heat exchanger (1)		60
Intermediate loop TEM pumps (2) and expansion compensators (2)		215
Power Conversion System Total		5,800
Structural weight		1,617
Radiator skin	510	
Meteoroid armor	554	
Frames	553	

---

*Not included in PCS enclosure.

**Components mounted in PCS package only.

***200 lb weight included in MORL Electrical Control and Conditioning System.

Table 3-15

BRAYTON-CYCLE SYSTEM ELECTRICAL WEIGHT
(All components located in the MORL)

Component	Number	Weight (lb)
Alternator load control system		
Parasitic load control assembly	(2)	120[1]
Parasitic load resistors	(2)	60
Generator load control breakers	(2)	6
Subtotal		186
Control and conditioning system		
Dc system[2]		
Transformer-rectifier unit	(2)	90
Main dc voltage regulator	(2)	50
Ac system		
High voltage rectifier	(2)	150
Square wave inverter	(2)	168
Sine wave inverter	(1)	102
Variable frequency start and emergency inverter	(2)	200
Load control system	(2)	20
Switches, circuit breakers, relays	(37)	129
Subtotal		909
Bus and distribution system		
Subtotal		1,000
PBC standby system electrical equipment[3]		
Subtotal		855
Total electrical equipment in MORL vehicle		2,950

Notes:

1. Required quantities are shown in parentheses.
2. The dc link type of frequency converter is used to convert 850 to 400 Hz ac.
3. The PBC weight estimate includes the alternator auxiliary electrical equipment, such as exciters and regulators.

When the reactor is near full power, electrical heat is supplied to one leg of the thermoelectric pumps to increase the NaK flow rate; then time is allowed to increase the temperature of the reactor and intermediate loop to their full operating values.

When the high temperature loops are stabilized, each PCS module is started individually. Initially, one leg of the dc electromagnetic coolant pump, which removes the rejected heat from the cycle and cools the alternator and bearings, is heated electrically. Shortly after, the jacking gas compressor is started to pressurize the bearings. Variable frequency power, provided by batteries and variable-frequency inverters, is then supplied to the alternator so that it functions as a starter motor.

The frequency output of the starting inverter is programmed to provide sufficient starting torque to bring the rotating assembly to a speed (20,000 rpm) where the aerodynamic components become self-sustaining and to continue to accelerate the CRU to the operating speed of 51,000 rpm. On reaching operating speed, the frequency sensor gates electrical power to the parasitic load bank.

3.4.2.2 Load Control

The parasitic-load speed control for the PCS is automatic and maintains the CRU at its nominal design operating speed of 51,000 rpm by adjustment of the electrical power or load on the alternator. Constant-speed operation is required to maintain electrical output power at essentially constant frequency at the system design efficiency and to prevent CRU overspeed.

The Brayton-cycle power system is used to supply constant base electrical power to the MORL. The standby power system follows load peaks and recharges the battery. The control system maintains turbine speed within a band equal to ±1.25% of nominal speed in all cases under normal loading conditions and under complete loss of useful load and energy storage. Under extreme fault conditions, such as failure of the alternator or parasitic load, an overspeed protection circuit will shut down the PCS. The actual power dissipation takes place in conventional load resistors mounted in the vehicle EC/LS coolant system. The actuating control signal is a speed difference obtained from comparing actual turbine speed to a reference speed.

3.4.2.3 Shutdown, Standby, and Restart

Closing of the NaK flow valve to the NaK-to-gas heat exchanger accomplishes shutdown of the power conversion module. Jacking gas is not needed in the bearings during the coast down. The coolant pump is operated for some additional period after shutdown to remove heat from the alternator that may be transferred from the surrounding parts.

To start any of the remaining standby modules, the NaK flow valve to the primary heat exchanger in that system is opened. The startup procedure is then identical with that described previously.

3.4.2.4 Performance Variation

The turbomachinery performance characteristics upon which the Brayton-cycle power conversion system design is based are considered to be attainable by applying presently available design technology. However, in view of the possible skepticism which may arise until further confirmatory data is accumulated on this equipment, the PCS was evaluated on a more conservative design basis. Accordingly, the compressor efficiency was reduced from 83% to 80%, and the turbine efficiency was reduced from 90.1% to 87% to determine the influence of this degradation on the integrated system design.

Figure 3-14 shows the variation of PCS weight, radiator surface area, and cycle efficiency for a 10-kWe system module as a function of turbine and compressor efficiencies.

The increase in weight for the integrated reactor power system amounts to about 2,000 lb under the degraded performance conditions. This resultant weight is within the capabilities of the selected launch vehicles for both integral and replacement launch provided the secondary shield is retained on the deployment boom when the system configuration is replaced.

The radiator area is increased to 1,600 sq ft, which exceeds the available surface of the conical configuration; a 6.6-ft extension of the 260-in.-diam cylindrical section is required to provide the additional 450 sq ft of surface.

An assessment of the system design under degraded performance conditions shows a practicable design which can be effectively integrated dispite the conservative basis of the imposed conditions.

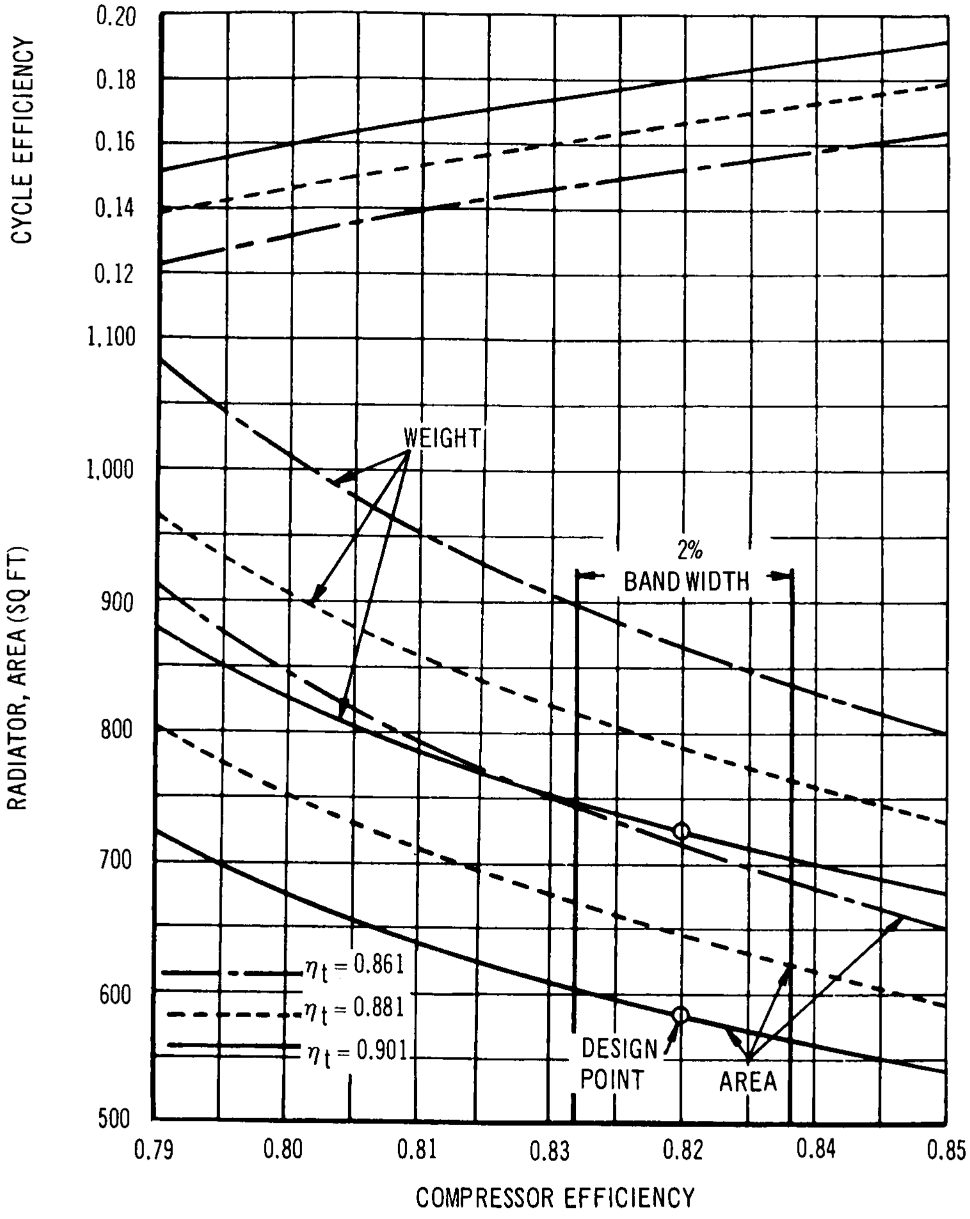
3.4.3 Reliability

The overall reliability of the reactor/Brayton-cycle power system includes a reactor and primary system reliability of 0.98 and a reliability of 0.99 for the electrical transmission and power conditioning subsystem. The reliability calculations are based on the Poisson distribution for standby redundancy; the component failure rates are assumed to be constant (an exponential distribution) over the operating lifetime.

The Brayton-cycle reliability model and computations are shown in Figure 3-15 for 6 power conversion modules with a lifetime goal of 1-1/4 yr for each module and 2-1/2 yr for the system. Operation of two modules is required to produce rated full power. The system reliability is computed on the basis of two groups of three modules each. In each group, the first module is assumed to operate for half the system lifetime, the second for the remainder of system lifetime, and the third is assumed to be in standby. The resultant reliability values for each group are multiplied inasmuch as both groups are required for success. The overall reactor power reliability is 0.927 based on the component reliability values provided by the subcontractor. However, to provide a more representative comparison with the Rankine cycles, the Brayton-cycle reliability goals were revised on a consistent basis with the Rankine-cycle subsystems. This is reasonable because the Brayton cycle would be expected to have fewer failure modes than the Rankine cycle (the absence of potential failure

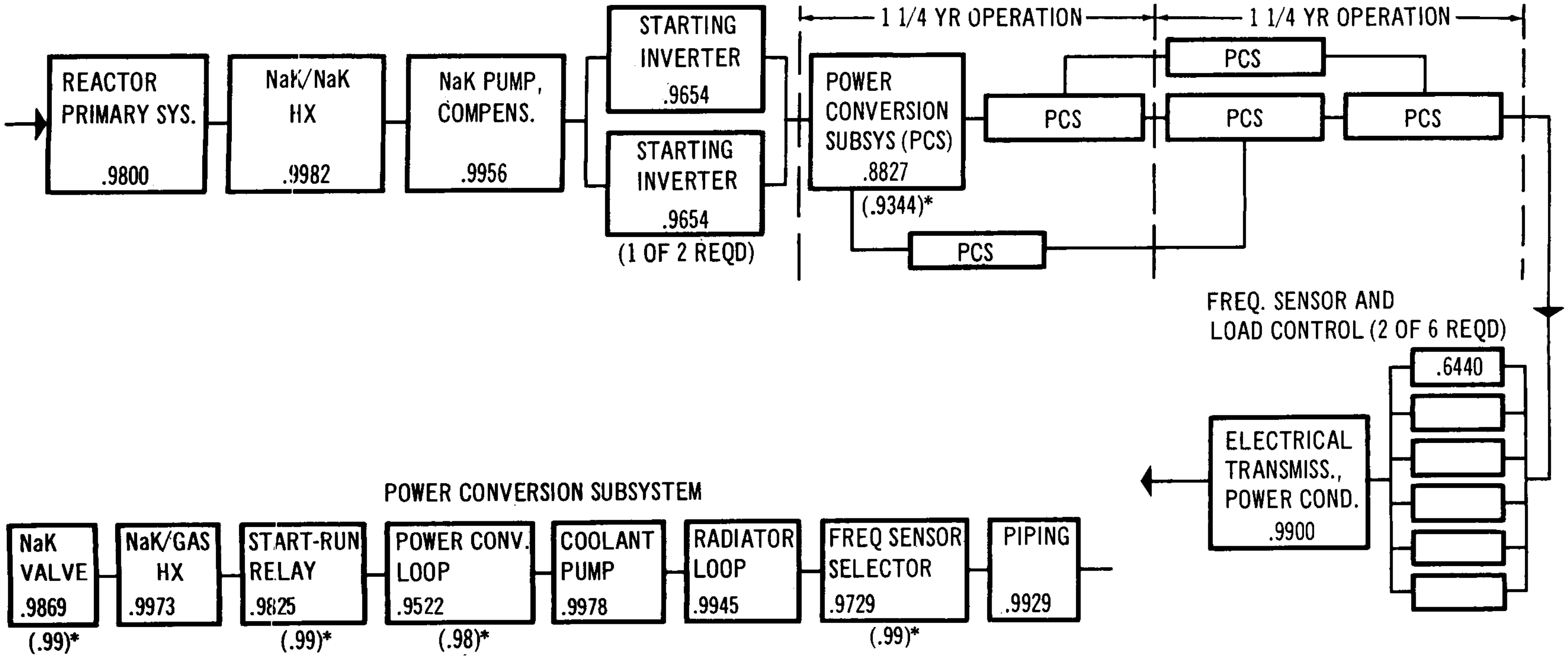
GENERATOR POWER OUTPUT = 12.2 kW
TURBINE INLET TEMPERATURE = 1250°F
COMPRESSOR INLET TEMPERATURE = 200°F

RECUPERATOR EFFECTIVENESS = 0.9
β = PRESSURE LOSS PARAMETER = 0.92
η_t = TURBINE EFFICIENCY AS INDICATED



*ESTIMATED SYSTEM WEIGHT FOR A 10 kW MODULE INCLUDES ONLY THE PCS AND ENCLOSURE. THE RADIATOR SYSTEM, CONTROL SYSTEM, AND INTERMEDIATE LOOP ARE NOT INCLUDED.

Figure 3-14. Effect of Off-Design Component Efficiency on System Performance



RELIABILITY CALCULATION:

$R\,(\text{STARTING INVERTERS}) = e^{-\lambda t}(1 + \lambda t) = .9654\,(1 + .0352) = 0.9994$

$R\,(\text{POWER CONVERSION SUBSYS, 1 1/4 YRS}) = (.9869)\,(.9973)\,(.9825)\,(.9522)\,(.9978)\,(.9945)\,(.9729)\,(.9929) = 0.8827$, AND $\lambda t = .1248$,

ALTERNATELY (0.9344, AND $\lambda t = .0679$)*

$$R\,(\text{FREQ SENSOR, LOAD CONTROL}) = e^{-N\lambda t}\left(1 + N\lambda t + \ldots + \frac{(N\lambda t)^n}{n!}\right) = 0.4148\left(1 + .88 + \frac{(.88)^2}{2} + \frac{(.88)^3}{6} + \frac{(.88)^4}{24}\right) = 0.9978$$

WHERE N = OPERATING UNITS (2)
n = STANDBY UNITS (4)

$$R\,(\text{REACTOR POWER SYS, 2 1/2 YRS}) = (.9800)\,(.9982)\,(.9956)\,(.9994)\,\underbrace{\left[e^{-2\lambda t}\left(1 + 2\lambda t + \frac{(2\lambda t)^2}{8}\right)\right]^2}_{\text{P.C.S.}}(.9978)\,(.9900) = 0.9227;\ (\text{ALTERNATELY } 0.9482)^*$$

*REFLECTS REVISION OF COMPONENT RELIABILITY VALUES TO GENERALLY CONFORM WITH BASIS FOR OTHER POWER CONVERSION SYSTEMS)

Figure 3-15. 20 kWe Brayton-Cycle System Reliability Diagram modes resulting from two-phase flow are one example) and, consequently, a reliability at least as high as the Rankine systems. The calculated reactor power system reliability, on this basis, is 0.9482.

3.4.4 Performance Analysis

Preliminary evaluation and parametric analyses were performed to evaluate a number of design alternatives; specific emphasis was placed on arriving at system design decisions. The design alternatives and selections are summarized in this section.

3.4.4.1 Component Operating Point Selection

With the turbine inlet temperature fixed at 1,250°F, optimizations were performed as a function of both varying recuperator effectiveness and compressor inlet temperature. Higher cycle efficiencies and lower radiator areas are attained with high recuperator effectiveness. The same trend occurs with system weights, these being lower for high recuperator effectiveness. Increases in effectiveness above 0.90 result in a sharp increase in recuperator weight and use of a higher component pressure drop allowance, thereby reversing this favorable trend. Thus a recuperator effectiveness of 0.9 was chosen.

The selection basis for the compressor inlet temperature is a tradeoff between cycle efficiency, overall reactor power system weight, and radiator area. As shown in Figure 3-16, the choice of a 200°F compressor inlet temperature allows for an essentially minimum radiator area system with a negligible system weight penalty, at a cycle efficiency of 18%. The results shown in Figure 3-16 are for an 87% compressor efficiency; however, the curves are almost identical for the selected 83% compressor efficiency.

3.4.4.2 Single-Shaft Versus Two-Shaft Turbomachinery Comparison

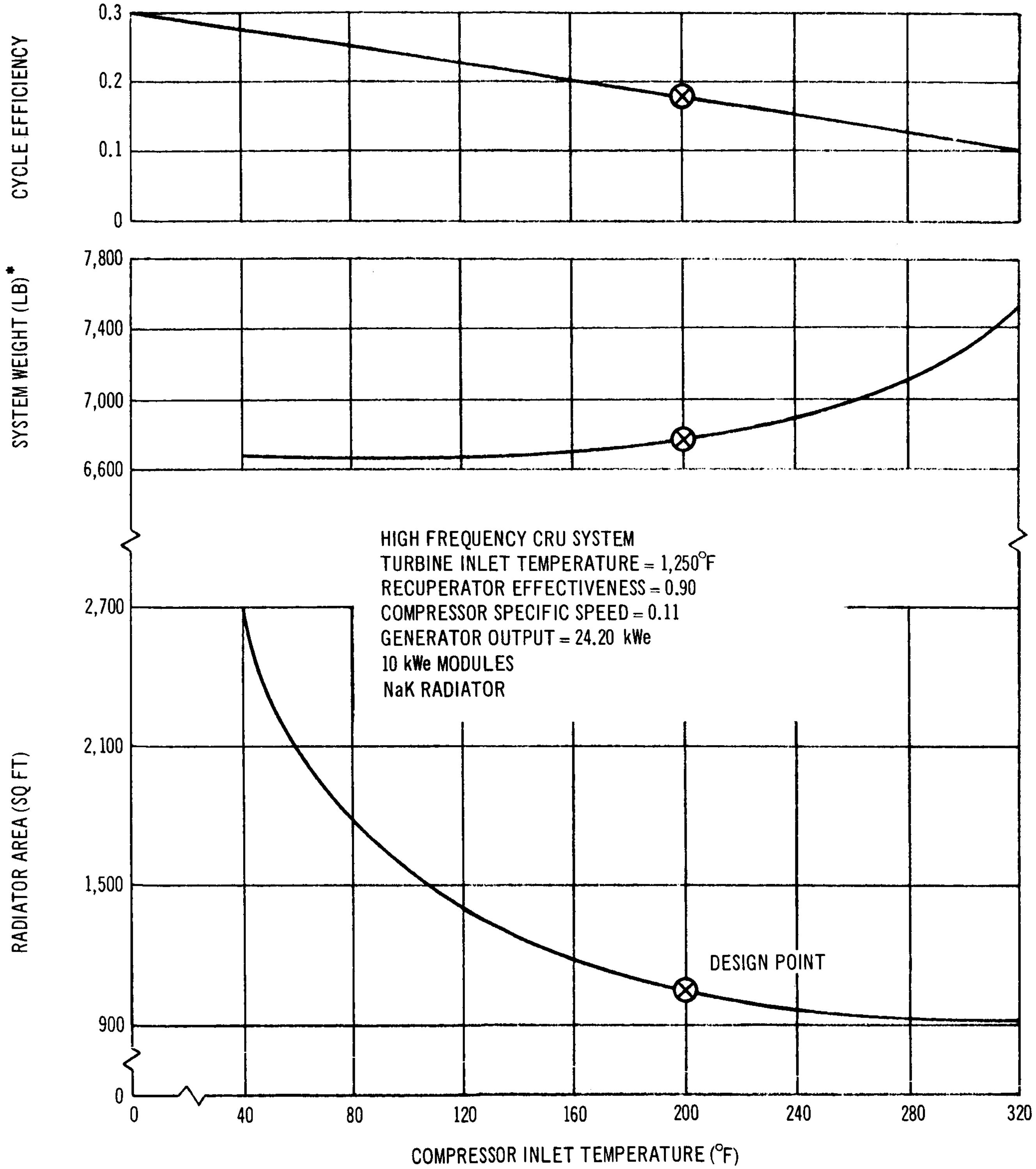
When compared on a performance-weight-surface area basis only, the single-shaft and two-shaft systems are competitive; the two-shaft system is slightly superior in cycle efficiency, radiator area, and provides slightly lower system weight. However, the single-shaft system is simpler to design and construct and is inherently more reliable than the two-shaft system as a result of fewer rotating components.

Although either the single-shaft or two-shaft concept can be successfully developed for manned Earth-orbital application, the single-shaft concept is the reference system design because of its added flexibility and fewer areas of uncertanity.

3.4.4.3 Intermediate Loop

An intermediate loop in the primary heat exchange system involves using a NaK-to-NaK heat exchanger in the gallery region. Although the intermediate loop does provide a slight weight and reliability penalty, the intermediate loop is considered to provide significant advantages which more than offset the weight and reliability penalties. These advantages include the following:

1. Minimum size duct penetrations through the secondary shield.
2. Greater versatility in packaging components into the gallery region.



*SYSTEM WEIGHT INCLUDES REACTOR, SHIELD, AND PCS.

Figure 3-16. Operating Point Selection Brayton Cycle

3. Elimination of lengthy gas ducts (and the associated pressure drop) by locating the NaK-to-gas heat exchanger next to the PCS.

4. Ease of replacement of a PCS.

5. Eliminates possibility of a NaK-to-gas heat exchanger leak, which results in activated primary loop NaK in the PCS.

3.4.4.4 Pump Selection

Direct radiating TEM pumps were selected for use in the intermediate loop and are the tentative choice for the radiator loops. At the present level of development effort being expended on pumps, it is highly unlikely that a single dynamic pump will have the reliability required for a manned MORL mission. Based on this premise, the static, highly reliable TEM pumps were selected for this application. However, final selection of the TEM pumps instead of motor-driven centrifugal pumps in the radiator loop will depend upon a further analysis of TEM pump capability at reduced operating temperature.

3.4.4.5 Radiator Design

The preliminary radiator performance, surface area, and weight relationship for direct (gas-cooled) and indirect (liquid-cooled) radiators were evaluated. The liquid-cooled radiator system weighs less because of higher cycle efficiency and because the smaller liquid tubes require less armor protection against meteoroid puncture. The difference in radiator area between the two systems is relatively small in the range of interest.

The three candidate heat rejection system fluids investigated included FC-75, NaK-78, and a eutectic mixture of sodium, potassium, and cesium (0.12 mol fraction Na, 0.47 mol fraction K, and 0.41 mol fraction Cs). The potential advantage of the NaK-Cs eutectic in comparison with NaK-78 is the significantly lower freezing temperature of the NaK-Cs (-110°F compared to 10°F for NaK), which greatly reduces the problem of maintaining the coolant in the liquid state during reactor shutdown periods.

The NaK and NaK-Cs systems use a cone with a surface area of 1,150 sq ft. The FC-75 system requires a slightly greater radiator area than required by the liquid metal systems because of additional film resistance in the tubes. With FC-75, there is the possibility of long-term thermal decomposition of the FC-75 at upper system temperature levels. Film temperatures in the heat-sink heat exchanger are near the critical temperature for FC-75. As a result, the FC-75 system is considered marginal at the present time. Although the NaK-Cs eutectic fluid appears to be an extremely favorable prospect, the reference system design utilizes NaK because further information and test experience is considered necessary to verify the attributes of NaK-Cs.

3.4.4.6 Unit Rating Selection

The weight, performance, reliability, and relative development effort associated with the application of a single, basic 10-kWe module design to satisfy the range of output power levels specified (10, 20, and 30 kWe) were evaluated in comparison with the use of unique designs for these discrete power levels (e.g., one 30-kWe unit, as compared with three 10-kWe units). The use of the smaller rated units permits continued operation at reduced power level in the event one PCS fails; this eliminates the need to revert to the emergency power supply until a standby unit is placed in service. At the reduced power level, it may still be possible to perform some of the planned experiments and complete some of the experiments which were being performed at the time of PCS failure. Also, replacement of the smaller, less bulky modules would be easier then replacing the larger size unit. The smaller rated modules are somewhat less efficient and their use results in a radiator area penalty of 7 sq ft/kWe; however the total PCS and radiator weight is considerably lower when 10-kWe modules are used than when single, full-rated units are used.

Because of the advantages to the mission of being able to operate at reduced power and because a significant weight advantage results with only a small radiator area penalty, the Brayton-cycle 10-kWe module, multiple-unit concept was selected as the baseline design.

3.4.5 Advanced Design Potential

Development in the following principal areas offers the potential of further improvements in the reactor Brayton-cycle system design within the projected schedule for this application:

1. Higher compressor efficiency.
2. Optimum xenon-helium working fluid.
3. Increased turbine inlet temperature.
4. Increased component lifetime.

The above items provide the potential for lower weight, improved performance, and lower radiator surface area. The following tabulation shows the quantitative improvements to be expected, assuming the cycle efficiency of 18% is maintained constant:

	System Weight Reduction (%)	Radiator Area Reduction (%)
Compressor efficiency (83% to 87%)	11	14
Xenon-helium mixture	20	5
Turbine inlet temperature (1,250° to 1,350°F)	12	21

3.5 THERMOELECTRIC POWER CONVERSION SYSTEMS

A 10-kWe silicon germanium (SiGe) direct radiating thermoelectric power conversion system and a 20-kWe lead telluride (PbTe) compact converter system were selected for analysis and design integration. The 20-kWe compact converter system is typical of the expected requirements of a second-generation MORL; whereas the 10-kWe direct radiating design represents a more advanced state of development which has already been demonstrated in space (SNAP-10A) and is a logical candidate for earlier application.

The most significant attributes of the selected thermoelectric system concepts are as follows:

1. High reliability for a 5-yr operating lifetime, resulting from the use of completely static components.
2. Full use of reactor and power conversion system components already developed or under active development to minimize the development risk.
3. Adaptability to a continuous range of output power requirements up to the limits imposed by physical integration constraints (notably weight and radiator surface).
4. Design for accessibility and possible maintenance of the compact converter system design but with dependence only on installed redundant capacity to meet reliability and lifetime objectives.

3.5.1 Configurations

3.5.1.1 20-kWe System

The 20-kWe PbTe compact converter system configuration is shown in Figure 3-17. The top of the radiator is located immediately below the secondary shield and the Apollo logistic vehicle attach ring is located at the 154-in. diam. A transition is made from a conical to a cylindrical surface at a 260-in. diam, and the cylindrical section is extended 163 in. to provide the required radiator surface. For the initial launch, the reactor power system configuration is placed on top of MORL, with the cylindrical section enveloping the conical hangar/test area of MORL to maintain launch vehicle height within allowable limits.

The location of converter clusters is dictated primarily by the desire to provide maximum accessibility for maintenance. Accordingly, the 14 converters are located around the inside surface near the base of the conical section, where the radiation field is comparatively low and personnel exposure to the thermal environment inside the radiator is minimized. The converters are connected to radiator segments on both the conical and cylindrical surfaces. The surface area of each quadrant of the cone is shared by two interlaced radiator loops to provide a total of eight loops on the cone. The remaining six loops are interlaced on the cylindrical section in a similar manner. Each loop on the cone is subdivided into two sections serviced by separate headers to facilitate the adjustment of tube spacing near the top and bottom of the conical surface as required to provide essentially equal fin widths along the length of the conical radiator surface.

To maintain the replacement power system configuration weight within the payload capability of the selected launch vehicle, the secondary shield is retained on the deployment boom after disposal of the initial power system. For this

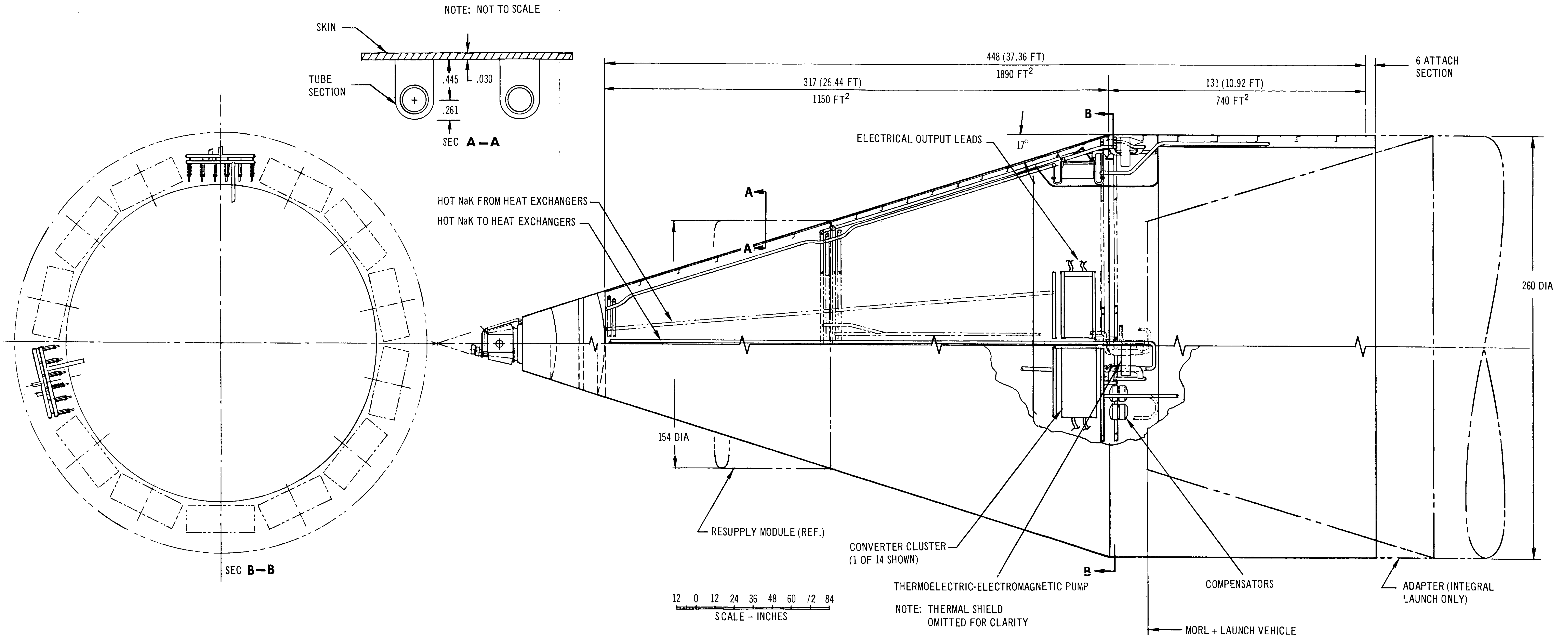


Figure 3-17. 20 kWe Thermoelectric Nuclear Power System

reason, the PCS components must be located outside the volume subtended by this secondary shield as it is removed. However, this requirement is readily satisfied because of the relatively large volume available in the configuration and because the most logical support point for major components is the surface of the configuration.

3.5.1.2 10-kWe System

The 10-kWe SiGe direct radiating system uses a conical surface having a base diameter of 260 in. and providing approximately 1,100 sq ft of radiator surface area, as shown in Figure 3-18. Each of the six loops occupies the full length of the conical surface. Because the close coupling of electrical and fluid systems makes interlacing the tubes impractical, each loop occupies a separate segment of the surface.

The arrangement of piping on the conical surface is designed to achieve individual couple radiator areas that are essentially square and approximately equal in area. Each of the 6 loops contains 17 converter tubes extending from the 66-in. diam to the 154-in. diam and 34 converter tubes from the 154-in. diam to the 260-in. diam. The radiator tubes transport heat to the thermoelectric hot junctions and cannot be placed in direct contact with the main support structure without excessive heat losses. Moreover, the radiator elements are necessarily discontinuous and cannot serve as structural members. Therefore, a titanium truss core sandwich structure is located inside the converter array to serve as an attachment surface for the converter tubes at approximate 12-in. intervals and to support the reactor and shield.

All of the main NaK supply lines are located inside of the truss core support structure, but the manifolds for the converter tubes are located on the outer surface, to avoid excessive shell penetrations. Although the converter elements are necessarily spread over the entire conical surface of the configuration, the location of pumps and expansion compensators is relatively flexible. These components are located near the base of the cone to maximize accessibility.

3.5.1.3 Integrated System Weight

Table 3-16 itemizes the integrated reactor-thermoelectric system weights. The reactor power system subtotal reflects all of the components contained in the configurations, whereas the associated weights include the deployment boom, related system components located in the MORL, and MORL weight penalties referenced to the baseline design. Table 3-17 itemizes the weights of electrical components, predominantly located in the MORL. The PCS weight breakdown is omitted because of its classification.

Integral launch of both systems with the MORL can be accommodated by the selected launch vehicle. The weight of the 10-kWe thermoelectric system configuration is sufficiently low that replacement system launch, if required, could be accomplished with a completely fixed shield, but with a reduced weight contingency, using the specified launch vehicle (18,100 lb payload). Moreover, further optimization of the structural requirements for this system configuration would be expected to yield a substantial weight reduction. The replacement 20-kWe thermoelectric system would require nominal increase in the selected launch vehicle payload capability despite retention of the initial secondary shield (amounting to 4,100 lb) on the MORL. However,

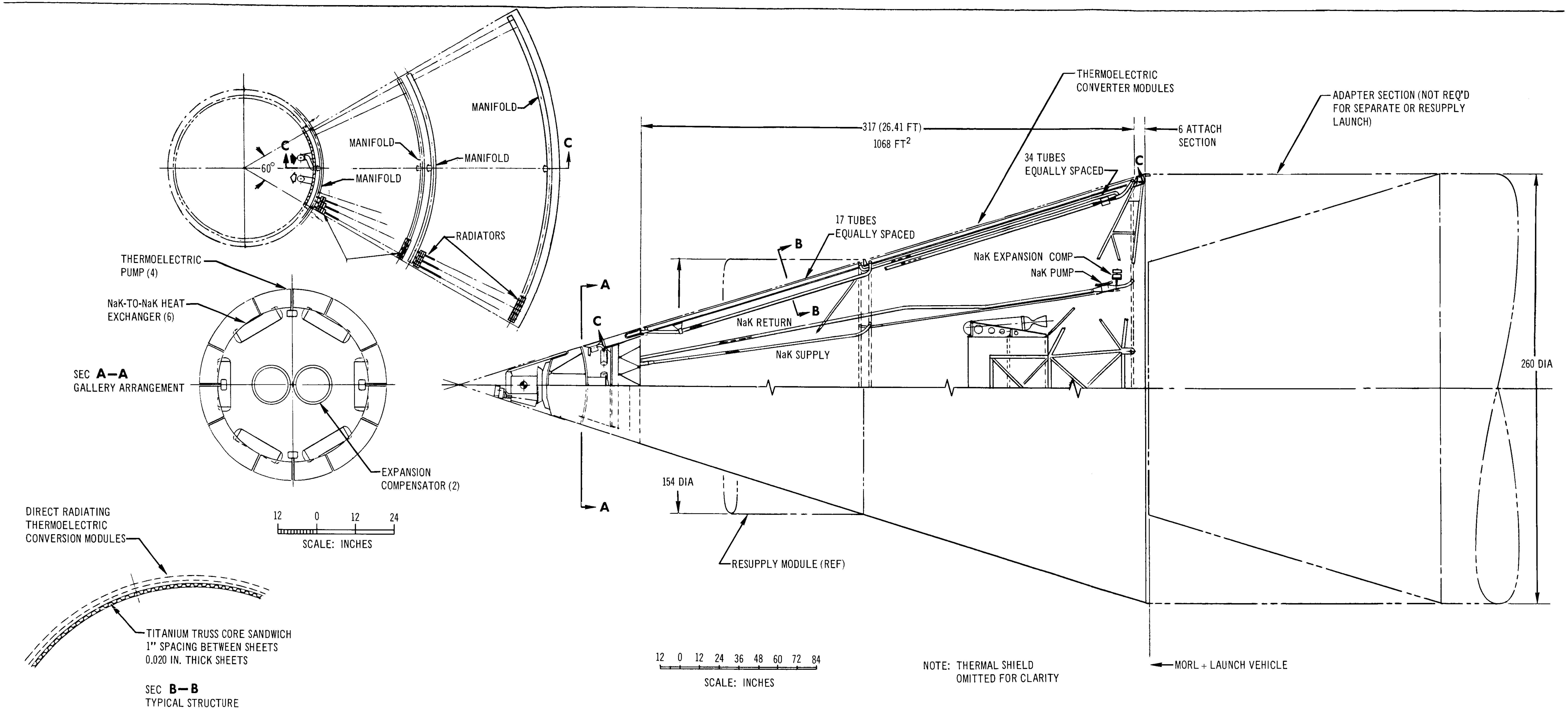


Figure 3-18. 10 kWe Thermoelectric Nuclear Power System

101-1

101-2

101-3

Table 3-16
REACTOR-THERMOELECTRIC POWER SYSTEM WEIGHT SUMMARY

	10-kWe (SiGe) System Weight (lb)			20-kWe (PbTe) System Weight (lb)		
Reactor power system weight:						
Reactor and primary system		1, 025			1, 258	
Shield		8, 083			9, 315	
PCS		2, 270			6, 992	
Electrical equipment on RPS configuration		300			400	
Structure		2, 256			2, 983	
Thermal shields and reactor disposal system		1, 606			1, 995	
Thermal shields	(1, 095)			(1, 484)		
Reactor disposal	(511)			(511)		
Subtotal			16, 540			22, 943
Associated reactor system weight, (1):						
Control moment gyro penalty		1, 182			1, 568	
Shield retention and deployment boom		2, 720			3, 450	
Structure (2)	(1,739)			(1, 619)		
Tension cables	(131)			(131)		
Electrical transmission cables	(850)			(1, 700)		
Standby power (3)		2, 957			1, 676	
Electrical system on MORL		3, 012			2, 524	
Power regulating system	(90)			(110)		
Control and conditioning	(1,011)			(489)		
Bus and distribution	(500)			(1, 000)		
Standby source electrical	(1,411)			(925)		
RCS penalty (4)		867			1, 436	
Tanks and supports	(242)			(325)		
Propellant	(625)			(1, 111)		
MORL extension (5)		---			354	
Fairing		30			30	
Subtotal			10, 768			11, 038
Reactor power system configuration total weight			27, 308			33, 981
Integral launch adapter			1, 020			404
Integral launch weight (6)			56, 238			62, 385
(with 20% contingency)			(61, 994)			(69, 262)
Replacement launch weight with shield retention			13, 040			18, 838
(with 20% contingency)			(15, 648)			(22, 606)
Replacement launch weight with fixed shield			16, 540			22, 943
(with 20% contingency)			(19, 848)			(27, 531)

Notes:

1. Components and structure which are retained by or are part of the MORL and are not resupplied with the replacement reactor power system configuration.
2. Subtract 320 lb (10-kWe system) or 200 lb (20-kWe system) for fixed shield design.
3. Solar photovoltaic (10-kWe system) and Pu-238 Brayton cycle. (20-kWe system) standby system designs.
4. RCS weight penalty is that weight in excess of the baseline MORL RCS weight (880 lb of propellant and 426 lb tanks and supports) for a 218-nmi, 50° inclination over a 147-day duration.
5. A 5.2-ft extension over baseline MORL length of EC/LS and standby power system radiator.
6. Includes 28,000 lb for the weight of the MORL less Pu 238 Brayton Power System.

Table 3-17

THERMOELECTRIC SYSTEM ELECTRICAL WEIGHT

Component	10 kWe (lb)		20 kWe (lb)	
Power Regulation System				
Parasitic load voltage control assembly	(2)[1]	60[2]	(2)[1]	50
Parasitic load resistors	(2)	30	(2)	60
Subtotal		90		110
Control and Conditioning System				
Dc system				
Main dc regulator units	(2)	30	(2)	50
Battery (1 at launch)	(1)	467[3]		---
Battery case and connectors	(1)	117[3]		---
Battery charger, regulators, power switches, and relays	(2)	60		---
Reverse current relays	(4)	20	(4)	20
Allowance for spare 4-cell battery modules	(4)	96		---
Ac system				
Square wave inverters	(2)	84	(2)	168
Sine wave inverters	(1)	51	(1)	102
Load control system	(2)	---	(2)	20
Switches, circuit breakers, relays	(37)	86	(37)	129
Subtotal		1,011		489
Bus and Distribution System, Subtotal		500		1,000
PBC Standby System (Electrical Equipment), Subtotal		---		925
Deployable Solar Cell Standby System (Electrical Equipment), Subtotal		1,411[4]		---
Total Electrical Equipment in MORL Vehicle		3,012		2,524
Total Electrical Equipment in Reactor Assembly[5]		300		400

Notes:

1. Required quantity shown in parentheses.
2. Includes part of battery charging control functions.
3. Battery weight increased to provide for solar cell charging requirements during standby/emergency operation.
4. Includes solar panels and related equipment. Does not include deployment mechanism or batteries.
5. Includes collector buses, reverse current relays, switches, and two servo-controlled switching modules. Reported as a part of PCS weight.

attainment of the specified 5-yr lifetime objective would make it unnecessary to replace either system during the mission.

3.5.2 System Design Description

3.5.2.1 20-kWe System

The PbTe compact converter thermoelectric system is designed to produce 22.5-kWe net output power at the load buses. Although an output power level of 20 kWe was initially specified, integration of the standby power source to satisfy peak load demands resulted in an improvement in the power conditioning efficiency sufficient for an output of 22.5 kWe by using the same installed converter capacity. The overall system is designed to provide a full power reliability of 0.95 for 5 yr of operation, exclusive of possible improvements resulting from component replacement or maintenance.

A schematic diagram of the system is presented in Figure 3-19. The SNAP-8-type reactor produces 622 kWt at a nominal reactor outlet temperature of 1,300°F. The primary coolant system includes 8 direct radiating TEM pumps, 3 expansion conpensators, and 7 NaK-to-NaK heat exchangers located in a 20-in. shield gallery. Each NaK-to-NaK heat exchanger normally supplies 2 power converter loops, located behind the secondary shield and sized to deliver 1.875-kWe net output power each at the end of life. Interconnections are provided to facilitate the operation of converter loops with the adjacent heat exchangers, as well as with the normally associated heat exchangers.

In normal operation, only 6 of the 7 heat exchangers and 12 of the 14 power converter loops are required for full power. The two redundant loops are isolated and maintained in the cold condition to minimize degradation of the standby converter capacity. Only 22 of the 24 tubular converters in each loop are required to produce loop rated power; remaining two tubular converters provide operating redundancy. When all converters are functioning, rated output power is achieved at a reduced hot side temperature. Similarly, output power density is maintained constant throughout lifetime by operating initially at reduced hot side temperature and by adjusting this temperature periodically throughout lifetime, according to the converter degradation.

The 14 converter loops are serviced by individual radiator loops; the radiator tubes are interlaced around the inside surface of the configuration and provide a total radiator surface area of 1,891 sq ft. The relatively high temperature difference between the converter coolant supply and the radiator fluid loop facilitates the application of across-the-line thermoelectromagnetic pumps, powered by this temperature differential.

The system operating parameters are shown in Table 3-18. The average temperature of the coolant supply to the converters is 1,150°F at the end of life, based on the use of a 200°F fluid temperature and allowance for a 50°F terminal difference across the heat exchangers. The average cold side temperature is 550°F and the associated fluid temperature drop is 200°F. The 200°F temperature drop was chosen to optimize pumping power requirements and the 50°F terminal difference in the heat exchangers was selected to minimize heat exchanger size. Selection of the average cold side temperature was based on a system weight/radiator area optimization.

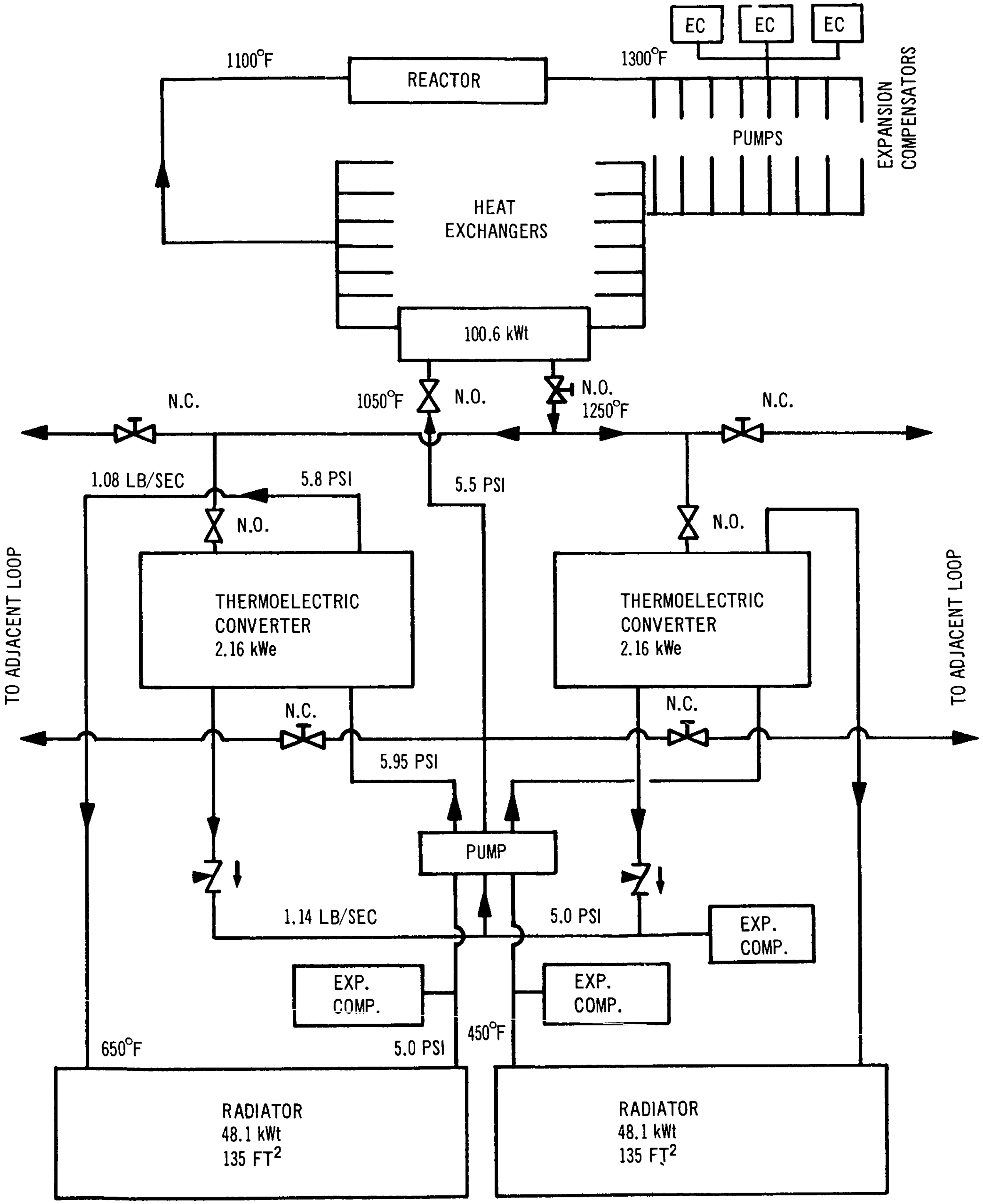


Figure 3-19. 20 kWe Power System Schematic

Table 3-18

THERMOELECTRIC CONVERSION SYSTEM OPERATING PARAMETERS

Parameter	SiGe Direct Radiating System	PbTe Compact Converter System
Rated power, conditioned (EOL*), kWe	9.8	22.5
Net system efficiency (EOL), %	2.32	3.62
Radiator surface area, sq ft	1,068	1,891
Reactor and primary coolant system		
Reactor power, kWt	422	622
Reactor inlet coolant temperature, °F	1,100	1,100
Reactor outlet coolant temperature, °F	1,300	1,300
Primary flow rate, lb/sec	9.72	14.2
Primary pressure drop, psi	0.94	1.6
Primary thermal requirement, kW (heat loss and pumps)	14	18
Power conversion system		
Converter loop average fluid temperature, °F	1,150	1,150
Radiator loop/cold side average temperature, °F	550	550
Coolant (NaK) flow rate, lb/sec		
Converter loop	1.60	1.141
Radiator loop	---	1.078
Pressure drop, psi		
Intermediate/converter loop	0.4	0.5
Radiator loop	---	0.95
Pumping power, hydraulic, W		
Intermediate/converter loop	2.8	2.6
Radiator loop	---	4.4
Primary system loss, %	3.0	3.3
PCS pumping power, %	1.2	1.3
Power conditioning efficiency, %	81.7	87.0
Number of converter tubes per loop	34 (bottom) 17 (top of config)	
Number of loops installed/active, full power	6/5	
Number of converter modules per loop		24
Number of converter modules required for rated loop output power		22
Number of converter loops installed/active, full power		14/12

---

*EOL = End of Life

3.5.2.2 10-kWe System

Figure 3-20 shows the schematic diagram of the SiGe direct radiating system. A slight reduction in output power, from 10 to 9.8 kWe, occurred from a nominal variation in power conditioning efficiency resulting from design integration. The primary system includes 4 direct radiating TEM pumps, 2 expansion compensators, and 6 NaK-to-NaK heat exchangers located in a 14-in. shield gallery. Six independent converter loops are provided, each loop containing an expansion compensator, a TEM pump, and an array of converter tubes arranged around the conical configuration. Each loop contains 51 converter tubes, with 17 tubes occupying the upper surface of the conical configuration and 34 tubes occupying the lower surface. Operation of only five of the six loops is required to produce full power output. The remaining loop is maintained in standby at a temperature sufficient to prevent coolant freezing; a bleed flow may be used if necessary.

Design and operating parameters are presented in Table 3-18. The average temperature of the coolant supply to the converters is 1,150°F at the end of life, based on the use of a 200°F fluid temperature drop and a 50°F terminal difference across the heat exchangers. The corresponding average radiating temperature is 550°F. The 200°F temperature drop was chosen to optimize pumping power requirements, and the 50°F terminal difference in the heat exchangers to minimize heat exchanger size. Selection of the average radiating temperature was based on a system weight/radiator area optimization.

3.5.3 System Operational Requirements

The power conversion system is filled with the required NaK inventory prior to assembly of the launch configuration. Thereafter, the coolant is maintained in the liquid phase and temperature equilibrium is achieved by pump operation. For this purpose, the pump inlet lines may be heated electrically to establish the temperature differential necessary for operation of the pump thermoelectric elements. The use of a thermal shield over the radiator minimizes the power to be supplied from the standby source (150 to 200 W) to maintain acceptable temperature levels.

3.5.3.1 Startup

The reactor power system is started after the MORL has been manned, the system fully deployed, and electrical cables and instrumentation connected and tested. Electrical circuits and valve positions should also be checked prior to startup to confirm operational status. Startup of both thermoelectric systems is essentially automatic and coincident with reactor startup and primary coolant system heatup. Because the thermoelectric pumps in the converter loops are located remotely from the primary heat exchangers, electrical heating (powered by the standby source) of the pump inlet lines is used to provide a sufficient temperature difference across the pump thermoelectric elements to initiate flow. As the primary coolant system flow rate and temperature increase, the converter loop pump flow increases to the steady state value.

The thermal shields are removed during startup, but before attainment of criticality to avoid a neutron scatter source to MORL during shield deployment. The interval between shield deployment and reactor operation at a self-sustaining power level should be limited to approximately 30 min. to prevent

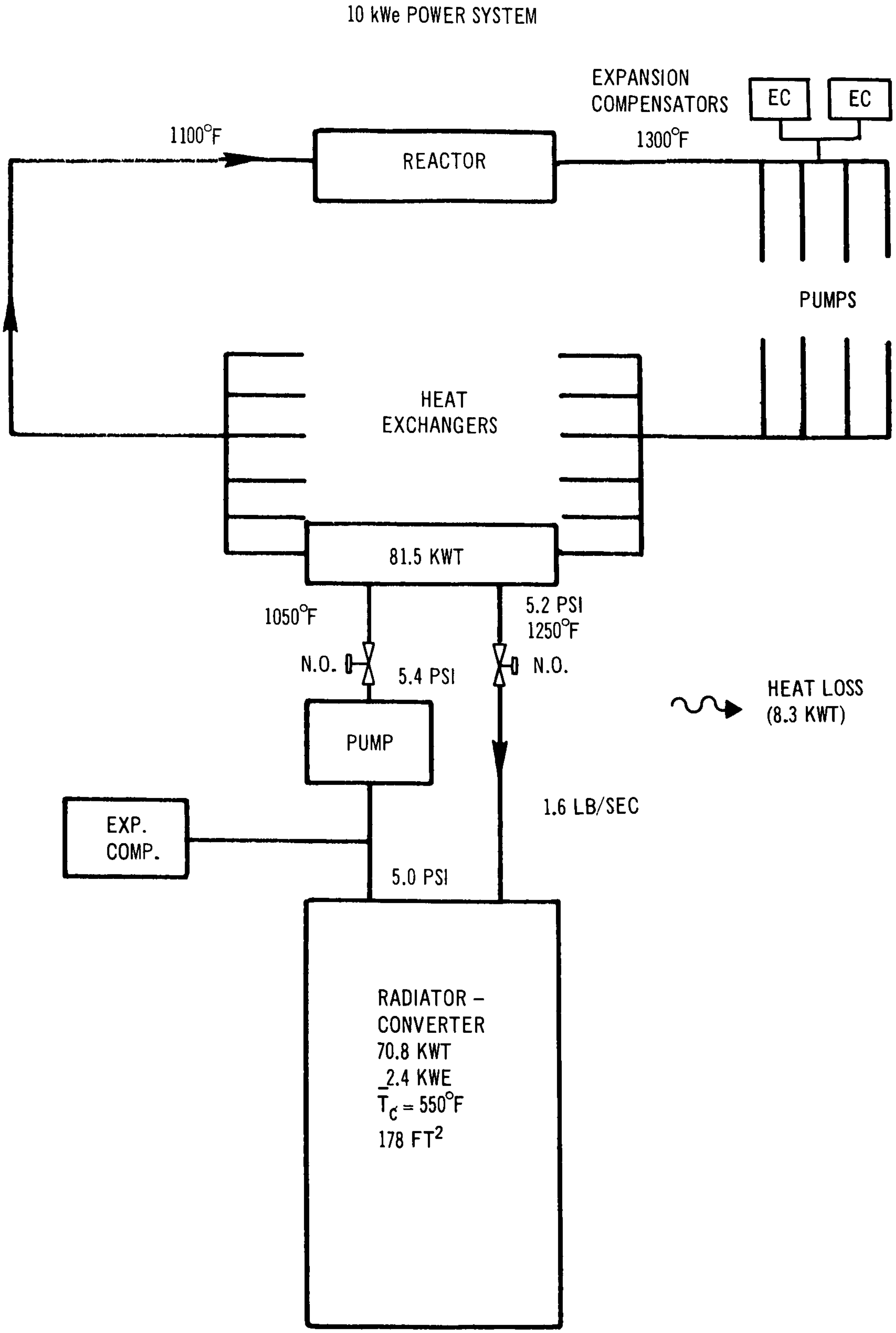


Figure 3-20. 10 kWe Power System Schematic

freezing of NaK because of the exposed radiator surface. Once the reactor is operating in the power range, a supply of approximately 60 kW to the radiator loops is sufficient to maintain coolant temperature above 100°F. Further detailed development of the startup procedure is required because of the critical time interval involved in this operation.

3.5.3.2 Normal Operation

The normal mode of operation for both systems produces 56 Vdc power, which is supplied to the power conditioning system at ±28 Vdc. Reverse current relays are used to switch modules on or off as required to maintain voltage within prescribed limits. A servo controller activates or deactivates the reverse current relays in a fixed sequence as the load demand varies. By this means load changes as small as 150 W of conditioned power are possible. A parasitic load dissipates excess power during transients and also provides fine adjustment of the voltage during steady state operation.

The Pu-238 Brayton cycle standby system supplies the peak loads and recharges the battery for the 20-kWe system. Peak loads for the 10-kWe system are supplied by the battery. Both thermoelectric systems are only required to follow the load variation below the average load demand level.

The overall transient response of a reactor-thermoelectric power system is relatively slow in comparison with the rate at which the load demand can change. The overall response time associated with the converter heat supply exceeds 1 min. The thermal response time of the converters is also significant with estimated response times of about 15 to 30 sec for the direct radiating converters and 1 to 1.5 min. for the tubular converters. These slow response times do not directly affect the amount of power avaliable after a step change in load, although the attainment of stabilized operating conditions requires several minutes. Orbital variations cause transient effects of relatively small magnitude in the power system; these amount to no more than approximately ±1% heat flux variation.

3.5.3.3 Shutdown and Standby

The shutdown of an individual converter loop is normally accomplished by switching off the surplus converter capacity and, for prolonged shutdown periods, by loop isolation. In the 20-kWe system, the radiator tubes associated with the individual loops are interlaced so that a satisfactory temperature level is maintained in an isolated loop by thermal conduction from the operating loops. In the 10-kWe system, the radiator tubes are not interlaced; and, consequently, positive means of maintaining a satisfactory temperature level in an inactive loop are required. This is accomplished by maintaining a low bleed flow through the inactive loop.

3.5.4 Maintenance

The shield gallery is completely inaccessible because of the excessive nuclear radiation levels. However, most of the 20-kWe PCS components, including the converters, are located behind the secondary shield where the nuclear radiation level is sufficiently low that short-term access can be considered while the reactor is operating at a low power level (approximately 10%). Under these conditions, the dose rate at the cone-cylinder interface of the 20-kWe system configuration is approximately 25 to 50 mRem/hr. This radiation level is tolerable for a limited period, but care must be taken to simplify the tasks to be performed while the reactor is operating to avoid overexposure. When the reactor is shut down, the maintenance period is limited to a lesser degree, although prolonged exposure would be inadvisable even under these conditions.

The outside surface of the conical configuration is completely inaccessible after startup because it can be reached only by the astronaut outside the shielded volume. Unrestricted accessibility of the surface from the interior of the 10-kWe system configuration is not possible with the selected truss core sandwhich structure; however, if more detailed vibration analysis indicates an open support structure to be feasible, most of the surface would be accessible from within. Because the interior of the 20-kWe system configuration is accessible, the compact converter components are more adaptable to maintenance operations than are the direct radiating converters.

The pipelines to the 20-kWe system converter modules have been arranged to facilitate converter module removal without interference. Although flanged joints would simplify this operation, mechanical seals are not considered highly reliable for liquid metal lines. In addition, reliable shutoff valves or freeze plugs would be needed to prevent excessive loss of NaK. Pump replacement is in a similar category, although possible modifications could be considered to eliminate a bond with the tube throat. While future effort may simplify such maintenance capabilities, reliance on replacement in the system design at this time appears impractical.

Because the PCS has no moving parts in normal operation, the major design effort is directed toward maximum reliability and installed redundancy, rather than provisions for replacement. The only maintenance that has been specifically required in either system design is control relay and servo control unit replacement, which should both be plug-in-type units. This equipment is located near the cone-cylinder interface of the configuration. Valve operation, if necessary, is also accomplished in that location.

3.5.5 System Reliability

The reactor-thermoelectric power conversion system reliability objective is 0.95, based on operation at rated power for the 5-yr system lifetime. Redundancy, simplicity of design, and derating of components, whenever appropriate, are considered to ensure high reliability. Although access for maintenance is provided to enhance reliability, the system reliability objective must be obtained without relying on extensive maintenance or replacement. To meet the overall reliability goal, the PCS reliability must be at least 0.97 to 0.98.

3.5.5.1 20-kWe System

Multiple converter, radiator, and intermediate loops provide the necessary system reliability. However, a practical limit is placed on the number of converter/radiator loops by the integration constraints, including the maximum available surface area, physical arrangement of interlaced radiator tubes, system weight limitations, and system complexity.

The radiator area is a function of radiating temperature, radiator effectiveness, and installed redundancy. An average radiator fluid temperature of 550°F was selected on the basis of a weight/surface area optimization. A radiator effectiveness of 0.8 was used for the redundancy analysis, although it was recognized that nominal variations would result as the number of loops is changed. Based on these parameters, analysis indicated that the application of redundant loops to achieve system reliability goals imposes a heavy penalty in radiator surface area for fewer than seven loops (total). Moreover, replacement launch configuration height limitations place an upper limit of approximately 1,900 sq ft on the radiator area.

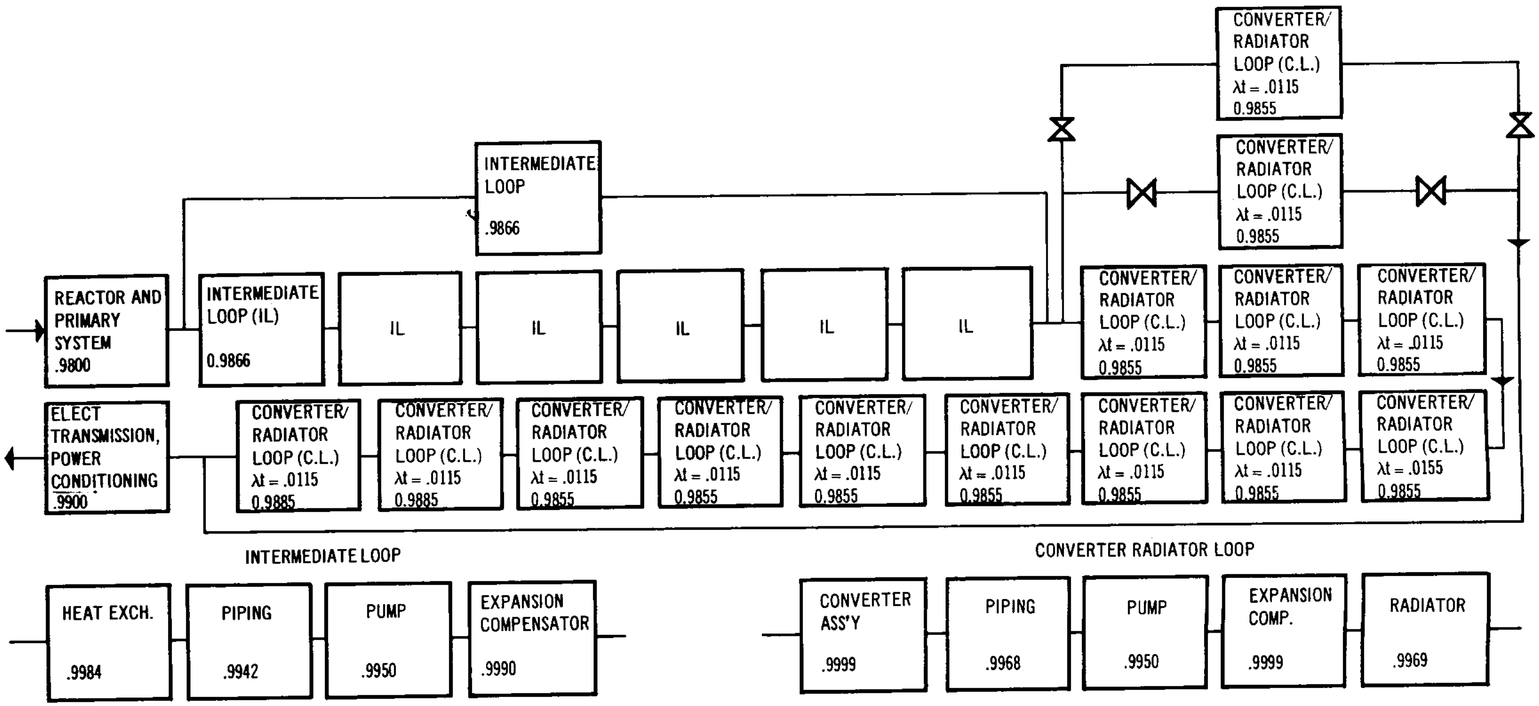
The power conversion system weight decreases as the number of loops increases because the total installed converter capacity, or the amount of redundancy, is reduced as the number of loops increases for a constant number of redundant loops. This trend reverses as the total number of loops is increased beyond 14 because the increase in weight associated with the greater number of loop components overrides the proportionate decrease in redundant converter capacity. Therefore, the selection of 14 converter/radiator loops (2 redundant loops) results in a minimal weight system, commensurate with the provision of redundant capacity within the radiator surface area limitation of the configuration.

The reliability analysis is based on component reliability goals provided by the system subcontractor from currently available information. In particular, the Westinghouse reliability goal for the compact converter is 0.9999 for 1 yr of operation, based on the systematic identification and evaluation/elimination of failure modes through continuing development.

The resulting reliability diagram is shown in Figure 3-21. With the selection of 12 operating and 2 redundant converter/radiator loops (serviced by any 6 of 7 installed intermediate loops), an overall reactor power system reliability of 0.966 is obtained. Attainment of this reliability assumes the ability to supply converter loops from adjacent heat exchangers, as well as the normally associated heat exchangers, through cross-connections provided for this purpose. Considering the possibility that the valves in these cross-connection lines may be inoperable because of malfunction, the power conversion system reliability would be reduced to 0.947 because the converter loops can only be supplied by their normally associated heat exchangers in this eventuality.

3.5.5.2 10-kWe System

The simplicity of the 10-kWe power conversion system design results in a relatively high theoretical reliability. The advanced state of direct radiating converter development coupled with the SNAP-10A operating experience provide a higher level of confidence in reliability prediction. However, the provision of a single converter loop would not provide sufficiently high reliability to meet the MORL application requirements. Considering a minimum required radiator surface area of 885 sq ft (with no redundancy) in comparison with the maximum available area of 1,150 sq ft on the conical surface of the selected configuration, a maximum redundant capacity of approximately 30% could be accommodated. However, based on the application of an integral number of equal-capacity loops, a maximum of only 25% redundant capacity, equivalent to 1 of 5 loops, can be installed. In the selected design, the redundant capacity is further reduced to 20%, or 1 of 6 loops, because the system weight is decreased and the resultant power conversion system reliability is maintained



RELIABILITY CALCULATION:

$$R\,(\text{INTERMEDIATE LOOP}) = (.9984)\,(.9942)\,(.9950)\,(.9990) = 0.9866$$

$$R\,(\text{CONVERTER/RADIATOR LOOP}) = (.9999)\,(.9968)\,(.9950)\,(.9999)\,(.9969) = 0.9885$$

$$R\,(\text{INTERMEDIATE LOOPS INSTALLED}) = \sum_{i=r}^{n} \binom{n}{i} R^i (1-R)^{n-i} = R^7 + 7R^6 (1-R) = (.9866)^7 + 7\,(.9866)^6\,(1-.9866) = 0.9964$$

WHERE n = NUMBER INSTALLED

(n-r) = REDUNDANT UNITS

$$R\,(\text{CONVERTER/RADIATOR LOOPS INSTALLED}) = e^{-N\lambda t}\left[1 + N\lambda t + \frac{(N\lambda t)^2}{2!} + \ldots + \frac{(N\lambda t)^n}{n!}\right] = R^{12}\left[1 + 12\lambda t + \frac{(12\lambda t)^2}{2}\right] = (.9885)^{12}\left[1 + (12)\,(.0115) + \frac{(12)\,(.0115)^2}{2}\right] = 0.9989$$

WHERE N = NUMBER OPERATING UNITS

n = NUMBER STANDBY UNITS

$$R\,(\text{REACTOR POWER SYSTEM}) = (.9800)\,(.9964)\,(.9989)\,(.9900) = 0.9656$$

Figure 3-21. 20 kWe Thermoelectric Power System Reliability Diagram well above the acceptable minimum level. The reliability diagram is shown in Figure 3-22. An overall reactor power system reliability of 0.963 for the 5-yr mission is obtained.

3.5.6 Performance Analysis

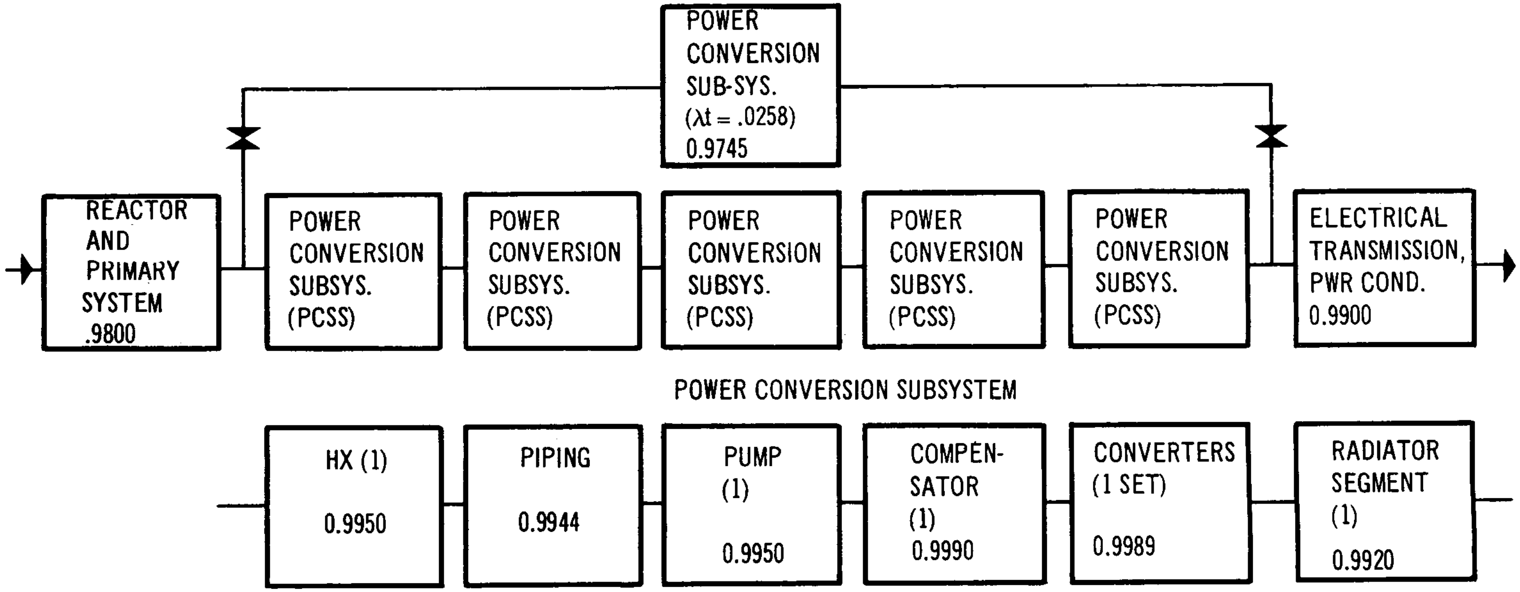
In the evolution of the selected system designs, extensive performance analyses were performed to select the compact converter concept (PbTe vs SiGe), determine the attributes of intermediate loop application, establish the converter operating temperatures, and develop the preliminary radiator and associated structure design. These aspects are briefly outlined in this section with the omission of specific data which are classified.

3.5.6.1 Operating Temperature Selection

Selection of the maximum converter operating temperature (1,250°F) is based on the reactor coolant outlet temperature limitation of 1,300°F; a heat exchanger terminal temperature difference allowance of 50°F is calculated. This 50°F allowance provides a satisfactory margin for the compact converter design and is especially conservative for the direct radiating system design which includes only a single heat exchanger in each loop. However, the performance differential at a slightly higher direct radiating converter operating temperature (1,275°F) would not effect the results within the practical limits of accuracy for this study. A 200°F fluid temperature drop through the converter loops was selected for both systems from a preliminary evaluation of pump requirements. The use of more refined pump design data would be expected to result in nominal variations in this value.

The radiator area requirements of the 10-kWe direct radiating system conform with the specified conical configuration, which provides 1,150 sq ft of available surface and a 260-in. base diam. Selection of an average cold side temperature of 550°F produces a radiator area (1,068 sq ft, including 20% redundant capacity) essentially corresponding to the available surface. A radiator area reduction of about 20% can be obtained at an average cold side temperature of 650°F, but a reduction in converter efficiency occurs. Under these conditions, an output power capability of about 13.5 kWe can be accommodated in the same configuration, with an increase in system weight which is within the selected launch vehicle capabilities. A capability of approximately 20-kWe could be provided by using a configuration equivalent to that of the 20-kWe PbTe system, although an increased reactor size capable of about 900 kWt would be required. Moreover, the selected replacement system launch vehicle payload capability would be inadequate, and the integral launch vehicle capability would be marginal even without weight contingency.

An average cold side temperature of 550°F and a coolant temperature drop of 200°F were selected for the 20-kWe compact converter system on the basis of minimum system weight and radiator area. Both of these parameters are especially important for this system because of launch height and replacement system launch weight limitations.



RELIABILITY CALCULATION:

R (POWER CONVERSION SUBSYSTEM, 5 YEARS) $= (.9950)^2 (.9944)(.9990)(.9989)(.9920) = 0.9745$

R (POWER CONVERSION SYSTEM, INSTALLED) $= e^{-N\lambda t}\left[1 + N\lambda t + \frac{(N\lambda t)^2}{2!} + \ldots + \frac{(N\lambda t)^n}{n!}\right] =$

$$R^5 [1 + 5\lambda t] = (.9745)^5 [1 + 5(.0258)] = 0.9924$$

WHERE N = NUMBER OPERATING UNITS
n = NUMBER STANDBY UNITS

R (REACTOR POWER SYSTEM) $= (.9800)(.9924)(.9900) = 0.9629$

Figure 3-22. 10 kWe Thermoelectric Power System Reliability Diagram

3.5.6.2 Radiator Design Optimization

20-kWe System

The radiator is composed of a continuous conical and cylindrical surface of aluminum; aluminum-armored stainless steel tubes are bonded to the inside surface. The optimization studies performed during Task Area II indicated that, although an overall radiator effectiveness of approximately 0.6 results in the minimum weight fin-and-tube radiator, significant decrease in surface area is achieved with a nominal weight increase by raising the effectiveness to 0.8. Accordingly, the design based on an effectiveness of 0.8 requires a fin thickness of 0.030 in. and an average coolant temperature of 550°F. Under these conditions, and with the specification of a surface emissivity of 0.9 and an effective sink temperature of -20°F, the radiator rejects 0.347 kWt/sq ft.

With these parameters fixed, the variation of radiator weight as a function of radiator tube pressure drop was determined. Although the radiator weight decreases as the allowable radiator tube pressure drop is increased, the feasible operating range of the across-the-line thermoelectric pump design used in the radiator loops, together with practical limitations on the minimum tube size, establish a limit on the pressure drop. Accordingly, a fluid pressure drop limitation of 0.2 psi through the radiator tubes was established. To minimize fabrication problems, stainless steel tubes with a 0.375-in. OD were selected; this resulted in a tube pressure drop of 0.15 psi.

Based on a total vulnerable area of 198 sq ft, the required aluminum-armor thickness is 0.272 in. Full-armor thickness is applied on the front of the tubes, with one-quarter armor thickness applied around the sides and back. All piping and headers are clad with aluminum of one-quarter armor thickness.

The PCS structure must support the conversion system components, the reactor and shield (except for the separable secondary shield), and the Apollo logistic vehicle used in replacement launches. For the 20-kWe system, a structural analysis of the fin-and-tube radiator design indicated this type of radiator, with supplementary stiffening rings for reinforcement, to be lighter than a MORL truss core sandwich structure (3,500 versus 3,720 lb structure with tubes and armor). In the fin-and-tube design, the radiator tubes and tube armor serve as the longitudinal support members.

10-kWe System

The radiator surface of the 10-kWe system is composed of individual radiator platelets which are integral with the thermoelectric couples and have a relatively high fin effectiveness (0.9). As a result of the high fin effectiveness, the specific area is a relatively low 2.4 sq ft/kWt.

The vulnerable area, including tubing and main piping, is approximately 200 sq ft; and a single-sheet, aluminum-armor thickness of 0.275 in. is required Because the radiator fin is treated as a bumper, the equivalent total armor thickness of 2 separated sheets is taken as a factor of 0.29 of the single-sheet armor thickness in accordance with the study criteria. A total armor thickness of 0.080 in. is required. Based on a uniform radiator fin thickness of

0.053 in., the remaining equivalent aluminum-armor thickness of 0.027 in. is provided by the coolant tube wall. No additional armor is required.

The combined weight of the titanium truss core support structure and the thermal shields amounts to approximately 2.9 lb/sq ft of configuration surface (1,150 sq ft for the conical configuration). However, studies by Atomics International, as well as the actual structural requirements for SNAP-10A, would indicate the possibility of substantially lower weight, as low as 1.5 lb/sq ft, for support and thermal shield structure. While a weight reduction of this magnitude has not been verified for the specific configuration design of this study, it is expected that more detailed structural design optimization, based on dynamic analysis, would produce a substantial weight saving.

3.5.6.3 Intermediate Loop Application

The application of an intermediate loop was evaluated primarily for the 20-kWe compact converter system design. It was concluded that an intermediate loop would increase system flexibility by packaging heat exchangers rather than converters in the shield gallery and would provide the capability for maintenance of converters and associated electrical equipment behind the shield. The growth in size and complexity, inevitable when a design is further detailed, can be more readily handled by the three-loop system, both in the restricted gallery area and in the converter area behind the shield.

The two-loop system is the simpler, more direct design with fewer components. Its converters can operate at a 10° to 20°F higher hot side temperature, giving somewhat higher converter efficiency and lower radiator area. However, because the converters are inaccessible, a higher degree of redundancy is required. This involves complicated piping and valve arrangements in the gallery, increasing its size and the number of shield penetrations. The increase in gallery size significantly increases the shield weight.

In view of the prospects for reduced system weight, added system maintainability, and flexibility through application of the intermediate loop system, this design was incorporated in the compact converter system design.

3.5.6.4 Compact Converter Materials

The PbTe and SiGe compact converter systems were compared for a three-loop system in which the converters are located behind the shield. In both systems, NaK-to-NaK heat exchangers, located in the shield gallery, provided the interface between the primary system and the converters. The study indicated that the application of PbTe compact converters results in a significant overall system weight and radiator surface area advantage in comparison with the SiGe compact converter design. This is attributed mainly to the higher PbTe converter efficiency at comparable operating temperatures and consequent reduction in reactor, shield, and radiator weight. These advantages more than offset a SiGe converter weight advantage.

3.6 ELECTRICAL SYSTEMS

The MORL mission establishes electrical power requirements for EC/LS functions, lighting, communications, data acquisition and processing, and direct support of space experiments. In addition, MORL requires electrical power for guidance and control, attitude control thrustors (propulsion), logistics vehicles, and maintenance. All systems require electrical power for status displays, controls, and instrumentation.

3.6.1 MORL Load Requirements

The 24-hr average electrical power requirements have been projected from the present baseline MORL requirement of 8.78 kWe to an immediate requirement of 10 kWe (nominal), and to possible future requirements of 20 and 30 kWe. Table 3-19 shows a representative load analysis for a 20-kWe system.

EC/LS system thermal requirements are partially satisfied by electrical heaters supplied by 3.3 kWe of unconditioned MORL main bus power for the 20- and 30-kWe system applications. The division of ac and dc load is based on supply of optional loads from the most efficient source for the dynamic power systems. However, the thermoelectric systems may supply heating, lighting, and propulsion loads, now shown as ac power, directly from the MORL main bus without power conditioning to increase efficiency and reduce weight.

Load following capability is provided in the electrical power conditioning and control systems to meet the variations in real MORL loads without significant degradation in power quality. The typical load profiles developed for this study are shown in Section 2.2.

3.6.2 Electrical System Description

The electrical power systems selected for the individual power conversion concepts were based on an evaluation of alternative systems as presented in the Task Area III report. Figures 3-23 to 3-26 are block diagrams of the selected system designs showing the power distribution to meet the MORL load demand and the respective electrical system efficiencies. Primary design criteria were: (1) alternate path redundancy for high reliability, (2) flexibility to accommodate future load characteristics and to deal with operational changes and maintenance, and (3) a high degree of commonality between systems. Electrical schematics in the Task Area III report exhibit adherence to these criteria.

The reactor power system operates at constant output power corresponding to the average load demand, with excess power dissipated in parasitic load resistors cooled by the EC/LS cooling system. Electrical load following is provided by the standby system or the battery. The standby system is a Pu-238 Brayton-Cycle (PBC) system in the 20-kWe and 30-kWe designs. The standby source for the 10-kWe system is a deployable solar panel supplemented by the system battery. The standby source supplies essential MORL loads when the reactor is shut down as well as the nominal heating requirements of the reactor power system configuration. During normal operation of the 20- and 30-kWe designs, EC/LS thermal load requirements are supplied partially by unconditioned electrical power and partially by direct regenerative heat transfer from the PBC standby source.

Table 3-19

20-KWE POWER SYSTEM LOAD ANALYSIS SUMMARY (Normal Operation)

A. Power in Watts

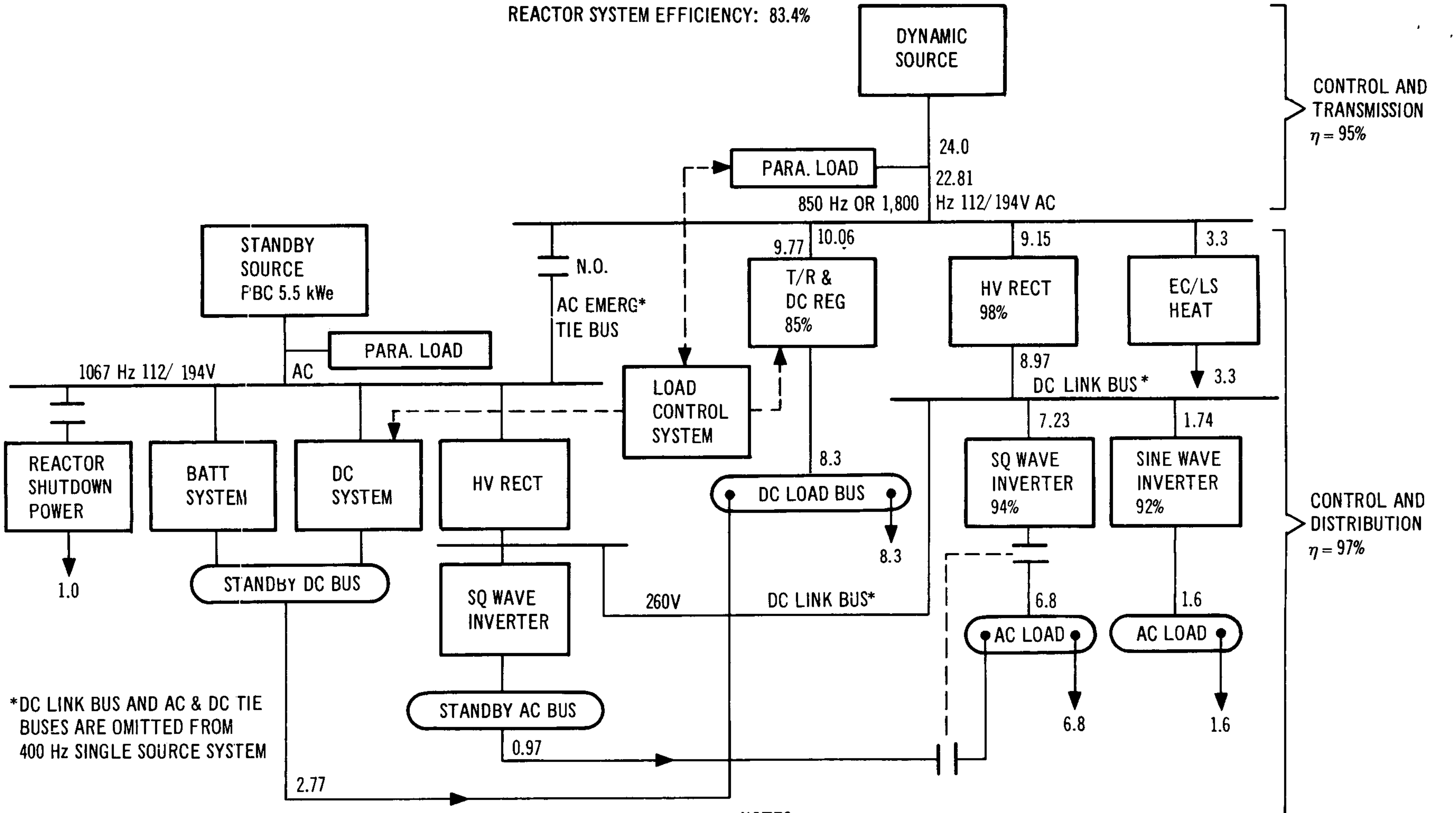
Requirement	Square Wave ac		Sine Wave ac		56 (± 28) Vdc	
	Connected	Average	Connected	Average	Connected	Average
Guidance and control	1, 183	1, 101	89	68	421	236
Communication and data acquisition	150	150	175	175	2, 155	1, 142
Environmental control and life support	3, 269	2, 718			3, 008	2, 790
Display, control, and instrumentation					760	311
Logistic vehicle and maintenance	780	740	2, 368	87		
Lighting and miscellaneous	1, 063	268				
Propulsion	5, 850	2, 283				
Total housekeeping load	12, 295	7, 260	2, 632	330	6, 344	4, 479
Reflected to the source bus (unconditioned):						
Houskeeping load (supplied as conditioned power)		8, 580		400		5, 720
Houskeeping load (supplied as unconditioned power)		3, 300				
Experimental load						
Total allocated load		11, 880		1, 900		8, 720

B. Source Bus Load Summary (W)

Housekeeping	18, 000
Experimental	4, 500
Contingency	1, 500 (3, 400 for thermoelectric)
Total	24, 000 (25, 900 for thermoelectric)

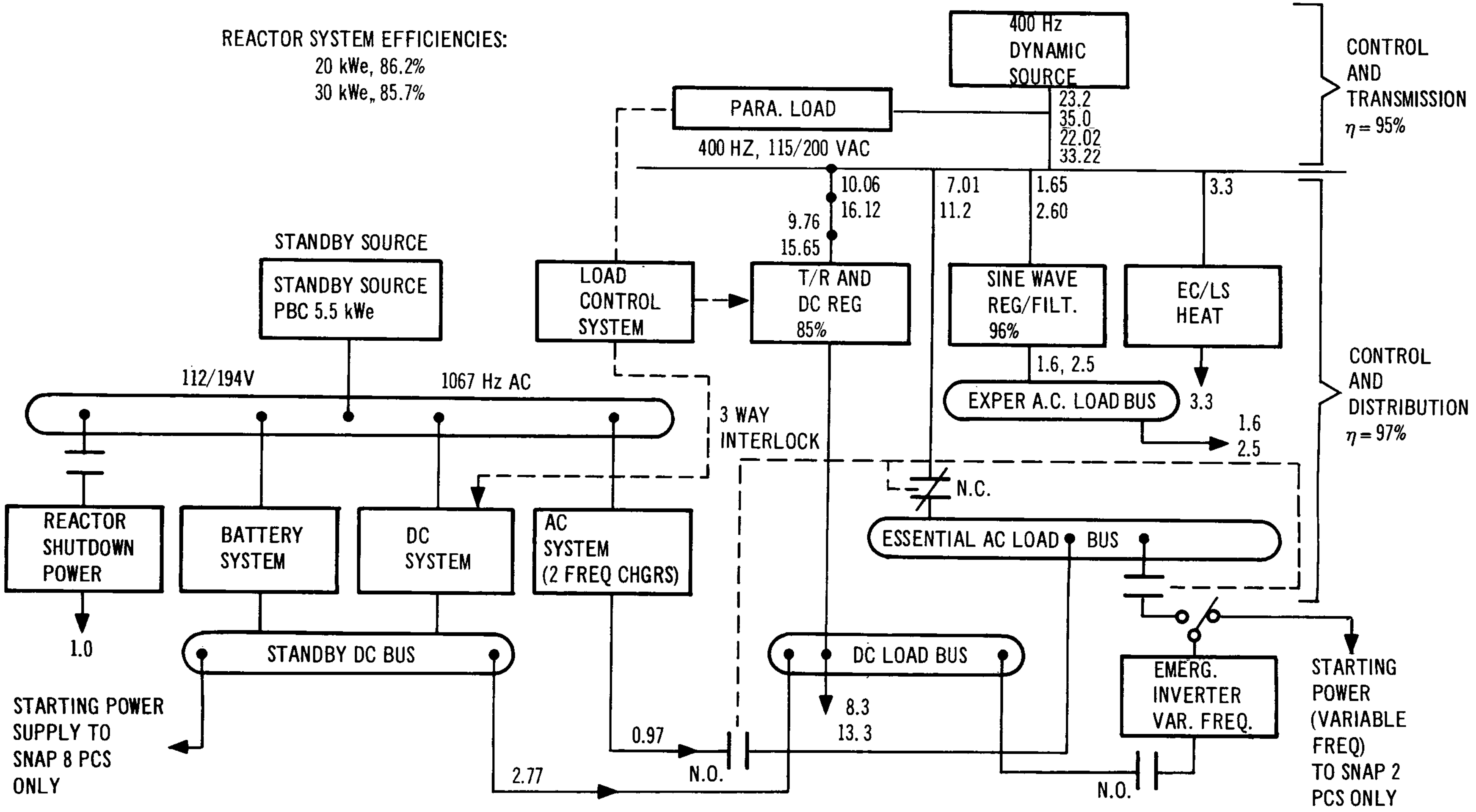
Notes:

1. Approximately 2. 7 kW of EC/LS heating is assumed to be available from the standby power source fuel block for a 9-man crew, in addition to the power allocations shown.
2. Connected loads represent the total of all equipment load if operated simultaneously.
3. Average load is the integrated 24-hour average load requirement, based on the duty cycle.
4. Propulsion load is based on possible application of resistojet thrustors.



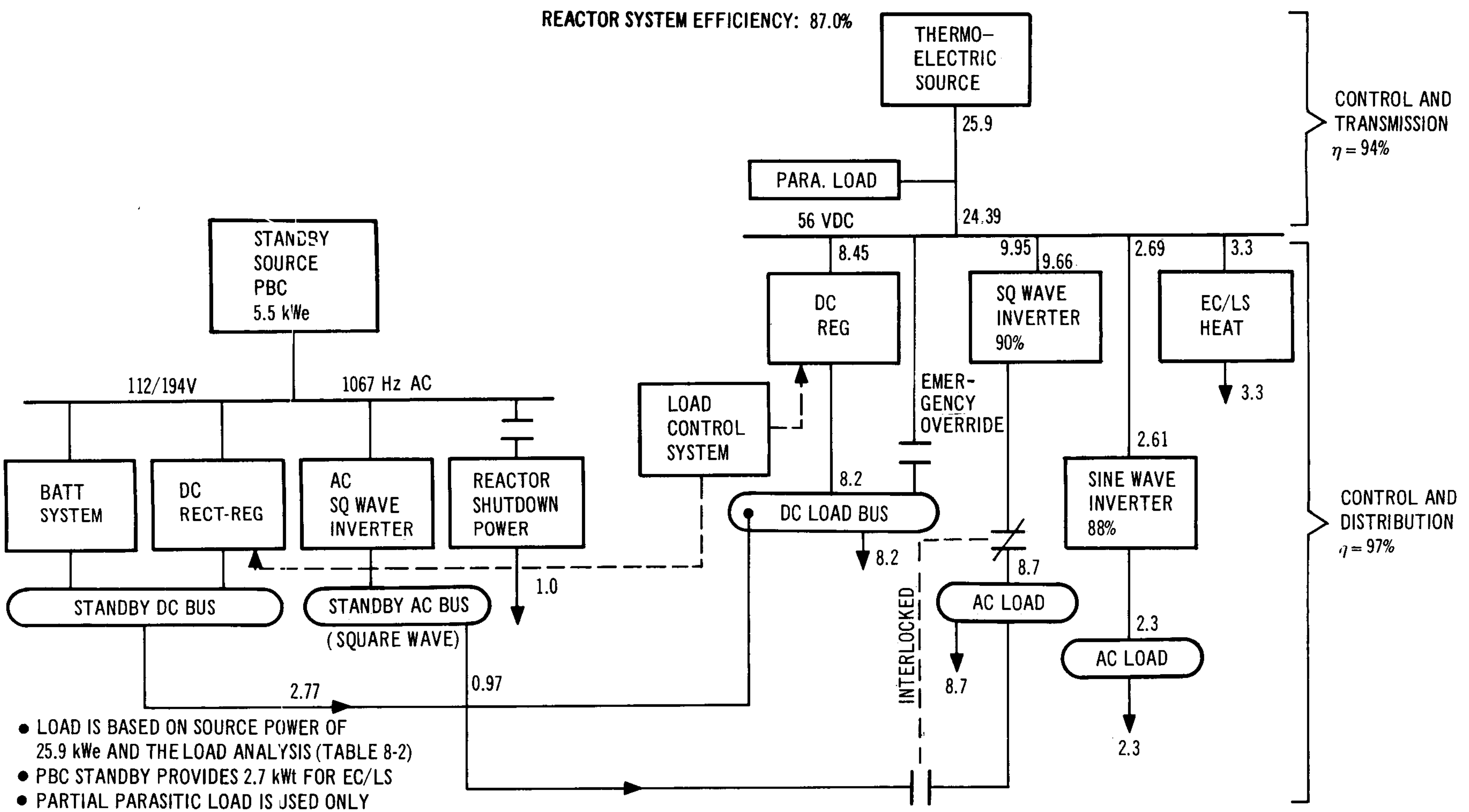
NOTES
- LOAD IS BASED ON 20.0 kWe AT LOAD BUSES AND ON THE LOAD ANALYSIS OF TABLE 8-2
- PBC STANDBY PROVIDES 2.7 kWt FOR EC/LS
- ALL POWER LEVELS ARE SHOWN AS 24 HOUR AVERAGE kWe
- REACTOR SYSTEM PROVIDES CONSTANT LOAD; STANDBY SYSTEM PROVIDES LOAD FOLLOWING CAPABILITY

Figure 3-23. Primary Standby System Integration – 20 kWe SNAP-2 and Brayton Cycle High Frequency PCS



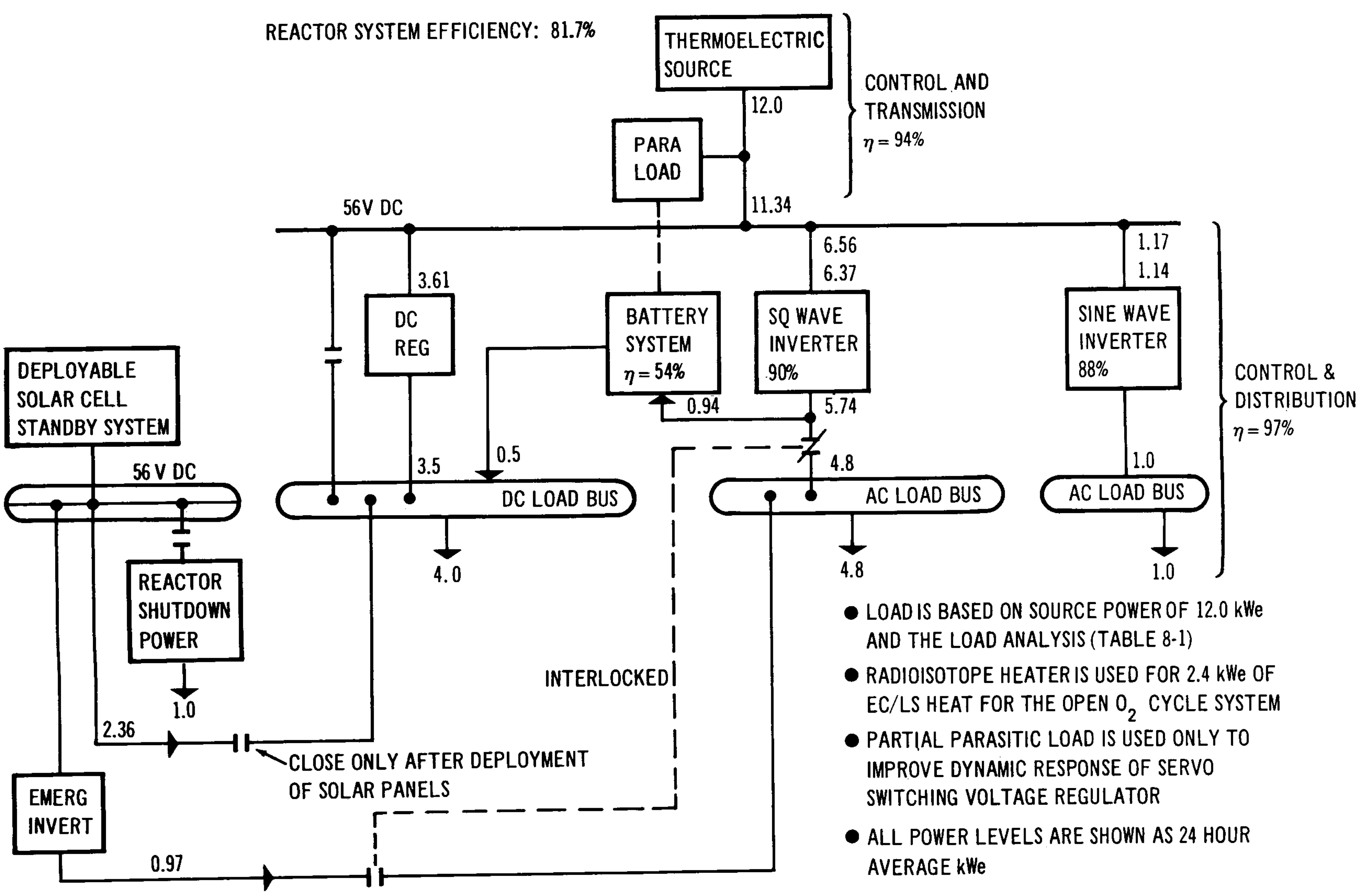
- MULTIPLE REACTOR SOURCES (E.G. SNAP 2 ADVANCED DESIGN) ARE NOT PARALLELED ON 400 Hz AC BUSES, BUT LOADS ARE APPROX. BALANCED. Dc LOAD BUSES ARE PARALLELED WITH A VOTING TYPE OF DC LOAD CONTROL SYSTEM TO FORCE A TOTAL LOAD UPON EACH SOURCE WHICH IS EQUAL TO ITS CAPACITY.
  - LOAD IS BASED ON 20.0 OR 30 kWe AT LOAD BUSES AND ON THE LOAD ANALYSES (TABLES 8-2 AND 8-3)
  - PBC STANDBY SOURCE PROVIDES 2.7 kWt FOR EC/LS
  - ALL POWER LEVELS ARE SHOWN AS 24 HOUR AVERAGE kWe
  - REACTOR SYSTEM PROVIDES CONSTANT LOAD; STANDBY SYSTEM PROVIDES LOAD FOLLOWING CAPABILITY

Figure 3-24. Primary Standby System Integration – 20 and 30 kWe SNAP-8 and SNAP-2 (Advanced Design) 400 HZ PCS (Single or Multiple Sources)



- LOAD IS BASED ON SOURCE POWER OF 25.9 kWe AND THE LOAD ANALYSIS (TABLE 8-2)
- PBC STANDBY PROVIDES 2.7 kWt FOR EC/LS
- PARTIAL PARASITIC LOAD IS USED ONLY TO IMPROVE DYNAMIC RESPONSE OF SERVO SWITCHING VOLTAGE REGULATOR
- ALL POWER LEVELS ARE SHOWN AS 24 HOUR AVERAGE kWe
- REACTOR SYSTEM PROVIDES CONSTANT LOAD; STANDBY SYSTEM PROVIDES LOAD FOLLOWING CAPABILITY

Figure 3-25. Primary-Standby System Integration – 20 kWe Thermoelectric PCS



- LOAD IS BASED ON SOURCE POWER OF 12.0 kWe AND THE LOAD ANALYSIS (TABLE 8-1)
- RADIOISOTOPE HEATER IS USED FOR 2.4 kWe OF EC/LS HEAT FOR THE OPEN O_2 CYCLE SYSTEM
- PARTIAL PARASITIC LOAD IS USED ONLY TO IMPROVE DYNAMIC RESPONSE OF SERVO SWITCHING VOLTAGE REGULATOR
- ALL POWER LEVELS ARE SHOWN AS 24 HOUR AVERAGE kWe
- REACTOR SYSTEM BATTERY PROVIDES LOAD FOLLOWING CAPABILITY

Figure 3-26. Primary Standby System Integration – 10 kWe Thermoelectric PCS

The thermal requirements of the open-cycle EC/LS with the 10-kWe design are supplied by an auxiliary radioisotope heater.

The high-frequency dynamic conversion systems (SNAP-2 and Brayton, Figure 3-23) utilize multiple, isolated-source buses serving the individual alternators and a 260-Vdc link bus, which simplifies ac load sharing and isolates the alternator reactive power loop. The 400-Hz ac loads are supplied from this dc bus through a square wave inverter for essential loads and a part of the experimental loads, and through a sine wave inverter for those experimental loads which require the highest power quality. The 56-Vdc (±28) load buses are supplied directly through rectifiers from the source buses.

The 400-Hz dynamic system designs (SNAP-8 and advanced SNAP-2, Figure 3-24) reflect an increased efficiency because 400-Hz loads are supplied directly from the source bus. Because parallel operation of 400-Hz buses would not be practical, the control simplicity represented by a single source design (e. g., SNAP-8) is diminished as the number of sources increases. For the 20-kWe, dual-source, advanced SNAP-2 system, the loads on the individual buses are approximately balanced, and the dc load buses are paralleled with a voting type of control to force a capacity load on each source.

The electrical systems selected for the thermoelectric power conversion concepts (Figures 3-25 and 3-26) are based on dc transmission from the reactor configuration to MORL. Although this design is heavier and less efficient than the ac transmission system, the maintainability, switching complexity, reliability, and environment would be less desirable for solid state, dc-to-ac conversion equipment remotely located at the reactor. The required cooling equipment would offset the apparent weight advantage of ac transmission.

The electrical system associated with the 20-kWe thermoelectric system is the most efficient because dc loads are supplied directly from the source bus and the PBC standby source is used to supply peak load demands. The parasitic load is used to improve dynamic response characteristics during load changes; converter modules are switched out of service or into service as required to satisfy load demand variations below the average load. Because the 10-kWe thermoelectric system application utilizes a solar cell standby system which normally is not in operation, peak load demand is supplied by the battery. The resulting electrical system efficiency is reduced in view of the battery charging requirements.

The comparative weight estimates for the thermoelectric, SNAP-2, SNAP-8, and Brayton-cycle systems are presented in Table 3-20. The total weights are separated into the part located on the MORL, that located on the reactor configuration, and the transmission cables on the deployment boom.

The electrical equipment in MORL is concentrated in the operational control area; buses are located at the nearby centers of load. The concentration of equipment will facilitate the coldplating necessary for each module. It will also make reductions in weight and volume possible by the use of common partitions and enclosures for related equipment. The batteries will be located in a partially pressurized cabinet outside the occupied area, because of the venting requirements for toxic and corrosive electrolyte.

Table 3-20
ELECTRICAL SYSTEM WEIGHT SUMMARY

	10-kWe Thermo-electric	20-kWe Thermo-electric	20-kWe Brayton	20-kWe SNAP-2 1,800 Hz	20-kWe SNAP-2 400 Hz	30-kWe SNAP-8	20-kWe SNAP-8
Transmission cables(1)	850	1,700	400	450(2)	450(2)	600	400
Electrical system on MORL	3,012	2,524	2,950	3,500	3,020	4,493	2,661
Load control	(90)	(110)	(186)	(465)	(186)	(370)	(307)
Control, conditioning	(1,011)	(489)	(909)	(1,180)	(909)	(1,698)	(429)
Bus, distribution	(500)	(1,000)	(1,000)	(1,000)	(1,000)	(1,500)	(1,000)
Standby system, electrical	(1,411)	(925)	(855)	(855)	(925)	(925)	(925)
Electrical system (on reactor configuration)	300	400	66	Negligible	Negligible	220	~220

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1. Includes approximately 33 ft at reactor end and 25 ft at MORL end for access to electrical equipment.

2. Includes cable allowance for access to forward PCS units.

3.6.3 Standby/Emergency Power System Integration

The possibility of reactor system failure and the need for shutdown during maintenance periods impose requirements for a standby/emergency power system which must be capable of reliable operation up to 41.75 days at a reduced power level. Based on an evaluation of alternative designs, the Pu-238 Brayton-cycle (PBC) standby system was selected for the 20- and 30-kWe reactor power system applications, and a deployable solar cell and battery system was selected for the 10-kWe reactor power system. Both systems are designed for a nominal power requirement of 5.5-kWe unconditioned output.

3.6.3.1 Standby Power Requirements

Table 3-21 shows the average standby power requirements. An estimated 1,000 W of unconditioned power supplied directly from the PBC standby source bus provides for reactor system shutdown power requirements, including pump operation and makeup of heat losses from the confuguration. The heaters and/or pump motors can be designed to use power directly from the PBC source bus.

During standby/emergency, an open O_2 operating mode has been adopted in which CO_2 is vented to space and the Bosch hydrogenation unit is inactive. In this mode, 2.7 kWt (2.3 kWt for the 6-man design) are required for silica bed water desorption. Thermal power (2.7 kWt) is derived directly from the PBC standby system for the 20- and 30-kWe reactor system applications, whether the reactor is shut down or in normal operation. Thermal power (2.3 kWt) is derived from an auxiliary radioisotope heater with the 10-kWe system under all operating conditions. If the PBC standby system is inoperative or is shut down for maintenance, the 2.7-kWt requirement will be supplied by the reactor electrical system.

The standby power required at the power source is shown in Table 3-22. The present PBC system design rating is 5.5 kWe; the capability for an increase to 6.0 kWe or more by use of the contingency allowance is inherent. Furthermore, the normal orbital steady state power capability of the PBC system increases to 6.0 kWe at beginning of life and 5.8 kWe at end of life without design change. The solar cell and battery system is sized to provide a 5.5 kWe minimum with normal degradation.

3.6.3.2 Load Profile Integration

The control system previously established (in the MORL baseline design) for the single 5.5-kWe PBC system readily adapts to load following. It can also be paralleled with the primary system by means of both high-voltage and load-voltage dc links for supply to ac and dc load buses, respectively. Comparisons of the overall performance during normal condition and during standby, emergency, and reactor-shutdown conditions, favor a constant or base power concept for reactor power system operation with load-profile following by the PBC standby system. The solar panels, deployed only when needed, are not available for load-profile following. Therefore, it is necessary to provide a 107 amp-hr, 56-V battery, a parasitic load, and an energy management control system in the reactor power conditioning system, (Figure 3-26).

Table 3-21

AVERAGE EMERGENCY POWER REQUIREMENTS (KWE)

	Repair/Replacement Period						
	First 16.75 Days(1)			Next 24 Days[2]			
Using Subsystem	Dc		Ac	Dc		Ac	Remarks
Guidance and control	43		24	43		24	Assumes gravity gradient (Earth-centered) orientation except for brief excursions to bellydown for orbit keeping.
Communications and data management	38		-	38		-	
EC/LS							
Thermal requirement	Note(3)		Note(3)	Note(4)		Note(4)	Provided by Pu-238 heat source or PBC system waste heat.
Water electrolysis	1,480(5)		-	1,480		-	Assumes water electrolysis to obtain emergency O_2 for six men.
Miscellaneous	30		750	30		750	Assumes all men in one compartment. Would be 355/520 Wdc and 840/880 Wac with O_2 regeneration for 6 to 9 men, respectively.
Displays, controls, and instrumentation	100		-	100		-	
Logistic vehicle and maintenance	1,080		150	670		150	Assumes docked Apollo vehicles require 410 W each.
Lighting and miscellaneous	-		50	-		50	
Propulsion	1		-	1		-	Assumes nonelectric propulsion.
Reactor system shutdown power allowance		1,000(6)			1,000(6)		Preliminary estimate--depends on PCS system selected
Total	2,772	1,000	974	2,362	1,000	974	Load bus requirement.

Notes:
1. Nine men
2. Six men; three men sent home
3. 2.7 kWt for open cycle O_2 and 4.0 kWt for closed cycle O_2
4. 1.8 kWt for open cycle O_2 and 2.66 kWt for closed cycle O_2
5. Three men breathe stored O_2
6. Unconditioned 1,067 cps ac or dc power

Table 3-22

STANDBY POWER REQUIRED AT POWER SOURCE (W)

20- and 30-kWe Systems	First 16.75 Days	First 41.75 Days Next 24 Days
Dc load	2,772	2,362
Reactor shutdown power (unconditioned)	1,000	1,000
Ac load (400 Hz)	974	974
Subtotal	4,746	4,336
Power conditioning loss*	844	744
Load at source	5,590	5,080
Contingency	210	420
Source design power	5,800	5,500

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*Transmission and control efficiency = 95.5%
Dc conditioning efficiency = 85%
Ac (400 Hz) conditioning efficiency = 91.3%

In each system concept, the standby/emergency load is essentially constant; the battery remains nearly fully charged during standby operation. Therefore, the battery is available for restart, control, and life-essential power for short periods of approximately 2 hr at 2 kWe. Reactor power system and standby power system ac subsystems are interlocked to avoid inadvertent paralleling. However, dc load is shared at the dc-load buses and ac load can be shared in systems using the 260-Vdc link bus. This permits independent load following by ac and dc subsystems without changing either the balance or ac/dc load division and thereby improves regulation and transient performance. The 400-Hz, single-source system can operate in two modes: (1) with a standby power system assuming overloads by supply of dc power to the dc-load bus and with all ac supplied by 400-Hz dynamic source, or (2) with the ac load-bus split (under control of the 3-way interlock) and with one-half the power supplied by the standby source. This latter mode can progress to a limit in which all ac is supplied from the standby source and all dc from the reactor source to permit safe maintenance within the ac conditioning subsystem. This mode also provides simple, transient-free transfer to standby power in preparation for primary system shutdown or power conditioning system maintenance.

3.6.4 Electrical System Operation and Control

This section describes the operating characteristics of the selected reactor and standby power system configurations, the control subsystems and their functions, and the activation and shutdown procedures applicable to the power control and conditioning system.

3.6.4.1 Operating Characteristics

Two major reactor/standby electrical system operating concepts were compared: (1) a standby system to supply base load with the reactor system for peaking load, and (2) a reactor system to supply base load with the standby system (or battery, in the case of the 10-kWe system design) for peaking load. The latter system was found to provide a higher overall electrical system efficiency, and hence, a lower MORL surface area requirement for the EC/LS and standby system radiators. Moreover, the control requirements for a constant base load reactor power system design are less complicated than those associated with a load following design. For these reasons, the latter operating mode was selected.

In relation to the 20- and 30-kWe reactor power systems, the PBC standby power source follows load peaks within its nominal design capacity of 5.5 kWe at the alternator. This value corresponds to approximately 4.39 kWe at the load buses. These systems would require battery support of 0.61 kWe at 54% efficiency to meet the 1-hr daily peak bus loads of 25 and 35 kWe for the 20- and 30-kWe system ratings, respectively. However, because the higher electrical efficiency of the 20-kWe (nominal) thermoelectric system results in 22.5 kWe available power at the load bus, this configuration needs only 2.5 kWe from the PBC standby system during peak loads. The surplus power may be either dumped or used for thermal power requirements. Because the standby source is not normally in service for the 10-kWe reactor power system design, the peak loads are supplied by the battery. All systems require battery supply to meet the momentary peaks of 20, 30, and 40 kWe, respectively, for 5 min./day.

The EC/LS system heating loads require the provision of 6 kW for a 9-man, closed oxygen system associated with the 20- and 30-kWe reactor power system applications. Of this total, 2.7 kW is continuously supplied by regenerative heat transfer directly from the PBC standby power source. The remaining 2.3 kW is supplied electrically from the reactor power system, inasmuch as this power is not required under standby (reactor shutdown) conditions. By supplying this electrical power from the reactor system source bus rather than the conditioned power load bus, an increase in efficiency is obtained by eliminating power conditioning losses. The net gain in overall electrical system performance is shown in Table 3-23, which compares system efficiencies for the reactor system load following and constant base load operating modes as previously discussed, and for the selected system design which provides for EC/LS heater supply from the source bus, as well as the constant-base load reactor operation.

The EC/LS heating requirement for a 6-man open oxygen cycle associated with the 10-kWe reactor power system amounts to 2.3 kWt. This power is supplied by a separate Pu-238 heater in the EC/LS system, inasmuch as the solar cell/

Table 3-23

SYSTEM EFFICIENCY COMPARISONS, SELECTED SYSTEMS

System	Reactor System Load Following (%)	Reactor System Constant Load (%)	Reactor System Constant Load (with EC/LS Heater Bus) (%)
10-kWe thermoelectric	81.8	NA	NA, use Pu-238 heater and open oxygen cycle
22.5-kWe thermoelectric	83.0	86.2	87.0
20-kWe SNAP-2	78.8	81.4	83.4
20-kWe Brayton	78.8	81.4	83.4
30-kWe SNAP-8	82.9	84.5	85.7
20-kWe SNAP-8	82.0	84.5	86.2

battery standby source is not normally in service. Provision for this load electrically from the reactor power system would require an increase in output power rating.

3.6.4.2 Operational Control

The operating concept for the integrated reactor and standby system requires an adaptive control system for the PBC standby power system. All load variations must be sensed and compensated for by that control system while constant load is maintained on the reactor PCS. Table 3-24 shows the control system response for each operating condition.

A parasitic load-control system was selected for each reactor power system and for the PBC standby power system. The reactor PCS parasitic load control system provides a priority dc speed sensor or bus voltage sensor signal to the bias balancing circuitry in the load-control system module. This module is common to both reactor and standby system dc voltage regulators. The signal raises the voltage regulator output on one system and lowers the regulator output voltage on the other system to transfer load from the lower voltage source to the higher voltage source. This signal voltage and the resultant regulator control bias transfers load to the standby system if the reactor dynamic power system speed (or 20-kWe thermoelectric system bus voltage after all switched elements are placed in service) is below normal, corresponding to Condition 1 shown in Table 3-24. If the reactor dynamic power system speed (or 20-kWe thermoelectric system bus voltage after all switched elements are removed from service) is above normal, the control bias will be changed to transfer dc load from the standby system to the reactor power system. This corresponds to Condition 5 on Table 3-24. In each case, when the reactor power system speed (or 20-kWe thermoelectric system bus

Table 3-24

CONTROL SYSTEM OPERATION

Condition	Reactor System Load	Standby System Load	Control Reaction Signal
1	High	High, normal, or low	Transfer dc load to standby power system Proceed to Condition 2, 3, or 4
2	Normal	High	Battery support for vehicle dc load bus
3	Normal	Normal	No control action within dead band
4	Normal	Low	Charge battery Activate parasitic load if battery is fully charged
5	Low	High, normal, or low	Transfer dc load to reactor power system Proceed to Condition 2, 3, or 4

voltage) is normal, the control system will take appropriate actions to balance the power demand on the PBC standby system as indicated in Table 3-24 for Conditions 2, 3, or 4.

Similar control voltage signals are derived from the 10-kWe thermoelectric PCS main bus. During normal operation, however, the solar panels are not deployed. The reactor parasitic load-control system therefore commands battery support or battery charging, rather than reactor system dc regulator bias changes. Such commands are implemented by an energy storage-control system.

The integrated reactor system and standby system load control operation is dependent on the load following capability of the standby system and its control or on the battery energy storage control system for the 10-kWe thermoelectric system design.

In the dynamic systems, the standby turbine speed signal appears as a proportional dc voltage at the frequency transducer output. If this voltage is lower than 0. 25% below normal for rated speed, Condition 2, a proportional control signal, commands the battery to support vehicle load because the reactor and standby power systems are both fully loaded. The voltage of the battery output voltage regulator rises above 28 V as required to force the battery to assume sufficient dc bus load when the standby PCS is below normal speed.

When the battery remains in service and the PCS speeds are returned to values within the control dead band (±0.25%), Condition 3, the pulse-width-modulated battery voltage regulator provides normal output voltages of ±28 Vdc to each side of the 3-wire dc load bus.

If the speed of the standby power system rises above its 1/4% dead band, Condition 4, battery support for vehicle load is first reduced, then terminated. Battery charging is then initiated to the degree necessary to restore full load. If an overcharge signal appears from any cell, the battery charger switches off until the condition subsides, then restores charging if an excess of PCS power is still available. When the battery becomes fully charged and excess standby system power is available, the standby system parasitic load dissipates the excess power.

When the reactor power system PCS speed rises above the dead band and its dc regulator is at maximum voltage (thereby assuming all MORL dc load), it automatically activates the reactor system parasitic load control to accomplish sufficient power dissipation to return the speed to the normal range. The standby system power is then delivered to the battery or is dissipated in the standby parasitic load.

For the thermoelectric systems, the control system is similar with the exception that an actuating signal derived from the source bus voltage is used instead of a turbine speed frequency-to-voltage transducer voltage.

3.6.4.3 System Activation and Shutdown

The electrical load and speed control systems for all conversion systems are activated by the application of a speed or voltage sensor signal to the control system. Parasitic load control is activated by the application of power to the redundant reference voltage rectifiers. Instrumentation and status display systems are activated by dc power from the battery, followed by a signal derived from the controlled or instrumented parameter. The power conditioning system is activated by circuit breaker and/or control relay operation. These are selected manually to establish the desired conditioning system configuration. The miniature bus panel and status display arrangement facilitates orderly and logical activation, rearrangement, and shutdown of all electrical systems.

Activation and shutdown procedures are distinctly different for dynamic and static (thermoelectric) conversion systems, although no essential differences exist within each classification. The dynamic systems require a programmed control sequence which takes into account the acceleration period for rotating components, followed by a period of thermal stabilization before electrical load is applied. The starting cycle is controlled by speed sensors in the rotating units. When the system is thermally stabilized, the main generator power control and protection system circuit breaker is manually closed to energize the MORL main bus. Thereafter, load is applied by activating power conditioning modules and switching vehicle loads on the dc and ac load buses.

The dynamic system shutdown procedure includes a transfer of essential loads to the standby system or to the remaining conversion units of a multiple source system. Transfer to the standby system consists of switching nonessential loads and/or buses off, then switching the reactor power conditioning modules (rectifiers and inverters) off. The rotating units then revert to parasitic load control and are stopped. If only one of several rotating units is to be removed from, or replaced in service, and the bus load is within the capability of the combined remaining units and parallel operating standby system, then the related ac loads are transferred to adjacent buses (400-Hz sources) or left on the active ac load bus by switching the associated high voltage rectifier off. The unit to be removed then reverts to parasitic load speed control and is stopped.

The thermoelectric systems are activated and shut down more easily because no speed control is necessary and operation at partial or no load presents no problems. The system can be started either under load or unloaded conditions, but some loads could be damaged by low voltage. Therefore, the preferred procedure is to activate the conversion system, allow time for thermal stabilization, switch on the power conditioning modules, and then apply the vehicle loads. The startup time for thermal stabilization tends to be quite long unless an external power source is used to preheat the fluid. A reverse sequence is followed for system shutdown. Load transfer is accomplished by manual circuit breaker operation.

During shutdown of the standby power system, the sustained peak load and average load capability is limited to the rated power of the reactor system alone, except for the 10-kWe thermoelectric system which does not at any time depend on the standby system. The normal load following capability is provided to this system by the battery, which is recharged during underload periods. Therefore, for all dynamic reactor systems (SNAP-2, SNAP-8, and Brayton cycle), a reduction of vehicle load is automatically compensated for by an equal amount of parasitic load dissipation during standby system shutdown. For the 20-kWe thermoelectric system, reduced load is compensated for automatically by a reduction of connected converter modules under control of the servo switching systems and, if this is not sufficient, by parasitic load power dissipation.

3.6.4.4 Transient Performance

The normal load step changes are shared among the multiple-source PCS alternators. Short circuit current and power may or may not be shared, depending on the short circuit location. Those faults which cannot be shared, however, generally represent faults in major conditioning modules, buses, or feeders. These generally require component removal for repair. The tripping system should, therefore, operate to completely isolate the affected source alternator from the short circuit. Rapid tripping is ensured in this case by the low impedance to the fault. This action places an additional load on the remaining sources in multiple systems or on the battery in either multiple- or single-source systems. The control system design, therefore, considers fault current sharing, battery support for load and short-circuit currents during fault clearing, high short circuit current for rapid tripping, and power source isolation and removal as normal modes of response.

The impedances to short circuit on the load buses are lowered by multiple sources operated in a load sharing arrangement. This method of design provides correspondingly improved normal power quality and improved fault isolation by increasing the tripping current available, thus improving the sequential tripping capability and rapidity.

Within the limits of normal design accuracy, it is reasonable to assume a maximum exciter capability of three per unit fault current from Brayton-cycle and SNAP-8 power sources. The SNAP-2 alternator is rated for 5.6-kWe maximum. Therefore, the excitation capability would normally be for 9 kWe (3/unit) to a short circuit, or perhaps uprated to 10 kWe. This represents 2/unit on the 5-kWe nominal power base used for this study. This value is also a reasonable limit when the limited inertial energy storage capability is considered, and when the size of the rotor and magnetic paths are considered. Excitation capability would probably be limited by rotor stalling if increased short-circuit capability were attempted.

The design operating point for each thermoelectric element was set at approximately 50% of the short circuit current, which can be sustained indefinitely at 2/unit with no degradation in performance or appreciable converter temperature rise. Short circuit protection for the thermoelectric system, therefore, is concerned with sensing, removing, and replacing faulted circuit sections no longer serving the load buses. The servo switching systems will be commanded to connect additional converter modules, but short circuits will normally be tripped before these are switched into service.

The most hazardous result of a control system failure (that is, turbine runaway because of loss of load) is prevented by redundancies in the control system and also by an independent backup speed sensor which operates the turbine inlet fluid valve, thus stopping the rotating unit.

Turbine stall as a result of excessive load or PCS malfunction is prevented in the following three ways. (1) Transfer of excess load is made to the standby system alternator and/or battery by the load control system. (2) When load transfer, followed by automatic shedding of nonessential load buses, is insufficient to restore turbine speed and when 90% speed is reached, the main alternator circuit breaker is tripped, leaving only the parasitic load and its control system. This removes sustained main bus faults from the source, but maintains turbine operation while the fault is removed manually. (3) If these actions do not permit turbine speed recovery, a time delay relay trips the turbine inlet fluid valve to stop the PCS. This is based on the logic that the parasitic load, transmission line, source bus, alternator, or PCS must have sustained a fault or malfunction requiring major maintenance.

The control system selected for the thermoelectric reactor power system operates by switching elements into or out of service in response to the output voltage sensed at the MORL main source bus. A remotely driven proportional controller is used to actuate hermetically sealed electromagnetic reverse current relays located in the selected converter module circuits. This servo system is not rapid enough to affect or be affected by short circuits when the protection devices operate normally. The servo system is also not as rapid in response as the load switching rate. Therefore, a parasitic load and control system serves to improve the dynamic regulation by adjusting the total load in approximately 100 sec; it also provides a follow-up driving signal to the servo thermoelectric control units. When the servo system reaches the end of its control range, a signal is provided to the load-control system module to shift load to or from the standby system (20-kWe system) or the energy storage control system battery (10-kWe system).

3.6.4.5 Thermoelectric System Response Characteristics

The probability of an open circuit in a tubular module of the 20-kWe thermoelectric system is negligible in comparison with the observed occurrence of short circuits. Open circuits or relatively high resistances are much more likely to occur in the circuits external to the modules. The protection device selected for this system is a reverse current relay, which also serves as an on-off switching control device for system voltage regulation.

The effects of a short circuit within a tubular module depends partly on the electrical system arrangement. With the electrical system grounded, a short circuit to the cladding will cause the loss of output from two tubular modules. If the system were left ungrounded, two shorts would be required to cause an electrical failure. However, other benefits of grounding to the circuitry and to the protective system dictated this choice of system design.

For the PbTe thermoelectric generator operating between average NaK temperatures of 1, 150° and 550°F, the reduction in thermal load between matched load operation and no load (open circuit) is approximately 20%. In going from matched load to short circuit, the thermal load increases approximately 15%. Using these values, the changes in electrical load caused by loss of converter modules were evaluated. The loss of two tubular modules would result in a reduction of only 1.5% of the power supply and would probably show up only as a decrease in the parasitic load.

The effects of open and short circuits on the 10-kWe direct radiating system are somewhat different from those on the tubular modules, but the overall effects are similar. The basic electrical circuit is an array of three parallel strings of couples with cross ties to minimize the effects of open circuits. Each coolant loop includes many such arrays, and therefore, the smallest controllable unit consists of several arrays. Each controllable unit is provided with a reverse current relay. An open circuit in a single couple or two parallel couples has no observable effect on the power output because each string is capable of carrying the increased current density caused by this type of failure. The loss of a complete array is still a small effect because it may typically consist of 30 to 50 couples, supplying 20 to 25 W at less than 2 V. The smallest controllable unit of power is in the 100- to 500-W range. Because a short circuit could cause the loss of a complete unit, reliability requirements tend to promote the use of small units. Therefore, any one failure has a small effect on the system.

3.6.5 Instrumentation, Control, Display, and Protection

The electrical system instrumentation, control, and display are incorporated in a miniature bus control panel, on which the status indicator lamps and controls are arranged schematically for ease of subsystem analysis and operation. Selector switches and read buttons are used with a minimum of meters to obtain operating information on secondary parameters. Primary parameters are provided with continuous displays with alarm signals and/or annunciators when necessary.

The following criteria, in conjunction with standard human engineering design criteria, were derived for use in the control panel design:

1. Critical controls are self-locking or guarded to prevent inadvertant activation.
2. Controls that must be operated in precise sequence to avoid equipment damage or possible injury to the crew are sequentially interlocked.
3. Controls are operable by a space-suited crewman.
4. Display information is directly usable and does not require decoding.
5. All individual warning and caution signals are visual. Master warning and caution signals are visual and audible.
6. The displays are adjacent, as nearly as possible, to the respective control.
7. Controls and displays are functionally grouped.
8. Master warning and caution displays are located throughout the laboratory.
9. All critical switches of the system are lighted.
10. The control panel is designed to use standard hardware, thus minimizing the need for new control and display requirements.
11. The control and display system is designed for a maximum of automatic operation.
12. Manual over-ride control functions are provided for essential and for discretionary functions.

The reactor primary control parameter is the coolant outlet temperature, with a specified dead band. Long-term adjustments necessary to accommodate a load profile of lower demand than anticipated or higher conversion system output early in the mission (because of the degradation allowance) can be most easily made by controlling the temperature set point or the PCS feed flow (Rankine cycles).

The evidence of either lower demand or higher output will be an increase of excess power. The speed control of dynamic systems will sense a resultant increase of speed and will automatically increase the battery charging rate and initiate or increase parasitic load power dumping. Rapid battery recharging is a desirable reaction when it is possible. Therefore, this charging mode is adopted. Parasitic load dumping is an inefficient mode of operation and is, therefore, not desirable for a prolonged period. It is only an acceptable steady state operating mode for short periods; but it also is a practical means, both for suppressing transient effects and for accommodating normal load switching and short-term cyclic variations. Instrumentation is provided to notify the operator when power dumping through the parasitic load is in progress or, alternatively, when battery power is in use to support MORL electric loads.

System protection is based upon the use of electromagnetic circuit breakers. Major three-pole circuit breakers and feeder circuit breakers use auxiliary tripping power from the battery to avoid reliance on sustained circuit voltage during solid short circuits. Branch circuit breakers have sufficient impedance for self-activation. Reverse-current relays are used to prevent backflow of dc power. Diodes are used to suppress voltage transients in solenoid coils and other inductive circuits.

Power system conditioning modules will be designed for self-protection. Each will have the capability to limit and withstand short-circuit currents for a protective-device coordination period, followed by self-tripping before internal damage occurs.

Section 4

MISSION AND SYSTEM INTEGRATION

MORL is a versatile facility for experimental research which provides for the following objectives:

1. Simultaneous development of space-flight technology and man's capability to function effectively under the combined stresses of space environment for long periods of time.

2. Intelligent selectivity in the mode of acquisition, collation, and transmission of data for subsequent detailed scientific analyses.

3. Continual celestial and terrestrial observations.

The MORL configuration, less the reactor power system, in Figure 4-1 shows the location of the hangar test area (Section D-D), control deck (Section C-C), centrifuge, flight crew quarters (Section B-B), unpressurized equipment bay (Section A-A), and an external boom. This boom is normally used as an experimental handling boom for a number of experiments which must be conducted at a distance from the laboratory. The boom can also be used to transfer replacement parts from the logistics vehicle to the unpressurized equipment bay. The configuration as shown can accommodate a 10-kWe power system; however, it must be extended 5.2 ft to accommodate the EC/LS and standby power system radiator area for a 20-kWe system. Use of a 30-kWe reactor power system requires either a 14-ft MORL elongation or use of deployable EC/LS radiators.

Three orbits were specified to satisfy the potential of the MORL for this broad range of mission objectives: (1) the baseline 164-nmi circular orbit at 50° inclination, (2) a 164-nmi circular polar orbit, and (3) a synchronous orbit at 19,350 nmi. With the application of a reactor power source the altitude has been increased from 164 nmi to 218 nmi for the baseline and polar orbits.

Application of a 20- or 30-kWe reactor power system as the power source for the MORL allows permanent accommodation of a 9-man crew, thereby considerably broadening and expanding the experimental capabilities of the station. A 9-man crew allows 73.7 man-hours/day for experimentation as compared to 45.8 man-hours/day with a 6-man crew. The increase in available power also allows the inclusion of experiments requiring relatively high power, such as those in the areas of microwave radiometry and radar observations. Of the 157 experiments proposed for the MORL, 41 are sensitive to the effects of radiation. However, the radiation exclusion zone provided by the reactor shadow shield is sufficient to prevent any deleterious effects arising from the reactor source.

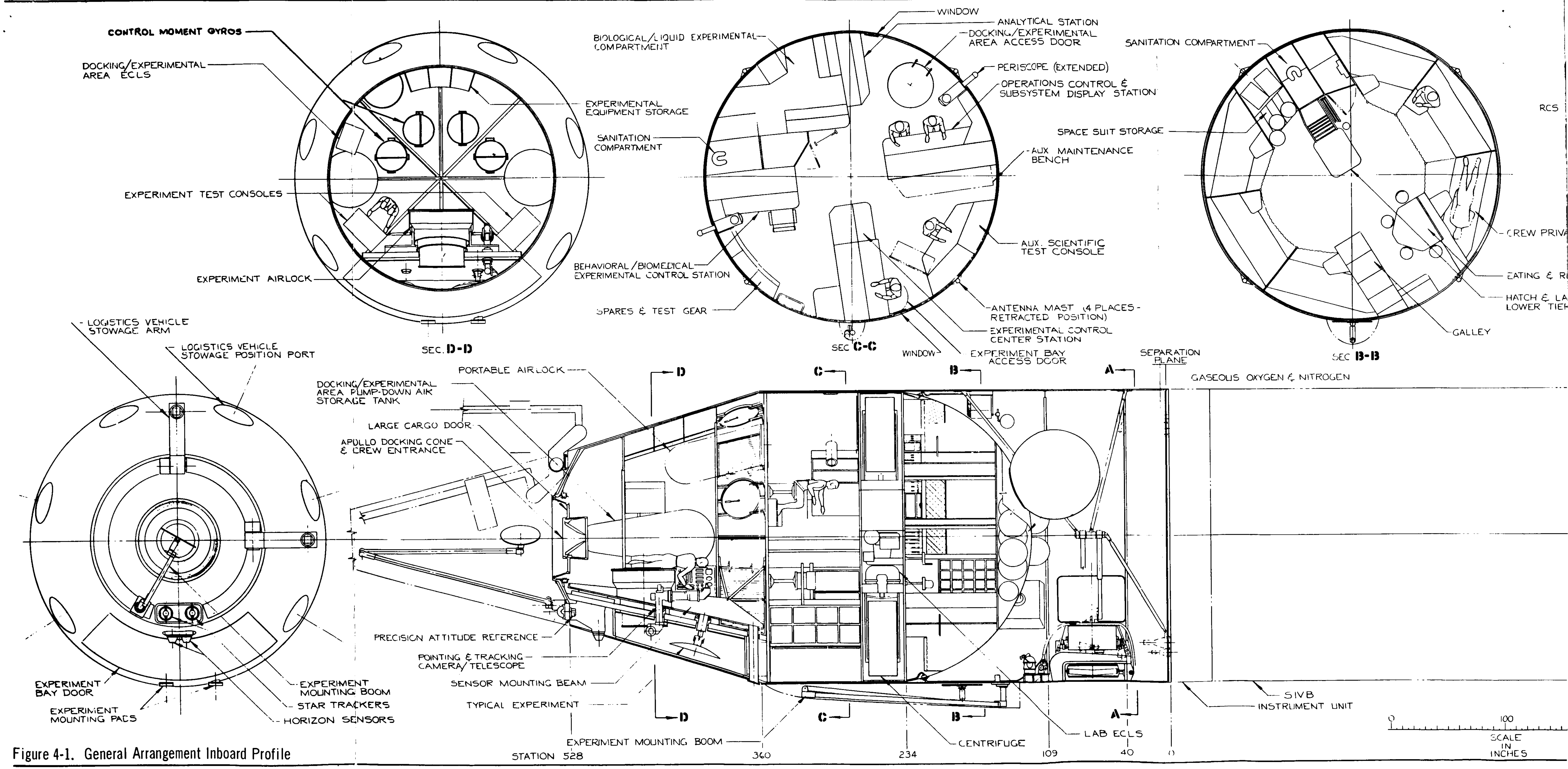
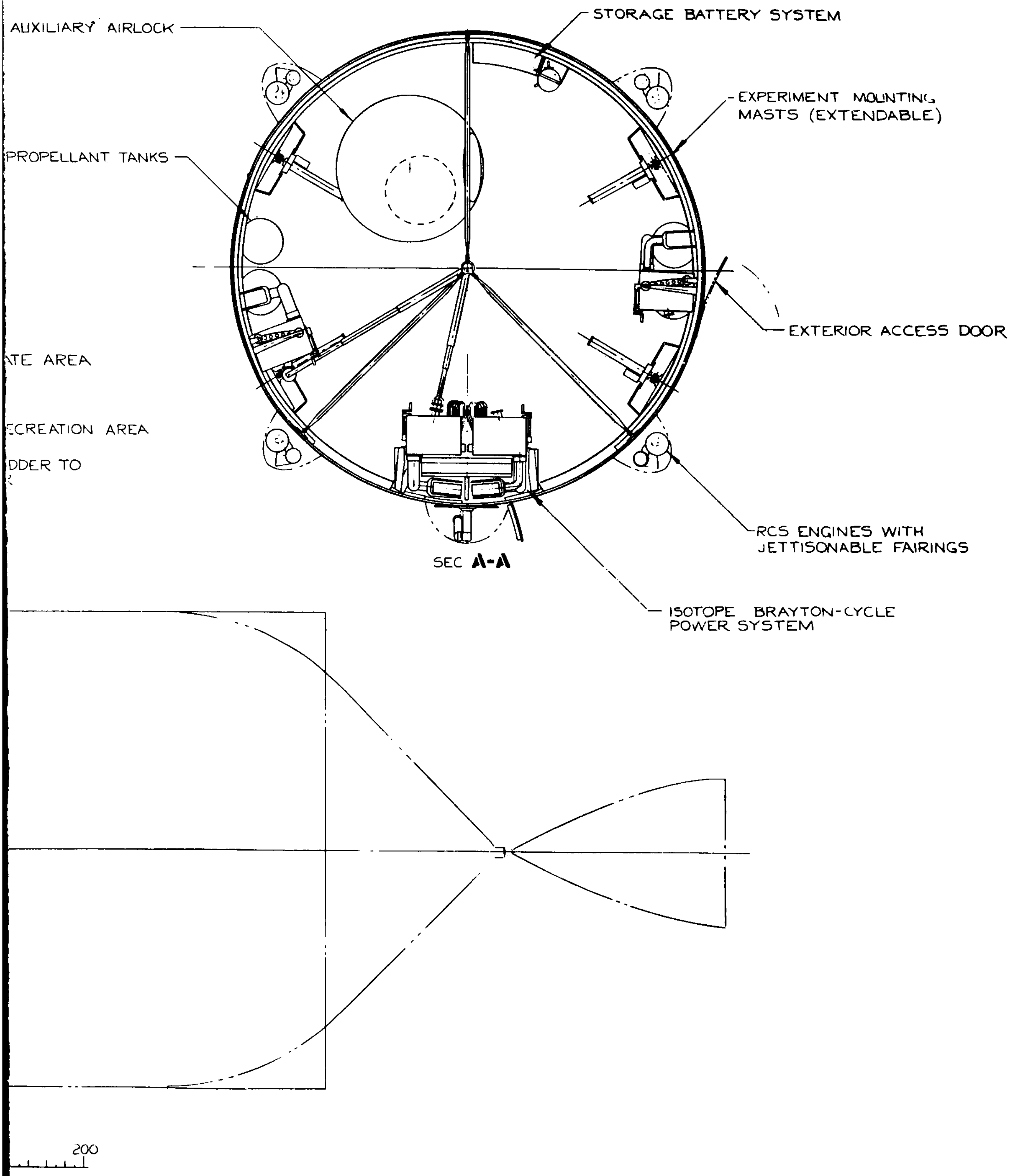


Figure 4-1. General Arrangement Inboard Profile


AUXILIARY AIRLOCK
PROPELLANT TANKS
ATE AREA
ECREATION AREA
DDER TO
STORAGE BATTERY SYSTEM
EXPERIMENT MOUNTING MASTS (EXTENDABLE)
EXTERIOR ACCESS DOOR
RCS ENGINES WITH JETTISONABLE FAIRINGS
ISOTOPE BRAYTON-CYCLE POWER SYSTEM
SEC A-A
200

4. 1 OPERATIONS

Mission-oriented operating requirements and reactor power system operations including provisions for maintenance are presented in the following paragraphs.

4. 1. 1 Launch Operations

Launch operations for the MORL/reactor power system (integral launch) and the replacement reactor power system (replacement launch) are conducted at KSC and from the ETR. Prelaunch operations for the MORL occur in the Merritt Island Launch Area (MILA) industrial area at KSC. It is necessary to use reactor power simulation for checkout because of the operational and safety problems associated with reactor operation and cooling of the reactor power system in the Manned Spacecraft Operations (MSO) building. Prelaunch checkout of the reactor power system will probably take place in a new separate building located near the MILA industrial area. The staging of the reactor power system, MORL, and MLV-SAT IB-11. 5, as well as the all-systems checks and terminal countdown are expected to require approximately 60 working days at Launch Complex 34, which has to be modified to accommodate an upgraded Saturn IB. The fuel block of the Pu-238 Brayton standby power system for 20- and 30-kWe reactor power system configurations is installed in MORL just prior to initiation of the final countdown. Shortly before launch, MORL is transferred from external to internal power supplied by the standby power system, thereby supplying the on-board systems which are activated at launch.

The replacement reactor power system/Apollo prelaunch operations, which also occur in the MILA industrial area, require approximately 68 working days. Launch operations for the MORL logistic vehicles occur on Launch Complexes 34, 37A, and 37B. One particular requirement imposed on the vehicle launch complex system is quick reaction time in the event of an unscheduled logistic operation. However, the replacement reactor power system cannot be stacked on the product-improved Saturn IB and remain in a T-3 readiness state until required because of (1) component and/or material shelf-life limitations of the Saturn IB and Apollo, and (2) only two launch pads, Launch Complexes 34 and 37A, can be involved in logistics operations at any given time. Meanwhile, two logistic vehicles must be available at all times with a payload consisting of the MORL multimission cargo module and the Apollo. As a result, a replacement power system launch requires unstacking the multimission cargo module of the routine logistics payload and then replacing it with the replacement reactor power system. This restacking operation requires approximately 6 days; consequently, 12 days are required to accomplish rendezvous when countdown, launch, and rendezvous are also considered. To facilitate this 12-day reaction time, the replacement reactor power system must be held in a T-1 to T-2 day readiness state for prolonged periods either in the MILA industrial area or adjacent to the launch complex in an environmentally controlled facility with provisions for monitoring.

Operational differences between the baseline and polar orbits result primarily from the use of the Saturn V as the launch vehicle. The following launch operation criteria are applicable for the polar mission: (1) Saturn Launch Complex 39 at KSC is available to the program and will be used, and (2) launch pad turnaround times, based on the capability of the vertical assembly building and mobile transporter concept are 5 weeks for the vertical assembly building and 1 week for the launch pad. While the Saturn IB launch complexes require assembly, checkout, and countdown of the vehicle on the launch pad, a mobile concept is employed on Launch Complex 39, the Saturn V launch facility. The mobile concept provides for assembly and checkout of the vehicle at a location removed from the launch pad, the vertical assembly building. At the launch pad, a mobile service tower is employed for final servicing of the vehicle. The launch azimuth to achieve the replacement reactor power system mission profile for the polar orbit is 44.5°. The replacement system payload is initially inserted into a 100-nmi, 50°-inclination phasing orbit by the Saturn V launch vehicle. The S-IVB is then used to rotate the orbital plane to a 90° inclination and to inject the spacecraft into a 100- to 218-nmi elliptical orbit, followed by orbit circularization at 218 nmi. Various trajectories, including those described, were analyzed with respect to the initial MORL/reactor power system launch into polar orbit; however, the described trajectory and all trajectories exhibiting northward doglegs did not exhibit the required payload while being compatible with minimum range safety requirements. The only other feasible launch trajectory providing the required payload capability exhibits a 146° launch azimuth, which results in a Cuban and Panamanian overfly. However, launch trajectories of this type have been flown in the Courier and Tiros programs after obtaining the necessary approvals. In addition, only the initial unmanned-MORL/reactor power system launch requires this launch azimuth because all subsequent manned replacement launches utilize the routine MORL 44.5° launch azimuth.

4.1.2 Orbital Operations

Orbital operations include activation, flight crew functions, command and control, logistics operations, tracking, and data acquisition. The boarding operation includes the period from the initial manned acquisition and entry into the space station until the permanent flight crew complement of six to nine men is on board. An initial crew of 3, especially trained for activation of the laboratory (including the reactor power system) boards the laboratory within 6 to 19 days (24 days to reactor startup) followed by full manning 45 days after MORL launch. A minimum of six programmed reactor power system shutdowns and subsequent restart operations per year has been established. This number is based on the maximum number of logistics launches per year envisioned for a nine-man crew, assuming that the reactor may be shut down during rendezvous, although reactor shutdown is not considered necessary. Regarding maintenance operations, four shutdowns per year has been established as a guideline where the specified shutdown period compatible with radiation dose tolerances for any given operation is limited to 5 days. It is conjectured that if maintenance cannot be accomplished within 5 days, the required repair would be of such a complex nature as to require a complete reactor power system replacement. The reactor disposal method compatible with MORL mission criteria for logistics disposal is entry and disposal into the Pacific Ocean, accomplished as follows:

1. Release of the reactor power system configuration from the boom attachment.

2. Initial separation of MORL and the reactor power system by a distance adequate to meet safeguard standards by thrusting of the MORL and/or the reactor power system configuration. Thrusting of the reactor power system is provided by the vernier control rockets attached at the base of the power system configuration.

3. The reactor power system configuration remains in orbit until it reaches a deorbit location compatible with a preferred depository area over the ocean.

4. Deorbit is achieved by firing solid propellant rockets in the proper direction so that the system enters the atmosphere at a shallow entry angle, thereby effecting intact entry. Assurance of impact within a 3σ CEP in an isolated area of the Pacific Ocean can be made.

4. 1. 3 Reactor Power System Operations

Prelaunch heating of the reactor power system is provided by ground support equipment, and consists principally of electrical heating applied at specific locations during checkout and until the time of launch. The NaK coolant in the primary system, intermediate loop, and radiator loops is circulated during the prelaunch and launch phase to maintain the fluid in a liquid state and to equalize system temperatures. For the 20- and 30-kWe reactor power systems, the associated PBC standby power source is cooled by a water circulating system. No ground cooling is needed for the 10-kWe reactor power system configuration, which uses a solar cell/battery standby power source. After ground checkout is completed, the electrical umbilicals are disconnected, and the reactor power systems are placed on internal control with the PBC standby power system providing the electrical power for the 20- and 30-kWe reactor power system configurations and the battery power source for the 10-kWe system.

For the 20- and 30-kWe systems, the PBC standby source is used as the electrical power supply for station keeping until the station is manned. Battery power sustains the station for the 10-kWe system application until orbit is attained, at which time the solar cell panels are deployed remotely from the ground. The standby power source also supplies power to maintain the reactor power system configuration within allowable temperature limits until reactor startup (24 days maximum after launch).

To accommodate the docking of the initial manned logistics vehicle, initial deployment of the reactor power system is accomplished remotely from the ground, using the MORL stowage arms and the deployment boom. The reactor power system configuration is separated from MORL, using stowage arms on the front of the MORL which are attached to the inside of the power system configuration. The configuration is then moved forward to clear the conical section of MORL and rotated on the stowage arm to clear the docking port. The logistics vehicle then docks and MORL is manned. Under local manual control, the deployment boom is unfolded, checked out, maneuvered into position, and attached to the reactor power system during the launch and premanning phase is then disconnected and replaced by the normal electrical connection to cables on the deployment boom. Power is supplied from the standby power source to the pumps in the primary system, intermediate loop, and radiator loops as required to maintain NaK (and SNAP-8 lube-coolant fluid) in a liquid state prior to reactor startup. The reactor power system configuration is then transferred to the deployed position.

During the checkout phase immediately before initiation of reactor startup, the standby power source is used to heat the radiator fluid and sustain it at a temperature of 200°F with the thermal shields in place. This initial heating is required to prevent the NaK in the radiator from freezing in the interval between removal of the thermal shields and the time at which the reactor is at a self-sustaining power level. After the reactor startup procedure is initiated and at a predetermined time before reactor criticality is attained (approximately 30 min), the thermal shields are removed from the radiator surface. Between the time of thermal shield removal and attainment of a self-sustaining output power level from the reactor, the radiator coolant is maintained in a liquid state by the continued supply of power from the standby power source.

4.1.4 Maintenance Requirements

In developing the reactor power system designs, permanently installed redundant capacity is applied to meet the overall reliability and lifetime objectives, rather than relying on substantial component maintenance or replacement. This approach is motivated primarily by the following two considerations:

1. Uncertainties in the extent to which maintenance can be successfully performed in space from the standpoint of facilities, down-time procedures, special tools, equipment requirements, and personnel capabilities.

2. Conflicts with the experimental program and other normal laboratory functions which may arise from extensive maintenance requirements, as well as the increased spectrum of specialized skills and qualifications which may be required of laboratory personnel. To attain mission objectives most effectively, a greater premium is placed generally on manpower allocation and use in meeting experimental requirements than on the weight penalties associated with increased redundancy to reduce maintenance of the power system.

For these reasons, the reactor power system designs are predicated on a minimum of operator attention commensurate with safety, supervisory control of system operation, and preservation of the satisfactory operating condition of the systems. Although the feasibility and utility of specified maintenance operations beyond these minimal requirements cannot be accurately defined at this time, it is desirable to provide sufficient flexibility in the integration of the systems to accommodate such capabilities, when this can be accomplished without compromising reliability or penalizing unduly the overall design. Accordingly, basic design provisions have been included in the integrated reactor power system designs to facilitate both the minimal maintenance requirements and the somewhat more comprehensive maintenance work which may be subsequently justified.

1. PCS components are arranged, in some cases, near the aft end of the configuration to provide maximum accessibility, minimum nuclear radiation exposure, and the most suitable thermal environment for personnel. Moreover, the application of an intermediate NaK loop greatly facilitates access for maintenance.

2. Electrical power conditioning and control components are located within MORL, where repair, replacement, and calibration may be performed in a shirt-sleeve environment.

3. The deployment boom design provides a tunnel 4-ft square, suitable for passage of a crewman in spacesuit, or for the transport of system components between the MORL unpressurized interstage section and the reactor power system configuration.

4. The reactor power systems are to be designed to sustain a minimum of six programmed shutdown and restart operations per year for the operating lifetime of the systems. System temperature levels are maintained within safe limits throughout the shutdown period by provisions for reactor decay heat removal, thermal shields around the radiators to prevent fluid freezing, and the supply of power from the standby source to make up for system heat losses and for necessary pump operation. Instrumentation is provided to monitor the status and to verify the integrity of the shutdown system.

5. The reactor shielding is sufficient to permit limited-time access to the PCS components for maintenance while the reactor continues to operate at self-sustaining power level. However, access under these conditions requires stringent safeguards against exposure of maintenance personnel outside the shadow-shielded zone and the provision of suitable automatic reactor protection under reduced power level (5% to 10%) operating conditions.

Typical requirements in the categories of minimal preventive maintenance and minimal corrective maintenance are shown in Table 4-1, classified according to the location (MORL or the reactor power configuration) at which the maintenance is performed. The performance of minimal maintenance work in the reactor power configuration would be expected to interrupt the maximum experimental program capability for estimated periods of at least 16 hr if reactor operation at low power level is sustained, or 1 to 2 days if the reactor is shut down. The remaining time is required to terminate certain experiments in progress, establish the proper system operating conditions, transfer laboratory loads, prepare for maintenance, and restore normal operating conditions. In view of existing uncertainties in the scope of reactor power system maintenance operations, and the attendant laboratory maintenance, resupply or crew rotation operations which may be most conveniently scheduled at the same time, an allowance of 5 days for each programmed major maintenance shutdown appears reasonable. In adapting the reactor power system to the MORL, it is considered that sufficient cross training in specialty areas and technician skills can be conducted to accommodate the required minimal reactor power system maintenance operations without significant effect on experimental program capabilities. At least two crewmen, including the physicist and an engineer, should also be cross trained in reactor operation and qualified as reactor operators.

4.2 SUBSYSTEM INTEGRATION

The EC/LS system interfaces with both the reactor power system and the standby power system. The most limiting interface condition between the reactor power system and the EC/LS system involves the provision of adequate radiator surface on the MORL to accommodate the total power dissipated in the laboratory. The EC/LS-standby power source interference is also of particular significance because a thermal power output of 2.7 kW is transferred to the EC/LS system from the isotope Brayton standby system, which is the selected

Table 4-1

TYPICAL REACTOR POWER SYSTEM MAINTENANCE REQUIREMENTS

Category	Location	Maintenance Requirement
Minimal preventive maintenance	MORL	Instrument calibration. Electrical component inspection and replacement. Operating set point adjustments. Exercising of idle power conversion components, and rotation of loop operation (remotely). Periodic reactor tests to confirm lifetime performance (as required). Exercising of deployment boom and thermal shields.
	Reactor configuration	Exercising of idle power conversion components and rotation of loop operation (locally). Inspection of components and structure. Nuclear instrument replacement (as required). Electrical component continuity checks and replacement. RCS equipment inspection, propellant resupply.
Diagnosis and minimal corrective maintenance	MORL	Adjustment of reactor and power conversion system operating conditions. Electrical component replacement. Isolation or removal from service of faulty component. Placement of redundant capacity in service.
	Reactor configuration	Minor structure repairs. Isolation of faulty components. Electrical component replacement. Electrical cable replacement. Deployment boom and thermal shield motor replacement. RCS equipment replacement. Possible location and correction of radiator tube leak.

standby system for the 20- and 30-kWe reactor power system applications. However, for the 10-kWe reactor power system application, this thermal load is supplied from an auxiliary isotope heater in the EC/LS system rather than from the selected solar cell/battery standby system.

4.2.1 Standby Power System

The standby system provides the MORL with only sufficient power to satisfy minimum station- and orbit-keeping requirements while the reactor power system is inoperative. The standby power system must be capable of at least 41.75 days of continuous operation at a gross power level of approximately 5.5 kWe. The 41.75-day duration is predicated on the maximum time required to replace the reactor power system assuming two launches are required to achieve a successful replacement and only two launch pads are available for replacement launch operations. The cumulative duration for which the standby system must be designed is variable, but it must include prestation manning, replacement, and at least six reactor power system shutdowns per year. The candidate standby power sources were a modified PBC system, a solar cell/battery system, and fuel cells.

The use of cryogenically stored hydrogen and oxygen reactants for a fuel cell system requires the use of a refrigeration system and resupply of the cryogens subsequent to use of the standby system. In addition, the fuel-cell system weighs approximately 7,750 lb, which is not competitive with either the solar-cell/battery or PBC systems, consequently, fuel cells were eliminated from further consideration. A solar cell/battery system is competitive with the PBC system in terms of weight, provided that 200 lb/month reaction control propellant penalty for drag resulting from deployed solar panel area is eliminated by retracting the solar panels when the reactor power system is operating. However, three system complexities result. The first involves the inability of the solar cell/battery system to supply peak power loads to supplement the reactor power system during normal operation of the MORL without increasing the battery capacity by approximately 50%. The second system complexity results from the need for a supplementary isotope heater to supply 2.7 kW of thermal energy to the EC/LS system during standby periods. Finally, the fact that standby power is not readily available until after a reactor system failure has occurred and the solar panels are deployed results in the requirement for an extremely high deployment system reliability.

The PBC system was selected as the standby power source because (1) the performance and output of the system are invariant to the vehicle orientation in space; (2) external appendages are not present, thereby simplifying extravehicular maintenance and eliminating drag penalties; and (3) the system is invulnerable to space radiation damage. In addition, this power system has the further advantages of supplying 2.7 kW of thermal energy to the EC/LS during standby intervals and of supplying peak power loads to the vehicle during normal operation.

Selection of the standby power conversion system (PCS) design parameters involved an overall analysis and optimization of the heat source, PCS, and radiator requirements with respect to performance, weight, and physical size, which resulted in a turbine inlet temperature of 1,640°F and a compressor inlet temperature of 65°F. The design requirements for individual components were evolved from cycle optimization within the envelope defined by these basic design parameters. The selected PBC system contains 1 fuel block, designed to produce a thermal power output of 21 kW. The thermal radiation mode of heat transfer from the fuel block to the power conversion system replacement, simplify the installation, and increase reliability. The integrity associated with hermetic containment of the working gas is maximized by avoiding any pipe connections between the heat source and the power conversion equipment which would have to be removed and reconnected for PCS replacement. A nominal fuel block surface temperature limit of 1,800°F was specified to meet the anticipated stress and creep limitations of the fuel block assembly, as well as the heat source heat exchanger material limitations under conditions in which the inactive heat exchanger would reach a temperature nominally equal to that of the adjacent fuel block surface. In the event of a PCS failure, it is necessary to provide emergency cooling of the associated fuel block to prevent overheating; this is accomplished by thermal radiation to space from the outboard surface of the fuel block through a heat dump door. The physical arrangement of the standby system and its installation within the MORL interstage is depicted in Figure 4-2.

The study guidelines assume that the PBC system may not be available as a prime power source for MORL at 10 kWe (possibly resulting from unavailability of sufficient Pu-238), leading to consideration of a reactor power system as a candidate for this first-generation MORL vehicle. On this basis, a PBC system cannot be used as the standby power system for the 10-kWe reactor power system. The candidate power sources considered included a solar/cell battery system, fuel cells using both cryogenically stored hydrogen and oxygen and storable reactants, and chemically fueled reciprocating engines. The solar cell/battery system was selected based on weight recognizing the system limitation that the standby system must be designed for a minimum of six reactor power system shutdowns per year; consequently, the use of a solar cell/battery system for standby power requires a highly reliable deployment and retraction system. In addition, a supplementary isotope heat source is required to supply 2.4 kW of thermal energy for the EC/LS system when the reactor system is inoperative. The battery capacity must also be larger than normally required, to accommodate the possibility of a reactor power system failure immediately following the use of battery power for peak demands and to permit solar panel deployment.

4.2.2 EC/LS System

To satisfy overall EC/LS system requirements, the system is subdivided into a number of individual subsystems whose functions are outlined in Table 4-2, in accordance with the MORL Phase IIb study. Although the system was originally designed for six men, the Phase IIb design includes provisions for increased flexibility and for the accommodation of a nine-man crew for extended periods. Accordingly, the design provides (1) a completely closed water cycle and an open oxygen cycle (wherein oxygen is supplied by electrolysis of resupplied stored water) for a six-man crew, (2) accommodations for a nine-man crew for relatively long periods (months) with no compromise to crew safety and only a modest operating inconvenience, and (3) provisions to retrofit the MORL with a hydrogenation reactor for a completely closed oxygen cycle mode suitable for a six-man crew or a partially closed oxygen cycle for nine men. However, additional changes to the design would be required to accommodate a nine-man crew permanently.

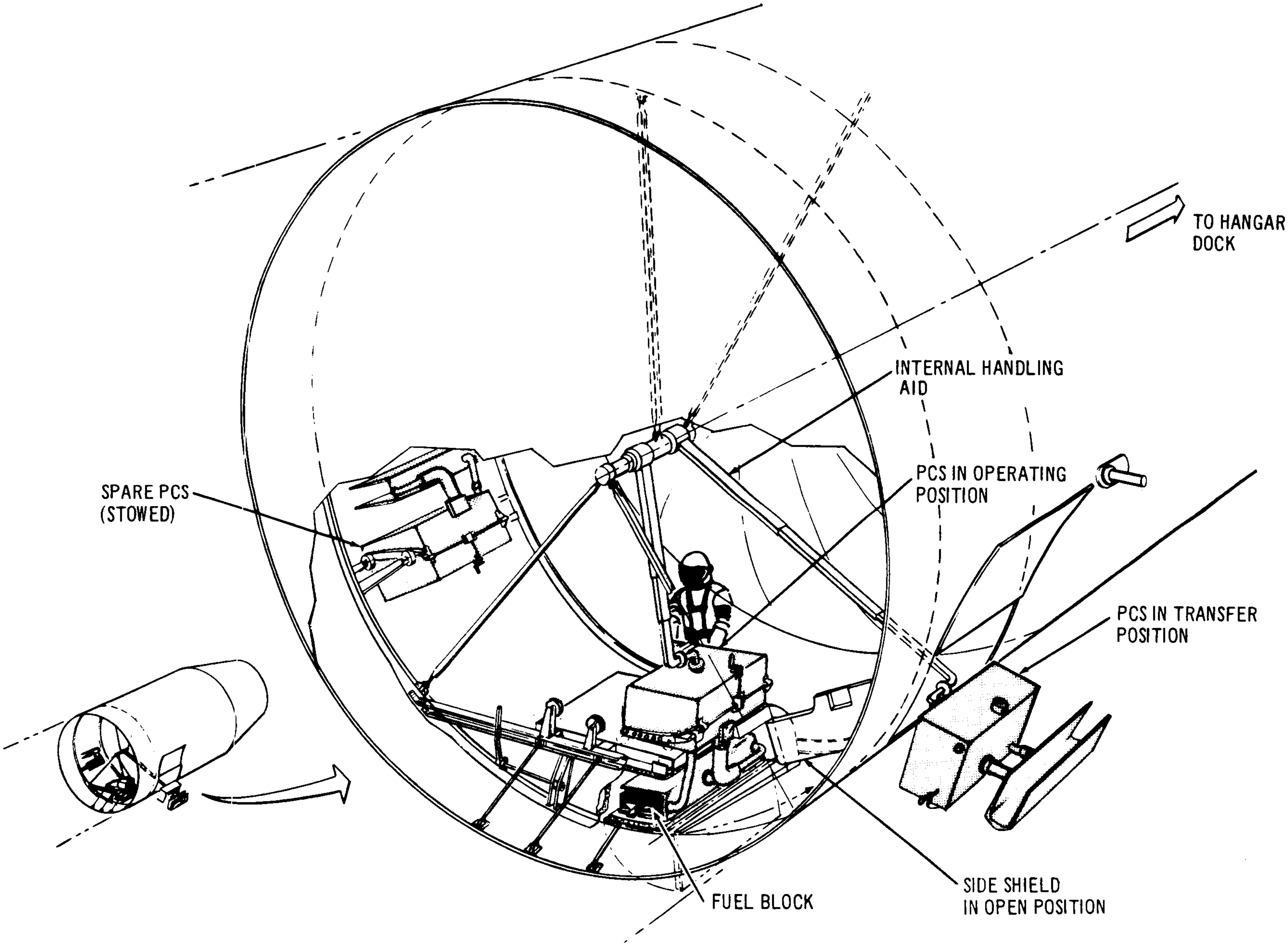


Figure 4-2. PBC Installation within MORL Interstage Area

Table 4-2

EC/LS SUBSYSTEM FUNCTIONAL REQUIREMENTS

Subsystem	Function	Changes for a Nine-Man Crew
Atmosphere supply	Supply breathing oxygen and nitrogen diluent. Provide pressure control within the compartments. Monitor atmospheric leakage to space.	*Addition of a fifth water electrolysis module, and an increase in average power demand from 1.48 to 2.12 kWe.
Atmosphere purification	Remove and control carbon dioxide. Control relative humidity. Remove and control trace contaminants. Control atmospheric bacteria. Provide for intravehicular space suit operation.	Consideration of increased carbon dioxide removal capability. Consideration of possible increase in intravehicular space suit operating capability to accommodate nine men.
Water management	Reclaim potable water from urine, perspiration, respiration, and wash water. Store both contaminated and potable water. Test potability of reclaimed water. Collect, transfer, process, and store or dispose of all laboratory wastes.	*Continuous system operation for 24 hours (instead of 18 hours) and increased evaporator and storage tank size; or resize for 9 men, 18 hours operation. None.
Compartment conditioning	Control air temperature. Circulate and mix atmosphere.	
Cooling circuit	Transfer and reject heat from the laboratory.	Radiator size increase commensurate with increased power source.
Heat transport circuit	Transport laboratory waste heat to the cooling circuit. Transport heat from the power system to certain EC/LS equipment in the laboratory.	Radiator size increase commensurate with increased power source. Increased thermal heat load, and pumping power increase to service-enlarged associated systems.
Atmospheric pumpdown	Minimize atmospheric losses caused by planned decompression of compartments.	None.
Carbon dioxide reduction	Convert carbon dioxide liberated by the molecular sieves into water using the Bosch process. This water is converted into gaseous oxygen by the atmosphere supply subsystem.	Increased design capability for a completely closed oxygen cycle.

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*Included in the present Phase IIb design.

4.2.2.1 Thermal Load

The EC/LS system heating loads include the air heater, water tank heaters, silica gel beds, and molecular sieve beds. Cyclic heating of the silica gel beds is necessary to liberate the collected moisture, which is removed by these beds prior to carbon dioxide removal in the molecular sieve. For the completely closed oxygen cycle, the molecular sieves are heated to liberate the collected carbon dioxide into the Bosch system, where water is formed and subsequently electrolyzed to produce oxygen for the laboratory and hydrogen for recycling through the Bosch system. For the open oxygen cycle, the carbon dioxide from the molecular sieves is vented to the space vacuum and a separate heat source is not necessary.

The estimated comparative thermal power requirements for six- and nine-man crews are as follows for the EC/LS subsystem:

	Thermal Load (kW)	
EC/LS Subsystem	Six Men	Nine Men
Water heater	0.15	0.22
Air heater	0.62	0.94
Silica gel beds (at 250°F)	1.50	1.50 to 2.24*
Open oxygen cycle subtotal	2.27	2.66 to 3.40
Molecular sieves (at 360°F)	1.73	2.59
Closed oxygen cycle subtotal	4.00	5.25 to 5.99

*The lower value relates to the capability of present baseline silica gel beds which can satisfy all functions except the intravehicular spacesuit operating condition for nine men. The higher value assumes an increased capacity to eliminate this restriction.

To allow for the cyclic heating loads of the silica gel bed and molecular sieve, a waste heat-dump heat exchanger is utilized to facilitate supplying these loads with a constant power source. During normal reactor operation, the total thermal power requirement of 6 kW is assumed to be supplied partially from the standby power source and partially from the reactor power system electrical output for the 20- and 30-kWe system designs. A thermal power output of 2.7 kW at 350°F is transferred directly from the heat-sink heat exchanger of the isotope Brayton-cycle system, and the remaining 3.3 kW are supplied by electrical immersion heaters from the source bus. Sufficient electrical heater capacity is provided to supply the total 6-kW load electrically from the reactor power source in the event of standby power system outage. When the reactor power system is shutdown, EC/LS system operation reverts to the open oxygen cycle mode, and the minimum required 2.7-kW thermal load is supplied by continued operation of the standby source. The selected EC/LS system thermal load division between the standby power source

(2. 7 kWt) and the reactor power system (3. 3 kWe) represents a compromise among the following three competing factors:

1. Providing the maximum available reactor power system electrical output power.
2. Maintaining EC/LS radiator area requirements at a minimum.
3. Minimizing design changes to the isotope Brayton-cycle standby power system, especially those changes involving an increase in isotope inventory or radiator size.

Considering these factors, three alternative design cases were evaluated in which the EC/LS thermal load is supplied completely by the (1) reactor power system, (2) the standby source, and (3) partially from each power source. The load division for the latter case was based on the provision of sufficient power from the standby source to sustain the open oxygen cycle loads in the laboratory when the reactor is shutdown without adjusting the standby system or heat transport system operating conditions. When reactor power is used to supply the total thermal loads during normal operation, such adjustment is necessary to transfer essential thermal loads to the standby source when the reactor is shutdown.

Use of the reactor power system electrical output to supply the total EC/LS thermal load results in the lowest EC/LS radiator area requirements, but the standby system radiator areas are relatively large and the net electrical power available in the laboratory is reduced by approximately 5 kW. A total EC/LS thermal load supplied from the standby power system results in the maximum EC/LS radiator area, highest available electrical power in the laboratory, and maximum power from the standby system. The selected alternative which shares the EC/LS load between the reactor and standby power sources results in reduced standby system radiator area. This partially compensates for the increase in EC/LS radiator size and decreases the net electrical output power available at the load bus by approximately 3 kWe, only a 10% to 15% reduction, respectively, for the 30- and 20-kWe reactor power system designs.

The 10-kWe (thermoelectric) reactor power system, coupled with a solar cell standby source, does not have sufficient capacity to satisfy EC/LS system thermal load requirements (2. 3 kWe for the open oxygen cycle with 6 men). Consequently, a separate isotope heater is installed in the EC/LS heat transport subsystem to provide the thermal power (2. 3 kW) necessary for this design.

4. 2. 2. 2 EC/LS Radiator Area

The EC/LS system radiator must reject the total heat load dissipated in the laboratory, while maintaining a habitable environment and temperatures within allowable limits for all subsystem components and experiments. The baseline MORL radiator design occupies a surface area of 822 sq ft along the conical section and forward 13. 2 ft of cylindrical section of the MORL, rejecting 49, 630 Btu/hr at an average surface radiating temperature of approximately 50°F. Because of the low radiating temperature, the increase in power source rating occasioned by application of a reactor power system has a pronounced effect on the required radiator size and, in turn, the capability of the MORL to accommodate this surface area.

The total heat load on the EC/LS system radiator is comprised of the following individual sources:

1. Reactor power system gross (unconditioned) output power.
2. Standby power system which is in operation concurrently with the reactor.
3. Battery power to accommodate peak loads beyond the capability of the operating standby power system and reactor.
4. EC/LS system heat loads supplied by direct thermal means.
5. Metabolic production (500 Btu/man-hr, shirt sleeve).

Because the EC/LS radiator must be sized to dissipate the full output power rating of the reactor power system, the associated parasitic load control can be installed in the EC/LS cooling system without further penalty. This arrangement maintains a relatively constant load on the EC/LS radiator and is, therefore, beneficial in preventing undesirable temperature fluctuations. Similarly, the isotope Brayton standby power system parasitic load can be installed in the EC/LS cooling system without further penalty because the design must accommodate the rated output of the standby source during peak load periods in any event. The application of a solar standby system in conjunction with the 10-kWe reactor thermoelectric power system eliminates standby power output as a factor in sizing the EC/LS system radiator because this power source is not in service while the reactor is operating.

Table 4-3 shows the total heat loads which must be dissipated in the EC/LS radiator for the individual reactor power systems. The variations from the 10- and 20-kWe-rated output power levels for the thermoelectric systems result from modifications to the power conditioning efficiencies to account for the integrated operating modes eventually selected for the reactor power system and standby power system in meeting the overall electrical load profile.

Based on an absorptivity-to-emissivity ratio of 0.25 which provides sufficient allowance for degradation of the surface coating materials during prolonged exposure to the space environment, the average heat influx, or the corresponding equivalent sink temperature, varies with the orbital position for the 50°-inclination orbit and polar orbit under the vehicle orientation conditions specified. The baseline MORL radiators are designed for 87% of the peak heat influx for the 50°-inclination orbit, or an equivalent sink temperature of -20°F, in view of the relatively small fraction of the orbital period (approximately 20 out of 94 min) in which the influx exceeds this value. The heat capacities and time delays in the various serviced fluid systems are considered to be sufficient to compensate for such peak conditions. From a reexamination of EC/LS system thermal transient design conditions presently in progress, it appears that a further reduction in the design sink temperature to -35°F may be acceptable for the 50°-inclination orbit. However, a constant

Table 4-3

EC/LS SYSTEM RADIATOR COOLING LOAD REQUIREMENTS

	Reactor Power System				
	10-kW	20-kW	20-kW	20-kW	30-kW
	(Thermoelectric)		SNAP-2	Brayton	SNAP-8
Gross reactor power system output, kWe[1]	12.0	25.9	24.0	24.0	35.0
Power conditioning efficiency, %[2]	81.7	87.0	83.4	83.4	85.7
Net reactor power system output, kWe	9.8	22.5[3]	20.0[3]	20.0[3]	30.0[3]
EC/LS radiator cooling loads, kWt:					
Reactor power system	12.0	25.9	24.0	24.0	35.0
Standby power system	0	5.5	5.5	5.5	5.5
Battery	5.6	0.4	0.4	0.4	0.4
EC/LS thermal power	2.3	2.7	2.7	2.7	2.7
Metabolic heat	0.9	1.3	1.3	1.3	1.3
Total	20.8	35.8	33.9	33.9	44.9

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[1] Exclusive of degradation allowance and installed redundant capacity.

[2] Battery follows load peaks for 10-kWe design. Standby system follows basic load peaks for 20-kWe and 30-kWe designs.

[3] Of which total, 3.3 kWe is removed directly from the source bus (unconditioned) to supply EC/LS system heating loads, amounting to the equivalent of about 3 kWe reflected at the load buses.

equivalent sink temperature of -28°F results during the polar orbit when the sun is normal to the orbital plane. Although other orientations relative to the sun result in a reduced sink temperature profile for the polar orbit, it appears that selection of an equivalent sink temperature of -28°F provides a sufficiently conservative alternative design basis to encompass all expected variations in the 50°-inclination orbit and the polar orbit. Under these conditions, the heat influx would exceed the design value for about 25 min. during the 50°-inclination orbit under the most conservative conditions. Attainment of an absorptivity-to-emissivity ratio below 0.25 would correspondingly reduce this transient period.

The EC/LS system radiator fluid inlet temperature of 107°F and outlet temperature of 35°F result in an average surface radiating temperature of approximately 50°F. The fluid inlet temperature is limited by a consideration of the acceptable operating temperature for electronics equipment, which is cold-plated in the heat transport subsystem. A maximum average coolant temperature of 120°F was selected at the outlet of the cold plates. Under the MORL baseline operating conditions, with a total heat load of 49,630 Btu/hr (14.5 kW), a cold plate coolant inlet temperature of approximately 73°F, and outlet temperature of approximately 111°F results for the average value of silica gel bed and mol sieve heating loads (these loads are cyclic). Hot spot temperatures within the electronics equipment are unique to the equipment design and exceed cold plate temperature by varying amounts. In the present reactor power system application, consideration was given to raising the EC/LS radiator fluid inlet temperature from 107° to 115°F, while maintaining the outlet temperature at 35°F, to determine the relative gain in required radiator surface area inasmuch as such a nominal temperature increase appears acceptable for the electronics equipment. This 8°F increase reflected at the electronics cold plate maintains the cold plate fluid outlet temperature at about 120°F under average cooling load conditions, although somewhat higher temperature peaks result. Figure 4-3 shows the comparative effects of equivalent sink temperature and EC/LS radiator fluid inlet temperature on the surface area as a function of the heat load. The total heat loads for the various reactor power systems are superimposed to indicate the relative size of radiator required. As a point of reference, the MORL baseline radiator design, based on -20°F sink temperature and 107°F radiator fluid inlet temperature, requires 1,050 sq ft of surface to dissipate 14.5 kW, although 1,290 sq ft is used to reduce radiator tube weight slightly. The total available surface area on the baseline MORL is approximately 2,150 sq ft, including 400 sq ft on the conical surface and 1,750 sq ft on the 29.5-ft cylindrical section. From an examination of Figure 4-3, it is apparent that additional surface area is required to accommodate the 20- and 30-kWe reactor power system designs; the present MORL baseline length is satisfactory for the 10-kWe reactor power system design. The additional surface requirement for 20- and 30-kWe system designs is significantly lower when using an equivalent sink temperature of -28°F and EC/LS radiator fluid inlet temperature of 115°F (in comparison with -20° and 107°F, respectively). Because the former temperature conditions are considered to be an acceptable and sufficiently conservative design basis, the 20- and 30-kWe reactor power system application are based on surface area requirements corresponding to these conditions for the 50°-inclination and polar orbits. An allowance of 350 sq ft, in addition to the surface area requirements shown in Figure 4-3, must also be included for the radiator of the isotope Brayton-cycle standby power system associated with these designs. The significantly reduced heat

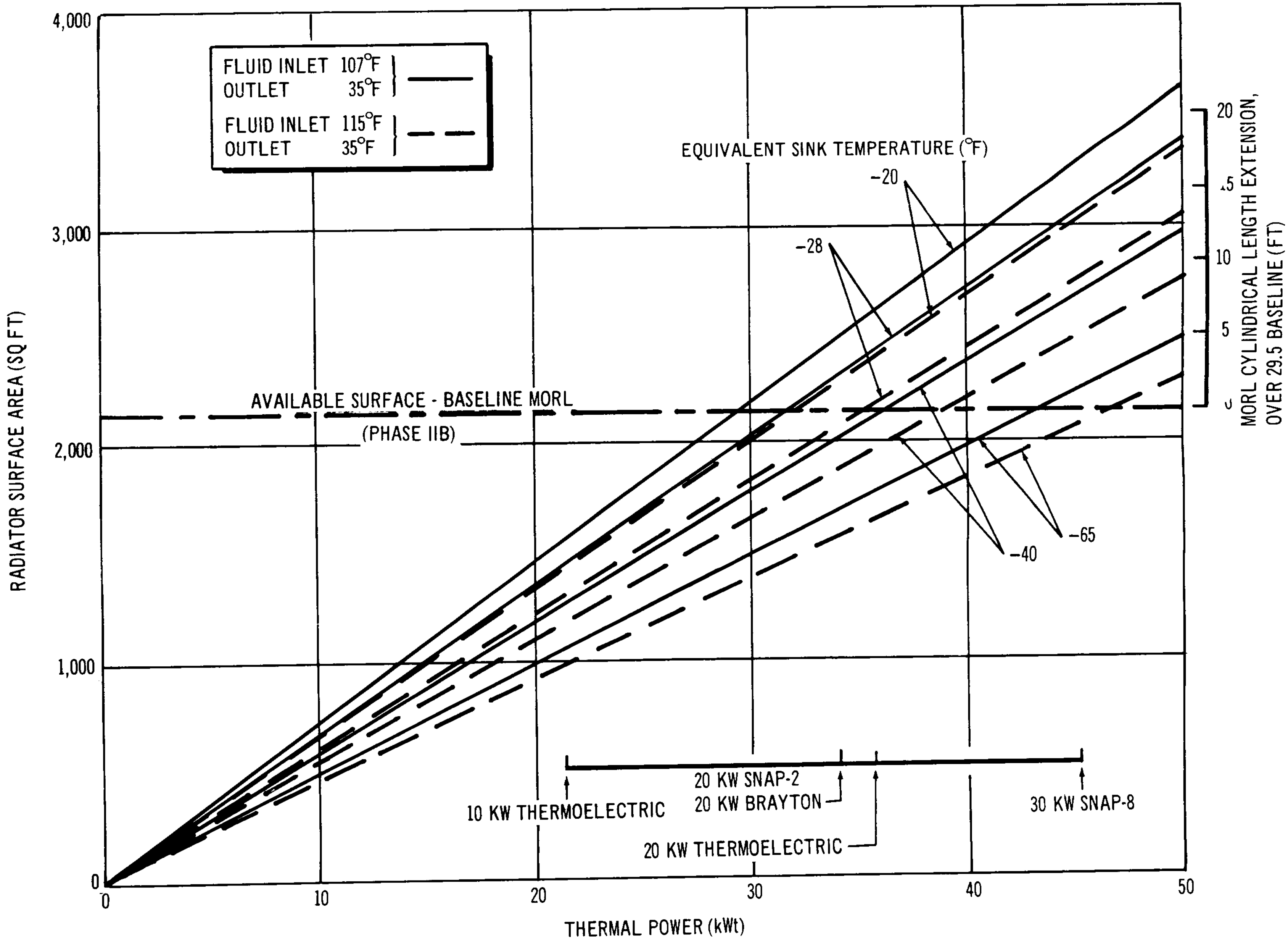


Figure 4-3. EC/LS System Radiator Characteristics

influx in the synchronous orbit results in equivalent sink temperatures no higher than approximately -100°F. Under these conditions, a nominal increase in surface area (under 100 sq ft) would be required only for the 30-kWe SNAP-8 system design.

The combined EC/LS system and standby power system radiator surface area require a 5.2-ft extension of the MORL unpressurized interstage to accommodate the 2,500 sq ft of the 20-kWe reactor power system. Accommodation of the 30-kWe SNAP-8 system (3,100 sq ft) requires a MORL elongation of approximately 14 ft which may be excessive, in which case deployable radiator segments could be considered.

4.3 STABILIZATION AND CONTROL

The functional and performance requirements of the stability and control system result from the various mission events, which are concerned primarily with injecting and maintaining the MORL in its prescribed orbit for its designated life and the experimental program needs. The specific mission events and functions which must be supported by the stability and control system (SCS) are as follows: (1) orbit injection, (2) short-term unmanned mode, (3) orbit-keeping or orbit altitude maintenance, (4) long-term manned zero-g stabilization, (5) rendezvous and docking, (6) artificial-g, and (7) experimental support.

Control torques, needed to maneuver the MORL/reactor power system or stabilize it in a selected orientation, are provided by control moment gyros (CMG) and the RCS. The CMG provide primary actuation because of the efficiency resulting from their momentum storage feature. The efficiency stems from their capability to counter cyclical disturbance torques with a minimum of RCS propellant. The RCS supplies external torques for desaturating the CMG and for other events requiring high torque capability.

During long-term operation of the vehicle in the zero-g mode, an orientation is selected which aligns the longitudinal axis with the velocity vector and maintains one side of the vehicle facing the Earth. This is referred to as the bellydown orientation. In addition to this basic orientation, the MORL must be capable of maneuvering to any desired inertial orientation for short-term experiment operations. This is referred to as the inertial orientation.

4.3.1 Control Analysis

The MORL/reactor power system configurations have large moments-of-inertia about the pitch and yaw axis and a small moment-of-inertia about the roll axis. Because the gravity gradient disturbance torque about a particular axis is proportional to the difference in moment-of-inertia about the other two axes, large gravity gradient disturbances occur about the pitch and yaw axis while the MORL/reactor power system is in an inertial orientation. Summarizing, long slender configurations like the MORL/reactor power system are subject to gravity gradient torque while in the inertial orientation. A constant gravity gradient torque exists about the pitch axis while the configuration is in a bellydown orientation because the principal roll axis is rotated from the horizontal by a cross product of inertia. However, it is of much lesser magnitude than the disturbances which occur in the inertial orientation. Another significant disturbance is aerodynamic drag which produces both orbit decay and disturbance torques. The aerodynamic disturbance torques are primarily cyclical and can be stored by the CMG without the expenditure of propellant. Orbit keeping, however, requires the expenditure of considerable propellant.

Design criteria applicable to the control analysis are as follows:

1. Maximum density, 1980 atmosphere.
2. MORL weight, 100,000 lb.
3. MORL/reactor separation distance, 125 ft.
4. Worst case inertial orientation, pitch or yaw axis aligned parallel to line of modes and other axis inclined 45° to orbit plane.
5. Near worst case baseline MORL configuration with the cargo module stowed on top of MORL and 2 Apollo modules positioned 37.5° below the pitch axis on either side of MORL.
6. Orientation duration, inertial orientation 4.5 hr/day and bellydown orientation 19.5 hr/day.
7. Maneuvers performed with the CMG.
8. Two types of RCS, a chemical bipropellant system (NTO/MMH) with a specific impulse of 300 sec and a resistojet electrical thrustor system with a specific impulse of 750 sec.

Several RCS arrangements were considered for the MORL/reactor power system configuration. Use of the baseline MORL RCS system was discarded because the reactor power system located 125 ft from the MORL resulted in inordinate propellant requirements as did the Earth-oriented SCS concept. This latter concept allowed the reactor power system and the deployment boom to act as a pendulum relative to the MORL; i. e. , the reactor power system is oriented along the local vertical during inertial orientations to eliminate gravity gradient torques. The selected configuration consists of two separate RCS systems, one located at the aft end of the reactor power system configuration and one aboard the MORL. The MORL RCS provides orbit keeping and desaturation of the roll CMG. The manner in which orbit-keeping thrust is applied provides pitch and yaw CMG desaturation as a byproduct without additional propellant expenditure. The RCS aboard the reactor power system configuration provides desaturation of the pitch and yaw CMG while the spacecraft is inertially oriented for experimentation. Thrustors are mounted radially to take advantage of the long moment arm without which propellant consumption during the inertial orientation would be excessive.

RCS propellant requirements for the MORL/reactor power system in the baseline MORL 164-nmi orbit were found to be excessive, even when the selected, two-separate, RCS systems were used. This excess was primarily attributed to drag makeup; consequently, a higher orbit altitudes were investigated, specifically subsynchronous orbits. That is, orbits in which the spacecraft periodically retraces its path over the Earth. For the altitude range of interest at 50° inclination, there exists an orbit at 192 nmi that is 2-day subsynchronous. Subsynchronous orbits also exist at 164 and 218 nmi, which are 3-day subsynchronous. A periodically repeatable orbit accrues benefits from both the experimental program and ground operations. Those experiments that require repeated coverage of the same surface areas over long periods will automatically have this requirement fulfilled. The work schedules and rendezvous launch missions in support of the MORL/reactor power system can be planned on a regularly scheduled basis.

An orbit altitude optimization was performed, the results of which are shown in Figure 4-4. For 20 logistic launches, payload is optimized at an orbit altitude of 207 nmi. However, a subsynchronous orbit altitude of 218 nmi was selected with a resulting payload penalty of approximately 1,000 lb. The benefits which accrue from a subsynchronous orbit are considered to offset the slight payload penalty. While this optimization is based on 4 logistics launches per year or 20 for 5 yr, conforming to the baseline MORL schedule, the 20- and 30-kWe system designs assume a 9-man crew which may require more than 4 logistic launches per year. As many as 6 launches could be used, but these would not be at 100% load factor based on present MORL requirements for a 9-man crew. Results of the orbit optimization for 6 logistic launches show a payload optimization at 200 nmi, indicated by the dashed line in Figure 4-4. For this case, a subsynchronous orbit of 192 nmi would be selected.

The frequency of logistic launches is a function of the quantity of stores to be resupplied and the crew rotation schedule. Because a product-improved Saturn IB has been adopted as the MORL/reactor power system logistics vehicle, in excess of 5,000 lb of additional stores can be supplied in a single resupply as compared with a baseline MORL resupply. This increased capability of the product-improved Saturn IB accommodates the additional stores required for a nine-man crew. Consequently, from a stores consideration, no additional logistic launches are required. Other factors contributing to maintaining a minimum number of logistic launches are logistic economics, use of second-generation MORL's permitting longer crew rotation times and eventual 2- to 3-yr mission durations for interplanetary flights. It has also been tentatively indicated that crew rotation schedules can be increased, with no deleterious effects on the crew. Because these contributing factors are, in fact, mission requirements, eventual decision on logistic launches will be made by NASA. However, it is considered that four logistic launches per year is valid for a payload optimization because the above mission requirements all suggest a minimum number of logistic launches. As a result, a new mission orbit commensurate with four logistic launches per year was established (i. e., a 218-nmi circular orbit that is 3-day subsynchronous). This change in mission altitude from 164 to 218 nmi makes necessary the recalculation of RCS propellant requirements for the various MORL/reactor power system configurations shown in Table 4-4.

For comparison, propellant requirements for the MORL vehicle in the baseline 164-nmi orbit with a 1972 atmosphere are 300 lb/month. Updating these baseline MORL propellant requirements to the 1980 atmosphere for subsynchronous orbits in the altitude region of interest result in Table 4-5.

4.3.2 Control Moment Gyro Sizing

The baseline MORL CMG must be resized for the MORL/reactor power system configuration to accommodate the large gravity gradient torques which occur

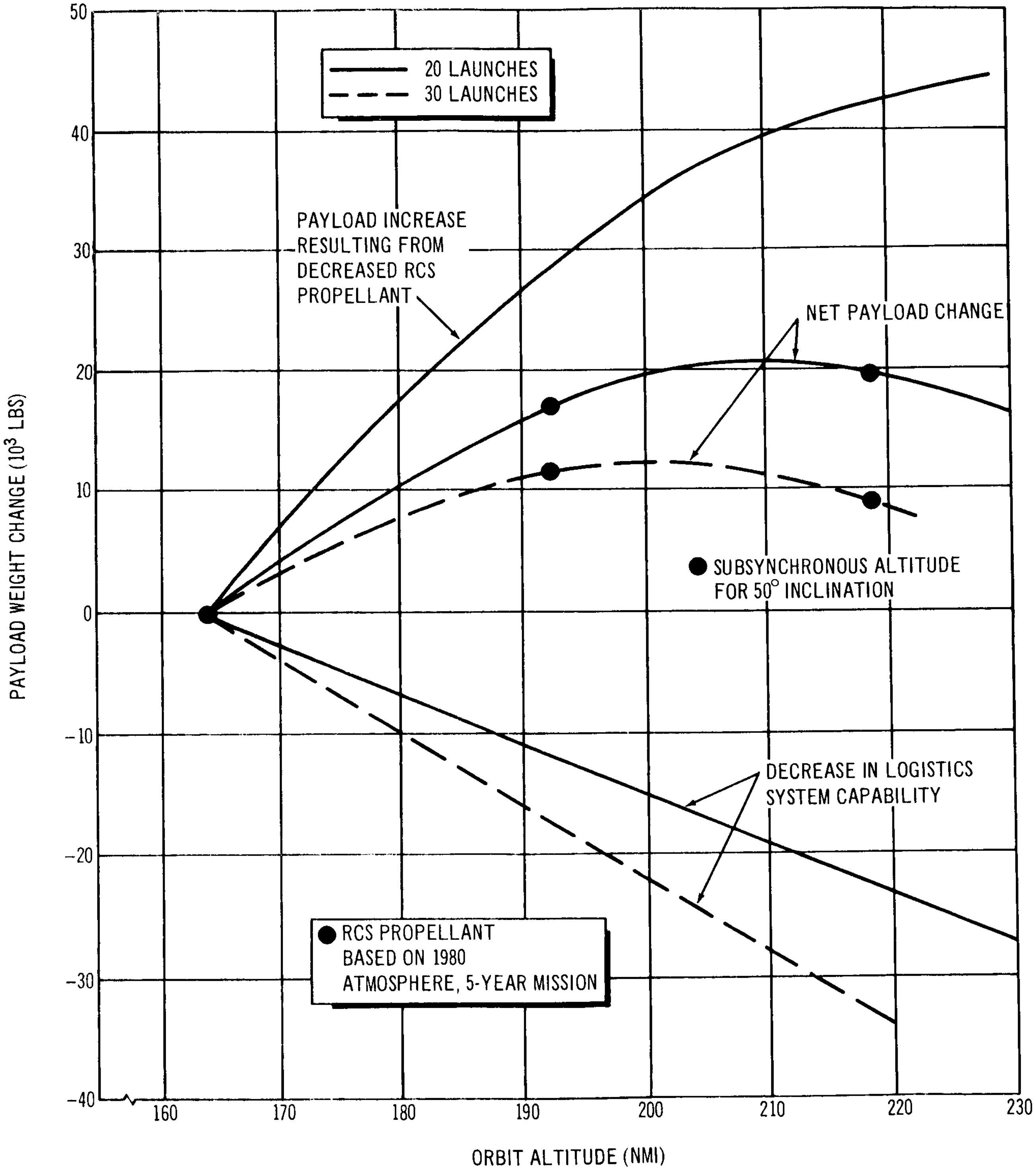


Figure 4-4. Orbit Altitude Optimization

Table 4-4

RCS PROPELLANT REQUIREMENTS FOR 218-NMI ORBIT

Configuration	Lb/Month
10-kW Thermoelectric	307
20-kW Thermoelectric	407
20-kW SNAP-2	320
30-kW SNAP-8	382
20-kW Brayton	308

during the inertial orientation. A resizing was conducted for the five selected systems in terms of momentum storage capacity and weight.

Prior to presenting sizing results, a review of the CMG configuration and design criteria is pertinent. The CMG configuration assumed in the sizing is that of the baseline MORL and consists of two single-gimbal CMG and two double-gimbal CMG. The single-gimbal CMG provides roll control and the double-gimbal CMG provides pitch and yaw control. Four distinct CMG designs were analyzed for each MORL/reactor power system configuration. They are restricted and unrestricted CMG maneuver capability accommodating either 1- or 9-g centrifuge runs. Restricted maneuver capability refers to the ability of the CMG to control the largest cyclical disturbance, consequently the CMG cannot accommodate certain maneuvers when it is nearly saturated from disturbances. Unrestricted maneuver capability refers to the provision of momentum storage capability in the CMG such that maneuvers can be performed at any given time regardless of the disturbance. A 1- and 9-g centrifuge capability refers to the sizing of roll CMG to store the angular momentum generated by centrifuge runs, where the acceleration experienced by the centrifuge occupant undergoing conditioning is 1 or 9 g's. With the roll CMG sized to accommodate either 1- or 9-g centrifuge runs, the roll CMG can perform all maneuvers provided that these maneuvers and centrifuge operation do not coincide.

Table 4-6 indicates the CMG weights for the selected MORL/reactor power system configurations. The first weight column lists the total CMG weight. CMG weight attributable to the reactor power system can be determined by

Table 4-5

BASELINE MORL RCS PROPELLANT REQUIREMENTS

Orbit Altitude (nmi)	Lb/Month
164	725
192	342
218	183

Table 4-6

CMG WEIGHT MATRIX

Configuration	Maneuver Capability	Centrifuge Capability (g's)	Total CMG Weight (lb)	CMG Weight Penalty (lb)	RCS Maneuver Propellant (lb/yr)
10-kW thermoelectric	Restricted	1	1,150	0	760
		9	1,412	262	
	Unrestricted	1	1,810	660	
		9	2,072	922	
20-kW thermoelectric	Restricted	1	1,320	0	913
		9	1,582	262	
	Unrestricted	1	2,196	876	
		9	2,458	1,138	
20-kW SNAP-2	Restricted	1	1,208	0	696
		9	1,470	262	
	Unrestricted	1	2,080	872	
		9	2,342	1,134	
30-kW SNAP-8	Restricted	1	1,304	0	884
		9	1,566	262	
	Unrestricted	1	2,188	884	
		9	2,450	1,146	
20-kW Brayton	Restricted	1	1,156	0	763
		9	1,418	262	
	Unrestricted	1	1,818	662	
		9	2,080	924	

subtracting the baseline MORL CMG weight (628 lb) from the total CMG weights indicated. Four CMG designs are presented for each MORL/reactor power system configuration--designs for restricted maneuver capability, when maneuvers are accomplished by the RCS and the CMG accommodates either the 1- or 9-g centrifuge runs; and designs for unrestricted maneuver capability where the CMG is sized to accommodate also maneuvers for either 1- or 9-g centrifuge runs. The second weight column indicates the CMG weight penalty for each CMG design, when the 1-g restricted maneuvers design for each MORL/reactor power system is taken as a reference point. The last weight column, RCS maneuver propellant, presents the propellant weight required to accommodate maneuvers if the restricted maneuver CMG is used. This propellant requirement is not applicable if the unrestricted maneuver CMG is adopted because maneuvers are accomplished by the CMG. The propellant weights shown are based on performing all RCS maneuvers at a constant angular rate of 0.075°/sec, which corresponds to the nominal CMG maneuver rate.

As noted in Table 4-6, the CMG weight penalty incurred for unrestricted maneuver capability is significant; however, the RCS propellant requirement is also significant. To determine whether the RCS or CMG should be used to accomplish maneuvers, both weight and CMG replacement times must be considered. For a CMG replacement time of 1 yr, CMG maneuvering with 1-g centrifuge capability results in a weight saving for the 10- and 20-kWe thermoelectric and 20-kWe Brayton cycle configurations, no weight saving for the 30-kWe SNAP-8, and a weight penalty for the 20-kWe SNAP-2 (compared to the use of RCS for maneuvering). As CMG replacement times increase over 1 yr, the weight advantage of the CMG maneuvering mode becomes more pronounced. As a result of this weight analysis, a CMG size which provides for unrestricted maneuver capability was selected.

Concerning CMG sizing for either 1- or 9-g centrifuge capability, Table 4-6 indicates a weight penalty of 262 lb for the 9-g capability. However, a weight penalty must also be assigned to the RCS for 9-g centrifuge control. Definition of this penalty requires a determination of the centrifuge 9-g run schedule, which is a function of the particular mission application, and an extensive attitude control system analysis. Consequently, a 1-g CMG centrifuge capability was tentatively selected.

4.3.3 Resistojet RCS for the MORL/Reactor Power System

An analysis was performed to assess the potential of the resistojet RCS for the MORL/reactor power system configuration. Items considered in determining the feasibility of this design included weight, electrical power required, and total thrust. In addition, an orbit altitude optimization was performed using resistojet RCS for CMG desaturation and orbit keeping. Logistic payload is optimum near the subsynchronous orbit altitude of 192 nmi, which is chosen as the mission altitude when the resistojet RCS is used. A resistojet RCS is of interest because of certain desirable features, such as (1) high efficiency, the nominal I_{sp} obtainable with H_2 propellant being 750 sec; (2) significant reduction of the noise level within the MORL during thrustor operation; and (3) CMG desaturation accomplished with a low, nearly continuous thrust and, therefore, the perturbing effect of desaturation on vehicle attitude and attitude rate is negligible. With the bipropellant-chemical RCS, constraints are placed on desaturation thrust levels and thrust duration to meet performance requirements.

While in the inertial orientation, at a 192-nmi orbital altitude, the RCS must supply 618 lb/sec impulse per orbit. A constant thrust of 0.112 lb over the entire orbit will supply the impulse. The continuous electrical power requirement would be 3 kW. The thrust level is reasonable because 150-mlb resistojet thrustors have been built and tested. During a bellydown orientation, 247 lb/sec of impulse are required for each orbit. The thrust level, assuming continuous thrusting, is 0.0446 lb, and the electrical power requirement is 1.2 kW.

The propellant requirement for the resistojet RCS using H_2 propellant is 198 lb/month or 970 lb/147 days. Of the 147-day propellant supply, 360 lb are expended by the RCS on the reactor power system and 610 lb by the RCS on MORL. The total equipment weight for each system is 350 lb for the system aboard the reactor power system and 261 lb for the system on the MORL. The total weight is 1,581 lb for a 147-day period.

The use of a resistojet RCS to provide orbit keeping and CMG desaturation does not affect CMG sizing. Maneuver requirements and aerodynamic and gravity gradient disturbances establish CMG size. A disadvantage of the resistojet system is its inability to perform functions requiring high thrust levels. Backup attitude control and high slew rates required for ground tracking experiments are two such functions. Therefore, the addition of a resistojet RCS does not eliminate the need for a bipropellant system. It does, however, reduce the total propellant requirement by a significant amount. Further analyses and better mission definition is required to demonstrate that overall advantage is gained by the addition of a resistojet RCS, consequently the bipropellant RCS system was selected at this time for use with MORL/reactor power system.

4.4 CONFIGURATION AND STRUCTURES

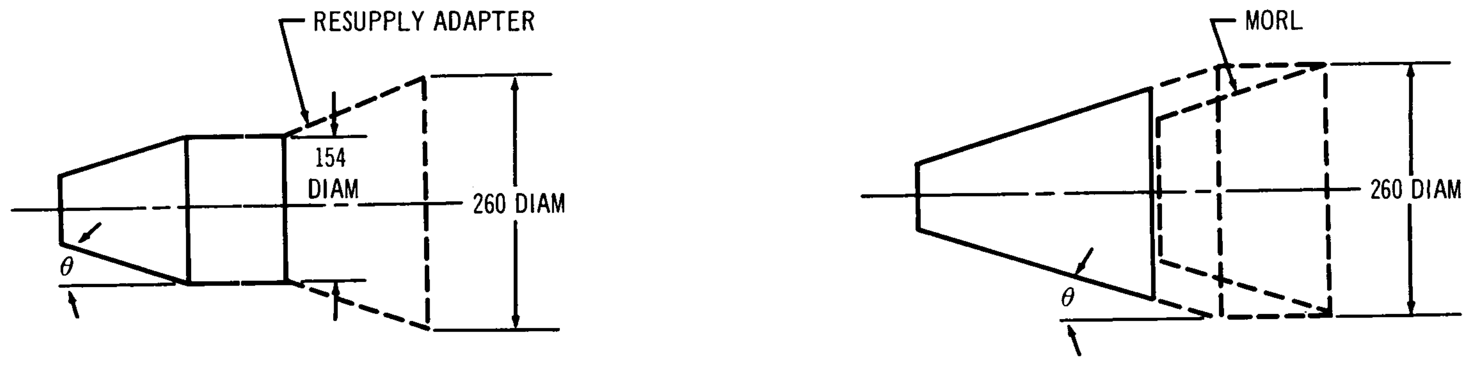
Development of the reactor power system configurations included the arrangement of reactor, primary coolant system, shielding, power conversion equipment, and associated structure to achieve the most effective integrated designs. The requirements of launch, deployment, resupply, and disposal of the reactor power system at the end of its useful life, as well as interactions with the MORL subsystem designs were considered in the evolution of these configurations.

The selected configurations were based on the design philosophy (delineated in Section 3) of reducing the number of variables under consideration for the various power systems being studied. It was established that the shield cone angle, the minimum and maximum diameters of the MORL, the diameter of the S-IVB stage, and the overall height of the assembled power system and launch vehicle combinations are the principal design constraints. It was also established that the configurations exhibit commonality of design between the integral and replacement launch configurations with the result that the replacement system configuration becomes the design condition. The selected configurations are sufficiently flexible to accommodate a reasonable amount of growth, such as changes in radiator surface area. The same basic configuration can be extended or reduced, within limits, to obtain the required area. Figure 4-5 shows the basic configuration types selected for each reactor power system. Configuration Types A, B-1, and B-2 are applicable to the Saturn IB launch vehicle, while configuration Type C is amenable to the Saturn V.

Integration studies indicated that installation of the PCS components near the aft end of the configuration provides the greatest accessibility, facilitates visual inspection, maintenance, and repair to the extent considered feasible based on PCS design considerations. Results of the structural analysis further indicated that the radiator should generally be used as the principal structural support for the configuration. The fin and tube radiator structure with circumferential stiffening rings was selected in preference to the MORL truss core radiator structure on the basis of comparative weight, strength, and area relationship.

4.4.1 Deployment, Resupply, and Disposal

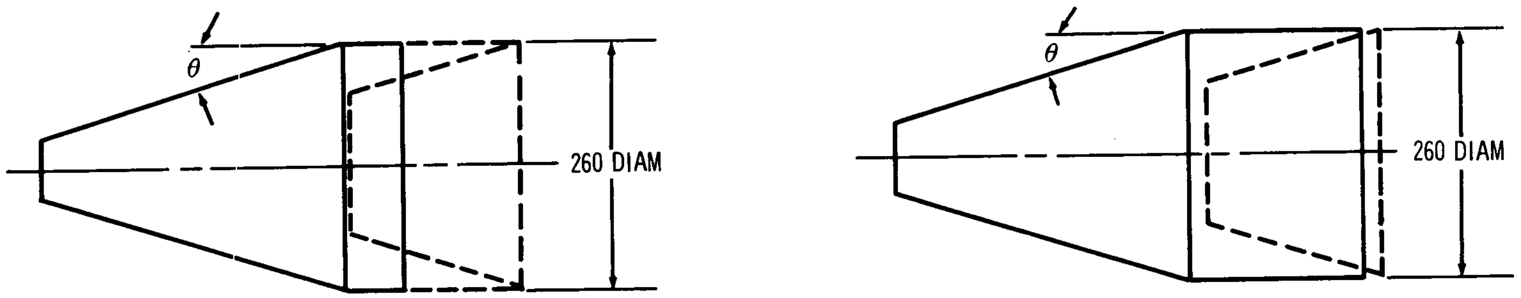
The deployment system provides a fixed separation distance of 125 ft between the reactor and the MORL during normal operation to maintain the exposure of personnel to reactor radiation within 20 Rem/yr/man, as well as



A, RADIATOR AREA:
350 TO 800 FT^2
20 kWe SNAP-2 = 757 FT^2

B-1, RADIATOR AREA:
800 TO 1,150 FT^2
10 kWe T.E. = 1,068 FT^2
30 kWe SNAP-8 = 1,075 FT^2
20 kWe BRAYTON = 1,150 FT^2

MAX HALF ANGLE (θ)= 17°



B-2, RADIATOR AREA:
1,150 TO 1,900 FT^2
20 kWe T.E. = 1,891 FT^2

C, RADIATOR AREA:
1,900 TO 3,000 FT^2
SATURN V LAUNCHED CONFIGURATIONS, e. g., 30 kWe T.E.

Figure 4-5. Reactor Power System Configurations accommodating deployment, replacement, and disposal of the reactor power system configuration. The following parameters and specific functions were considered in the selection and design development of the deployment system:

1. Reactor power system size and weight.
2. Location of the power system at launch.
3. Transfer of the power system to the deployment system.
4. Reactor power system separation distance.
5. Stowage of the deployment system at launch.
6. Requirements for jettisoning and disposal of the reactor power system.
7. Retention of a section of the shield.
8. Operating components of the deployment system.
9. Structural requirements.

These items all represent significant areas in the final selection of a feasible deployment system. The Task Area II report described the candidate systems considered and the process of selection. The selected design and the articulation features required for transfer of both the integrally launched and resupplied reactor power system are shown in Figure 4-6.

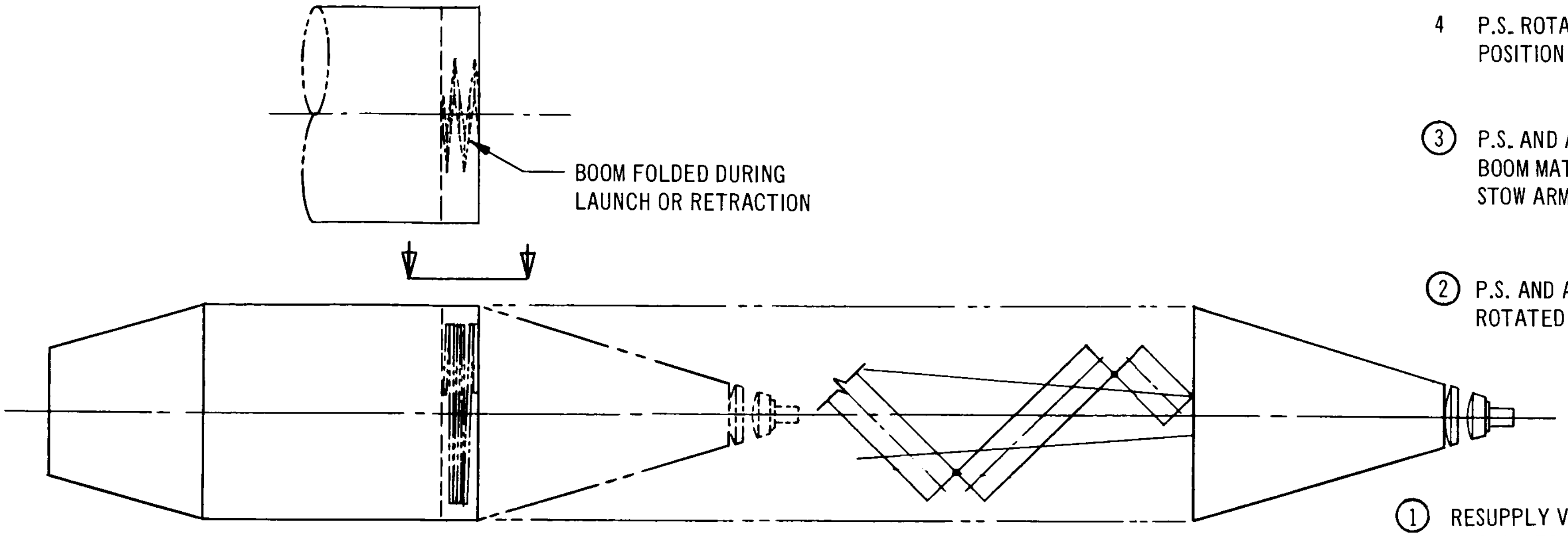
4.4.1.1 Deployment Boom Design

The deployment structure is unfolded and extended from its stowage position during launch by use of an electrically operated harmonic drive system attached at each of the booms lateral hinges. These drive systems achieve a large reduction in speed and consequent increase in torque with irreversibility and a minimal power requirement.

The deployment boom provides a protected passage between the MORL and the deployed reactor power system through which personnel in space suits may move without the restrictions of a tether. Welded tubular truss sections are used in the design. However, the tubular truss selected as the basic structure does not afford a smooth, fully enclosed passage. Therefore, a lining of 0.020- to 0.025-in. sheet aluminum is used to provide a smooth-surfaced enclosure for passage of personnel and to allow unrestricted movement of replacement components.

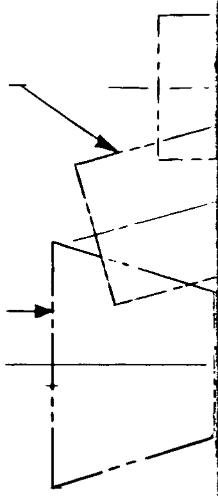
4.4.1.2 Secondary Shield Retention

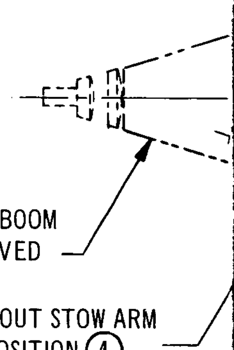
To maintain the weight of the replacement reactor power system configurations within the capabilities of the product-improved Saturn IB launch vehicle, it is possible to retain a portion of the reactor secondary shield with the MORL during system replacement. The selected method of shield retention involves support of the shield from a common structure used for deployment boom attachment, RCS support, and other appurtenances. Figure 4-7 shows the

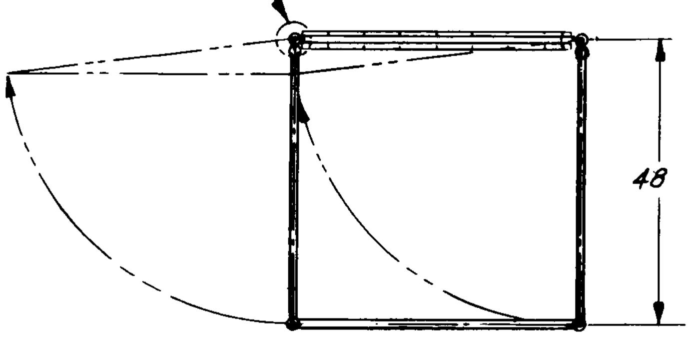


Ⓓ POWER SYSTEM FULLY RETRACTED

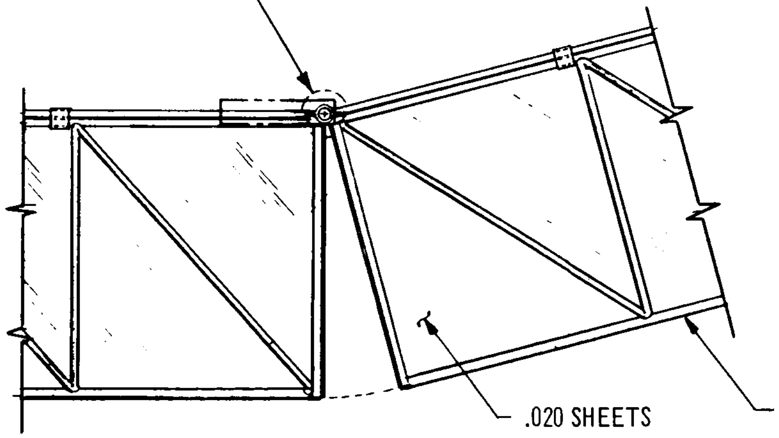
Ⓒ PARTIALLY RETRACTED POWER SYSTEM







SECTION E-E BOOM CROSS-SECTION



SIDE VIEW OF JOINT BETWEEN BOOM SECTIONS

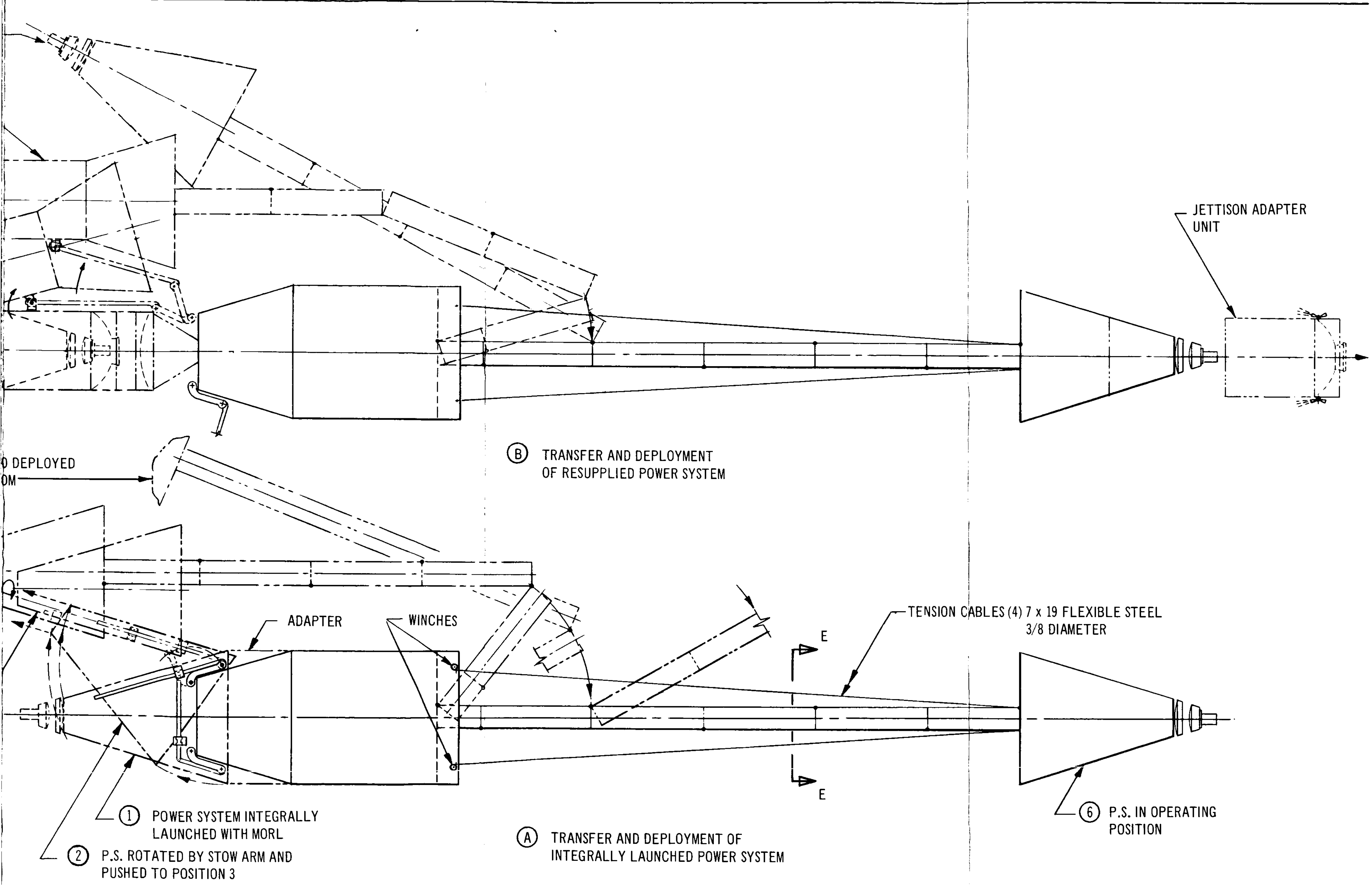
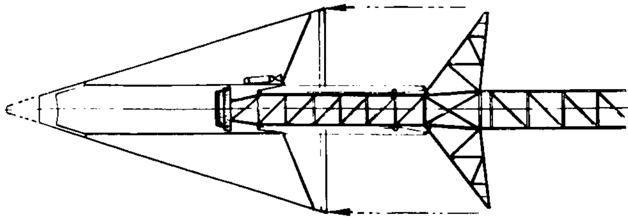


Figure 4-6. Deployment Boom



POWER SYSTEM AT END OF INITIAL EJECTION-READY FOR JETTISONING

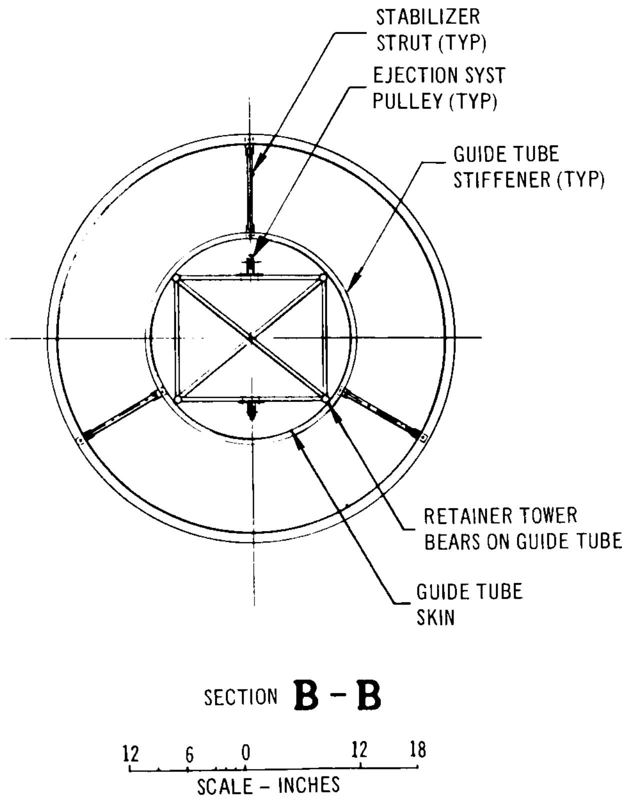
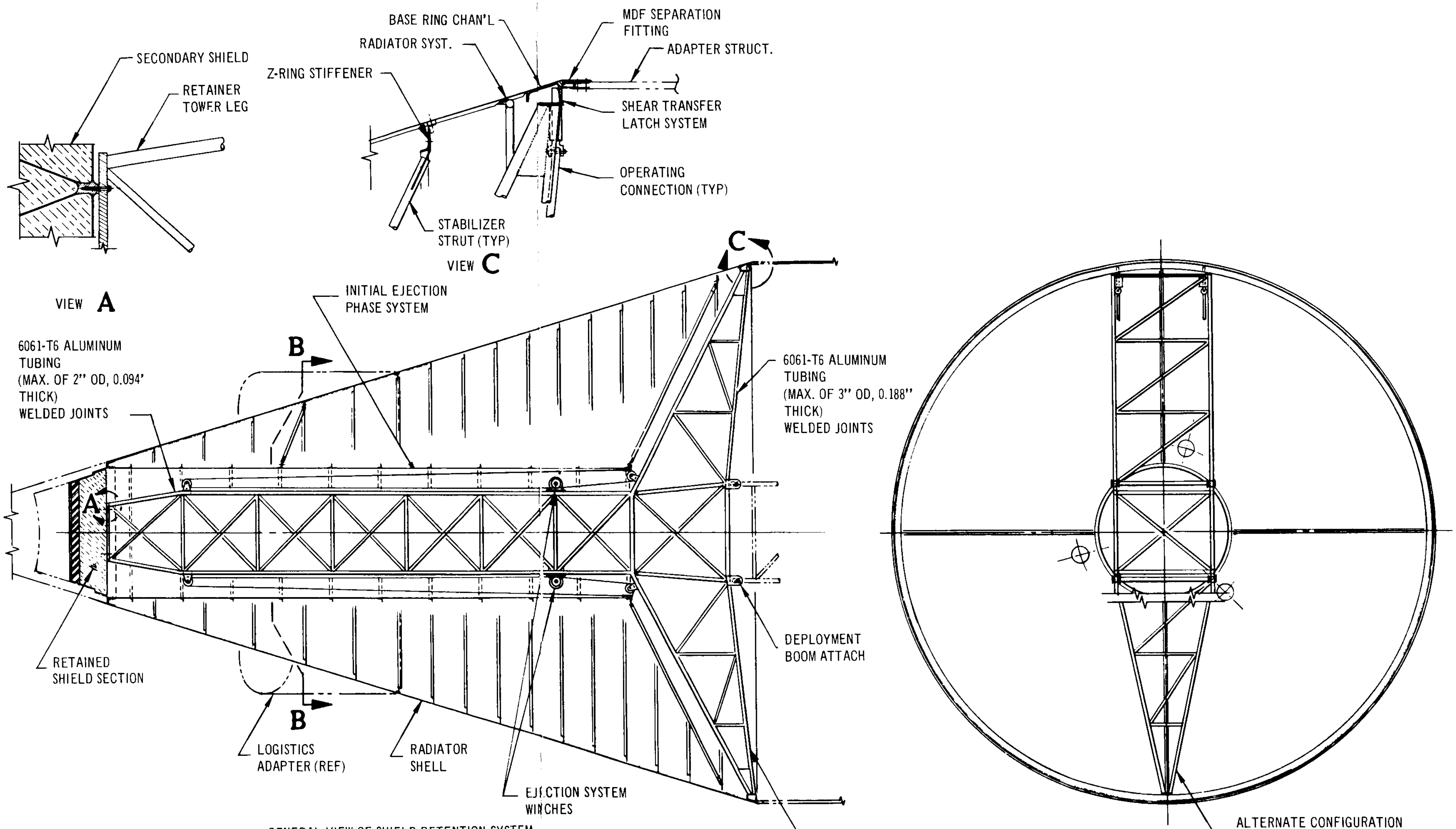


Figure 4-7. Secondary Shield Retention



GENERAL VIEW OF SHIELD RETENTION SYSTEM
AND INITIAL EJECTION METHOD
(POWER SYSTEM EQUIP'T OMITTED FOR CLARITY)

selected design of all reactor power system configurations requiring retention of the secondary shield. The secondary shield is attached to a tower structure extending along the center of the power system to a truss system spanning the diameter at the base of the configuration. This tower structure is fitted inside a reinforced tubular section attached to the upper support ring of the power system radiator and stabilized along its length by means of struts extending to the ring stiffeners of the radiator shell. This tube forms a guide to protect the power system components and to facilitate the alignment of the configuration during installation and removal from the deployment system. The guiding tube and retention clamps permit the insertion of the secondary shield into the replacement power system configuration with a large tolerance in its rotational orientation.

The attachment of the shield to the reactor power system configuration is achieved by clamps extending from the ends of the truss and engaging flanges of the stiffening ring at the base of the configuration. A system of cables and winches is provided to aid in the movement of the configuration along the tower guides to assure that the configuration will not jam during replacement operations. Because the release of the secondary shield is accomplished at the aft end of the configuration, maximum access is provided and the necessity of approaching the reactor to release support attachments is obviated. Provisions for jettisoning the reactor power system configuration are included in the system required for retention of the secondary shield.

4.4.1.3 Reactor Power System Disposal

Final disposal of the reactor power system is accomplished by a cluster of three solid rockets attached to the guide tube and canted such that the thrust vectors intersect on the axial center line of the configuration at the c. g. For purposes of the present study, provisions are made for either placement into higher orbit or re-entry of the reactor power system into a designated area, adhering to the following sequence: separation of the reactor power system from the MORL by thrusting the MORL and the reactor power system configuration until a separation distance determined by safeguard considerations is obtained; maintenance of an approximate deorbit attitude in orbit until the deorbit location is approached; and deorbit by firing of the three solid rockets. To achieve this objective, an elementary guidance system and an RCS must be used to supplement the main rockets.

The proposed guidance system consists of an attitude reference (made up of a horizon scanner) to provide pitch and roll attitude information, and a roll rate gyro (operating in a gyro compass mode) to provide yaw attitude information. Attitude command, to attain the correct attitude for deorbit and thrust initiation, is originated aboard the MORL. A radio command link relays the required signals from the MORL to the reactor power system configuration. The control system equipment consists of switching amplifiers and passive radio command networks, which use the attitude signals to derive rate which, in turn, is used to provide damping.

4.4.2 System Installation

With the exception of the 10-kWe thermoelectric system, the reactor power systems are supported by the radiator structural assembly. This structure consists of a shell of aluminum sheet, stainless steel coolant tubes (meteoroid armor on the tubes), and stiffening rings of cross-section Z-construction to provide the necessary resistance to buckling under axial and bending compressive loads. PCS components are supported by brackets attached to the stiffening rings. The reactor and primary shield (adjacent to the reactor) assembly are supported at the forward end of the radiator structure. Coolant lines from the primary coolant system to the PCS are routed through penetrations around the periphery of the secondary shield. For the 10-kWe direct radiating thermoelectric system the reactor and shield assembly are supported by a titanium truss core sandwich structure located on the inside of the converters.

Thermal shields have been selected to prevent freezing of radiator fluids when the reactor power system is shutdown. The selected thermal shield design of two sections of rigid shell structure attached to the aft support ring of the power system configurations through a mechanism which permits the removal, storage, and replacement of the shield sections as required. The rigid structure forming the thermal shield halves consists of a 1/2-in.-thick sandwich section with a 0.016-in.-thick aluminum skin and a fiber-glass honeycomb core. On the 10-kWe thermoelectric system design only, the skin thickness is increased to 0.020 in., and the core thickness to 0.75 in. The shield is separated from the radiator surface to preclude a direct conductive heat transfer path between the two surfaces. This is accomplished by separators, made of an aluminum Z- or channel-section, that are formed into half-rings and attached to the thermal shield sandwich structure. Thermal insulation is added to the inside of the thermal shield sandwich structure and consists of multiple layers of NRC-2 (aluminized Mylar). The fiber-glass honeycomb core provides further thermal insulation because of its low thermal conductivity.

Accessibility of the power conversion system for inspection requires that the temperature in the vicinity of the equipment be limited to acceptable levels. In each configuration, thermal shielding has been arranged to limit the temperature in the area of the PCS units through the use of reflective insulating materials. Additional thermal protection must also be applied as required around individual PCS components to further protect personnel during maintenance operations.

A meteoroid shield is provided to protect the components in the aft portion of the power system configuration. This meteoroid shield is tailored to the arrangement of the PCS, RCS, and related propellant tankage, with provisions for access to the components for inspection or maintenance. Where possible, it has been arranged to provide common support for the thermal insulation. In the case of 20-kWe Brayton-cycle system, the PCS modules are also protected by individual enclosures.

The stabilization and control requirements of the MORL and reactor power system configuration dictate the installation of reaction control thrustors and associated propellant tankage on the reactor power system configuration. The thrustors are attached near the center of the boom-attach structure to ensure that their plumes do not impinge on the thermal shield.

The propellant supply, consisting of nitrogen tetroxide (N_2O_4) and monomethylhydrazine (MMH) are stored in two pairs of similar tanks supported on the boom-attach structure. Positive expulsion of the propellants is achieved by pressurizing an accordion-pleated bladder in each tank by gaseous nitrogen. High-pressure nitrogen is stored in a spherical tank attached to the propellant tank assembly, together with the necessary pressure regulator and check valves.

4.4.3 Artificial-G MORL Design Configuration

The spin deployment system adopted for the MORL to obtain an artificial environment consists of an eight-cable truss system which connects to the S-IVB, and spin rockets with associated propulsion system components installed as modules on the S-IVB. The cable system provides a variable spin radius up to 70 ft from the common center of mass of the spinning configuration to the operation/experimental deck. The artificial-g field in the MORL can be as high as 0.6 g, although the nominal design is for 0.33 g. The 0.6- and 0.33-g conditions at 70-ft radius are achieved by rotating the deployed MORL S-IVB/reactor power system at 5.02 and 4 rpm, respectively. The design condition selected for the reactor power systems is as follows:

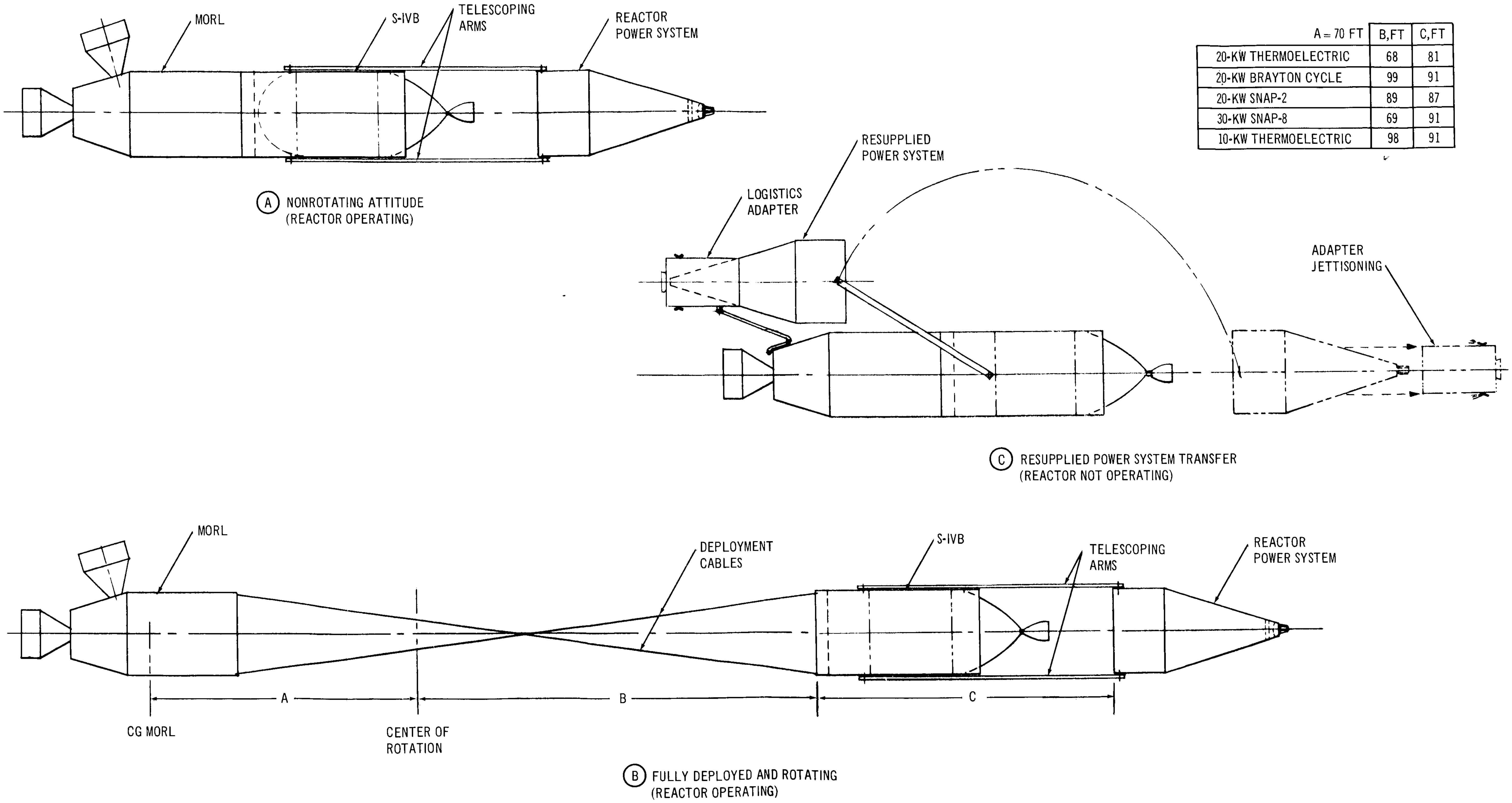
1. Gravity at MORL, 0.6.
2. Rpm, 5.02.
3. MORL weight, 100,000 lb.
4. MORL spin radius, 70 ft.
5. Reactor power system spin radius, varies according to reactor power system weight.
6. Design gravity at reactor power system, 2 g's.

The selected artificial-g design configuration, shown in Figure 4-8, includes a double telescoping arm deployment system for positioning the reactor power system at the required separation distance during operation in the zero-g attitude. Extension of the combined reactor power system and S-IVB is achieved by spinup using the cable system and the spin rockets of the propulsion system on the S-IVB forward skirt.

4.5 LAUNCH VEHICLES

The three types of launch conditions associated with the MORL/reactor power system are as follows:

1. Integral Launch--On the initial launch into orbit, MORL and the reactor power system are launched as an integral payload on the same launch vehicle.
2. Separate Launch--On the initial launch into orbit, MORL and the reactor power system are launched separately, necessarily followed by a rendezvous.
3. Replacement Launch--A reactor power system is launched into orbit when required to replace the initial reactor power system.



A = 70 FT	B,FT	C,FT
20-KW THERMOELECTRIC	68	81
20-KW BRAYTON CYCLE	99	91
20-KW SNAP-2	89	87
30-KW SNAP-8	69	91
10-KW THERMOELECTRIC	98	91

Figure 4-8. Artificial-g Configuration

Three launch vehicles were identified as candidates for these launch conditions and are presented in Figure 4-9 with their payload capabilities for the 50°-inclination, 218-nmi operational orbit. The product-improved Saturn IB is a minimum cost/minimum modification configuration. The modifications include the telemetry system, Saturn IB stage fin elimination and substitution of mounting structure, use of the H-1 and J-2 engines at their maximum thrust rating, and use of a programmed mixture ratio in the S-IVB. The MLV-Sat IB-11.5 is a zero-stage Saturn IB with four 120-in., 5-segment, solid propellant engines strapped to the Saturn IB stage.

4.5.1 Initial Launch

Selection of the integral launch mode over separate launch for initial MORL/reactor power system launch was made for reasons of cost, reliability, growth accommodation, and alternate mission compatibility. The cost of a Saturn IB launch is approximately \$43.5 x 10^6 (operational launch and vehicle procurement), but because the separate launch concept requires two launches, the cost is approximately \$90 x 10^6. The cost of an integral launch using a Saturn V is also approximately \$90 x 10^6, but, if the MLV-Sat IB-11.5 is considered, the cost is approximately \$50 x 10^6. At most, the cost of the integral launch mode is equal to the cost of a separate launch; if the MLV-Sat IB-11.5 is used, the cost is \$40 x 10^6 less. On the basis of these cost considerations and launch vehicle payload/MORL-reactor power system weight compatibility, the MLV-Sat IB-11.5 was selected as the launch vehicle for integral launch into the 50°-inclination, 218-nmi circular orbit. All launches into polar and synchronous orbits are accomplished by Saturn V. While the separate launch mode for initial launch was rejected for this operational integration of a reactor power system with MORL, potential advantages of a separate launch for a reactor power system orbital test are realized. Separate launch requirements, therefore, are subsequently presented.

The MORL/reactor power system integral launch weight shown on Table 4-7 consists of the reactor power system, associated reactor power system weight penalties and structures, the MORL, and the MORL-reactor power system adapter. Integral launch weights for all power systems considered are within the 69,000-lb payload capability of the MLV-Sat IB-11.5 with no weight contingency applied. However, when the standard 20% contingency is applied, the 30-kWe SNAP-8 system and, marginally the 20-kWe thermoelectric system, exceeds the payload capability. There are two methods of achieving payload compatibility for the 30-kWe SNAP-8 system: (1) use of an intermediate loop in the SNAP-8 design, or (2) realization of additional payload capability from the launch vehicle. Analysis of the 30-kWe SNAP-8 using an intermediate loop indicates that the intermediate loop system weighs approximately 3,000 lb less than the SNAP-8 system presented in Table 4-7, thereby negating any payload deficiency. Launch vehicle capability may be increased because the MLV-Sat IB-11.5 is only one of a family of upgraded Saturn IB launch vehicles yet to be developed. Additional payload capability may be realized if and when the MLV-Sat IB-11.5 is developed or possibly another upgraded Saturn IB of the family (but with additional payload capability) should be selected for development. The heights of the integral launch vehicles (the MLV-Sat IB-11.5, the MORL, and the reactor power system) are compatible with the structural limitations of the various booster stages and interstages.

PAYLOAD CAPABILITIES – LB (50° INCLINATION, 218 NMI)		WEIGHT AVAILABLE (LB)
PRODUCT IMPROVED SAT-IB	37,580	18,110
MLV-SAT IB-11.5	69,000	41,000
SAT V	~235,000	~207,000

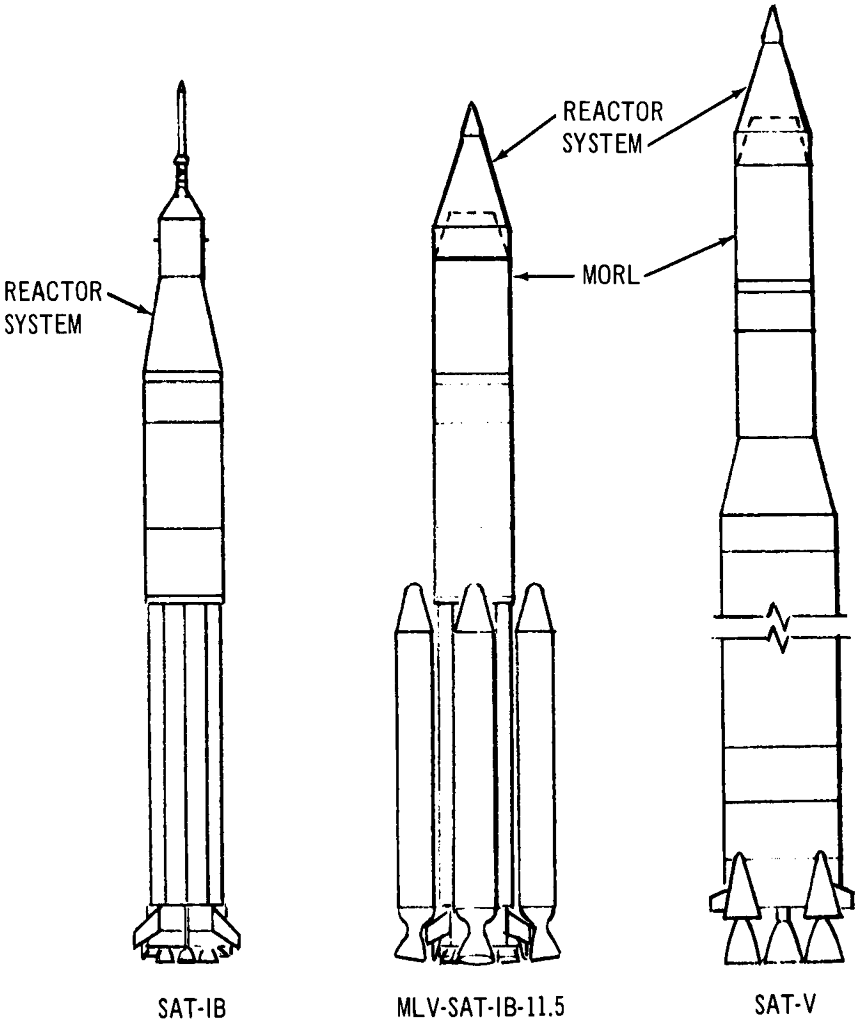


Figure 4-9. Candidate Launch Vehicles

Table 4-7

MORL/REACTOR POWER SYSTEM WEIGHTS

Power Conversion Cycle	Thermoelectric		Brayton	SNAP-2	SNAP-8
Power level (kWe at load)	10	20	20	20	30
Basic design	SiGe Direct Radiating	PbTe Compact	10 kW Modules	5 kW Modules	3 Boilers installed in gallery 3 Pcs's
Total reactor power system weight, lb	27, 308	33, 981	25, 983	24, 699	34, 826
Integral launch adapter, lb	1, 020	404	1, 020	120	1, 020
Integral launch weight,* lb (with 20% contingency)	56, 328 (61, 994)	62, 385 (69, 262)	55, 003 (60, 405)	52, 819 (57, 783)	63, 846 (71, 016)
Integral launch height, ft	220. 3	224. 2	225. 6	220. 8	225. 0
Replacement launch adapter	-0-	-0-	-0-	1, 030	-0-
Replacement launch weight, with shield retention, lb (with 20% contingency)	13, 040 (15, 648)	18, 838 (22, 606)	13, 698 (16, 438)	12, 275 (14, 730)	17, 509 (21, 011)
Replacement launch weight, with fixed shield, lb (with 20% contingency)	16, 540 (19, 848)	22, 943 (27, 531)	16, 748 (20, 098)	15, 520 (18, 624)	23, 074 (27, 688)
Replacement launch height, ft	220. 4	231. 1	220. 5	225. 7	219. 9
Separate launch weight, lb (with 20% contingency)	18, 125 (21, 751)	25, 078 (30, 094)	18, 343 (22, 011)	17, 256 (20, 708)	25, 087 (30, 105)

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*Includes dry MORL weight, less Pu-238 Brayton Primary Power System, of 28, 000 lb.

4.5.2 Replacement Launch

Because of the radiation environment indigenous to the reactor system, it generally is not feasible to replace the system on a component basis; consequently, nearly complete system replacement is required. The product-improved Saturn IB was selected as the launch vehicle for this replacement for economic reasons. To minimize the reactor power system replacement time, routine MORL logistic operations also must be conducted with the same launch vehicle as the replacement power system.

Like the integral launch case, the total launch vehicle payload capability is not available to the reactor power system in a replacement launch. The MORL mission rendezvous technique requires a manned logistics spacecraft; hence all MORL logistics launches require an Apollo CSM. The payload available for a replacement reactor power system is the product-improved Saturn IB payload minus the Apollo CSM, minus the reactor power system adapter structure, and minus the S-IVB reactor power system adapter, if required. This available payload weight is 18, 110 lb.

The replacement reactor power system launch weights presented in Table 4-7 are for two conditions: (1) retention of the secondary shield during system replacement, and (2) jettisoning of the secondary shield (no shield retention) with the reactor power system, thereby requiring inclusion of a secondary shield in the replacement system launch. When the secondary shield is retained during system replacement, all replacement reactor power system launch weights are within the payload available (18, 110 lb) of the product-improved Saturn IB with the exception of the 20-kWe thermoelectric system. However, when a 20% weight contingency is applied, the 30-kWe SNAP-8 system also exceeds the payload available to the reactor power system. Rationalization of this payload deficiency can be related to the selection of the launch vehicle. The particular product-improved Saturn IB was selected because it represented minimum cost/minimum modification to the presently conceived Saturn IB, but the presently conceived Saturn IB has not yet been definitely commited to an operational program and subsequent total development. When this final commitment is made, the payload capability may be increased, thereby accommodating the subject payloads.

Although jettisoning the secondary shield with the reactor power system simplifies the subsequent replacement operation, the replacement power system weight with the secondary shield included must be compatible with the replacement launch vehicle's available payload. If the secondary shield is not retained during system replacement, the corresponding replacement system weight increases 3,000 to 7,000 lb over the replacement system weights when the secondary shield is retained. Hence, none of the systems can be designed for replacement with retention of the secondary shield on the deployment boom, unless launch vehicle upgrading is considered.

Weight alone is not the only criterion of concern in selecting a launch vehicle for a replacement launch. Because of the additional height of the Apollo CSM which are stacked atop the replacement reactor power system, the overall launch vehicle height must be considered. The vehicle design structural loads are encountered at the maximum $q\alpha$ flight condition. These bending moments are affected by the magnitude of the $q\alpha$, vehicle height, vehicle shape, and vehicle weight distribution. Analysis has revealed that this height limitation for a replacement power system assembly on a product-improved Saturn IB is approximately 230 ft, precluding Saturn IB stage or interstage redesign. The launch heights of the replacement launch vehicles are all within this height limitation, with the exception of the 20-kWe thermoelectric system, although analysis has indicated marginal structural compatibility for this configuration.

4.6 ALTERNATE CONFIGURATION

Although the MORL-reactor power system design and configuration ultimately achieved as presented in the preceding paragraphs meets all the mission requirements, operational advantages can be realized by elimination of the deployment boom. This elimination can be achieved by relocating the reactor power system configuration adjacent or abutted to the MORL interstage section (aft end), thereby reducing the separation distance to approximately 50 ft (depending on the system) between the reactor and the living quarters deck. Because of this reduced separation distance, the shield weight increases significantly. This increase requires the use of a Saturn V for initial launch and an upgraded Saturn IB for replacement launch; these requirements do not meet the guidelines of this study.

The shadow-shield weight for a 50-ft separation distance and an 80-ft dose plane diameter approaches that of a 2π shield. The application of a near 2π shield requires such reactor and shield modifications as the use of cylindrical beryllium oxide control drums, the replacement of the primary gamma shield of U-8 w/o Mo by tungsten to reduce the heating rate, and provisions for active shield cooling. Moreover, it may be desirable to relocate that primary coolant system on the opposite side of the reactor from the 2π shield and power conversion system to facilitate retaining most of the shielding on reactor power system replacement.

Location of the reactor power system adjacent to the MORL also affects the stability and control system and the thermal protection of the system during reactor shutdown. The moment of inertia of the configuration about the pitch and yaw axes is reduced by approximately 50%, resulting in a similar reduction in the peak values of the cyclic disturbance torques and maneuver requirements. As a result, the CMG size decreases by approximately 50%. Conversely, the RCS mounted on the reactor configuration no longer provides its moment arm advantage and, consequently, is eliminated, resulting in complete reliance on, and subsequent weight increase of, the MORL RCS. It may be possible to eliminate the retractable thermal shield protecting the power conversion system radiators, inasmuch as waste heat from the Pu-238 Brayton standby power system could now be more readily transferred to the reactor power configuration for thermal protection.

To eliminate the relocation of the reactor power system from the forward to the aft end of the MORL after initial orbit attainment, the MORL would have to be launched inverted (with respect to the baseline design) and the configuration modified to provide a completely cylindrical configuration. Deployment would then be required only for the replacement reactor power system. This deployment could be accommodated either by a simplified transfer boom that swings from the forward end to the aft end of the MORL or by docking directly at the aft end of the MORL. Another docking port would then have to be located at the aft end on the side of the MORL and would require a handling arm, similar to the logistic vehicle stowage arms, to transfer the replacement system to its operating position.

The effects of this replacement operation on the ORL program can be minimized if the need for an unscheduled reactor power system replacement could be eliminated. This would have the effect of divorcing the replacement reactor power system launch vehicle from the routine ORL logistics vehicle because the replacement launch could now be scheduled. This would permit selection of a replacement launch vehicle with a payload capability compatible with the weight of the abutted reactor power system. Attainment of a reactor power system that would only require a scheduled replacement is contingent on developing sufficient confidence in the reactor power system design such that quick-response accommodation of an unexpected failure would not have to be a design objective.

Table 4-8 presents the 20-kWe thermoelectric system weights resulting from locating the reactor power system adjacent to the MORL for both an 80-ft and an infinite dose plane diameter. These weights represent preliminary estimates only, subject to verification based on more detailed shield analysis for the relatively small separation distances. Decreasing the separation distance to 50 ft results in an integral launch weight requiring a Saturn V because upgraded Saturn IB vehicles presently under consideration do not possess payload capabilities exceeding approximately 100,000 lb. The replacement system launch weights are strongly influenced by the amount of shielding which can be retained. A more detailed analysis is required to establish these requirements. However, with the assumptions made, Table 4-8 indicates that the replacement weight for the abutted design with an 80-ft dose plane diameter is only 10,000 lb greater than the baseline configuration with a 125-ft separation. This rather modest payload increase can be accommodated by an upgraded Saturn IB with a gross payload capability of 47,000 lb to the 50°-inclination, 218-nmi orbit.

Table 4-8

ALTERNATE CONFIGURATION WEIGHTS

(20-kWe Compact Converter Thermoelectric System)

Dose Plane Diameter (ft)	Separation Distance (ft)	System Weight (lb)	RCS Propellant (lb per resupply)	Integral(1) Launch Weight (lb)	Replacement(1) Launch Weight (lb)
80	50	72,866	2,400	115,920	32,168
∞	50	132,570	4,600	188,000	47,300
80 (baseline)	125	33,981	407	69,261	22,606

(1)Includes 20% weight contingency.

Elimination of the deployment boom by the design modifications described would improve system reliability and overall ORL-reactor power system acceptance because the configuration could be considered as a single unit until system replacement. Accessibility to the reactor power system would be improved, and piping interconnections between the MORL and the system to satisfy thermal requirements would be feasible. Although further investigation is required to develop replacement system rendezvous and deployment requirements, to achieve greater system confidence in system lifetime predictions, and to reduce RCS propellant requirements, no significant problem areas are contemplated. This concept, therefore, offers a significant potential, based on the use of a launch vehicle such as Saturn V which provides the required payload capability.

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Section 5

POWER CONVERSION SYSTEM CAPABILITIES

The individual power conversion systems were evaluated with respect to their effectiveness in meeting the principal integration requirements and limitations of the MORL/reactor power systems. These requirements and/or limitations, grouped into six basic integration criteria, are presented in Table 5-1, along with potential power conversion system improvements that enhance each criterion.

5.1 SNAP-8 MERCURY RANKINE POWER CONVERSION SYSTEM

The baseline 30-kWe SNAP-8 system can be satisfactorily integrated with the MORL; it also offers the potential for growth capability to the 50-kWe power level. Adoption of this growth requires a cylindrical extension to the MORL to accommodate the EC/LS and standby power source radiator, and a Saturn V launch vehicle.

5.1.1 System Weight

The 30-kWe SNAP-8 system integral launch weight is 63,846 lb compared with the MLV-Saturn IB-11.5 payload capability of 69,000 lb to a 50°-inclination, 218-nmi circular orbit. With a 20% system weight contingency, launch vehicle payload capability is exceeded by 2,016 lb. The replacement system launch weight of 17,509 lb, without contingency and assuming secondary shield retention on the MORL, is within the product-improved Saturn IB available payload capability of 18,110 lb. However, a weight deficiency of 3,000 lb for the replacement launch results when a 20% weight contingency is applied. These weight deficiencies require selection of a launch vehicle with greater payload capability than the MLV-Saturn IB-11.5 for integral launch and possibly an increase in Saturn IB replacement launch capability. The 20-kWe SNAP-8 can be accommodated in the integral launch by the presently selected launch vehicle. However, the replacement launch cannot be accommodated unless a reduced contingency is allowed.

The principal system design modifications providing the potential of a significant reduction in weight include the application of an intermediate NaK loop, with the possible use of thermoelectromagnetic primary pumps, and the increase in component lifetime capability from 1-1/4 to 2-1/2 yr. If the component lifetime is extended to 2-1/2 yr without increase in failure rate, the reactor power system reliability using two power conversion subsystems is equivalent to that of three power conversion subsystems with 1-1/4-yr components.

5.1.2 Design Integrity

The design integrity of the SNAP-8 system is affected by the location and design of the boiler, and by the use of lube coolant fluid for the primary

Table 5-1
INTEGRATION CRITERIA

System	System Weight	Radiator Area	Lifetime and Reliability	Design Integrity	Maintenance/ Replacement	Performance/ Flexibility
20-kWe and 30-kWe SNAP-8	1. Intermediate loop 2. 2-1/2-yr component lifetime		1. 2-1/2-yr component lifetime 2. Pump design 3. Startup	1. Boiler design 2. L/C fluid radiation tolerance 3. Thermal shields		1. Operation in zero-g and artificial-g 2. Growth capability
20-kWe SNAP-2	1. 2-1/2-yr component lifetime 2. 10-kWe CRU		1. 2-1/2-yr component lifetime 2. 10-kWe CRU 3. Startup	Installation complexity	5-yr system lifetime	1. State point selection 2. Operation in zero-g and artificial-g 3. Growth capability
20-kWe and 30-kWe Brayton	1. Xe-He mixture 2. Component efficiency 3. 2-1/2-yr component lifetime	1. Component efficiency 2. Absorptivity/ emissivity ratio	2-1/2-yr component lifetime	Thermal shields	1. PCS module replacement 2. 5-yr system lifetime	Growth capability
10-kWe Thermoelectric	1. Converter efficiency 2. Redundancy 3. Structure 4. Operating temperature	1. Converter efficiency 2. Operating temperature	Redundant capacity	Thermal shields	Converter accessibility	1. Converter and reactor operating temperatures 2. Growth capability
20-kWe Thermoelectric	1. Converter efficiency and degradation 2. Redundancy	1. Converter efficiency and degradation	Redundant capacity	Thermal shields	Converter module replacement	Growth capability

centrifugal pumps in the shield gallery. Either of these factors could result in premature system failure despite the specified redundancy provisions. Location of the boiler in the shield gallery results in the possibility of introducing activated primary NaK into the power conversion system or mercury into the primary coolant system in the event of boiler tube leakage. A redesign of the boiler represents a positive means of preventing intermixture of mercury and NaK. However, this redesign requires an increase in boiler size and weight because of the reduced heat transfer effectiveness.

The use of an intermediate loop minimizes the leakage problem, reduces system weight, and provides accessibility to the boilers for isolation and potential maintenance, since the boilers can be installed behind the secondary shield. Also, the liquid-vapor interfaces of the condenser and boiler can be installed at the same elevation, thereby improving system operation in either the zero-g or rotating mode.

The design integrity of the system is also affected by the radiation tolerance of the lube coolant used to cool the primary NaK pump motor assembly installed in the shield gallery. The use of lube coolant within the shield gallery is marginal and is dependent on accurate assessment of gallery radiation levels. However, alternative methods of providing coolant are possible. They include (1) use of an additional NaK to lube-coolant fluid heat exchanger located behind the secondary shield to cool a fraction of the heat rejection loop NaK flow, which in turn is used to cool the pumps; (2) use of heat rejection loop NaK at 500°F to cool the pumps directly, and (3) location of the primary pumps below the secondary shield with local shielding around each pump.

5.1.3 Performance/Flexibility

The MORL rotating mode has minimal effect on SNAP-8 system operation with the application of an intermediate loop because the liquid-vapor interface of the condenser and boiler can be installed at the same elevation. However, with the boilers installed in the shield gallery, the difference in elevation of boilers and condensers results in a higher pressure at the boiler inlet when in an artificial-g mode of operation, in comparison with zero-g operation. One method of correcting this problem involves the addition of a pressure regulating valve in the boiler feedline to maintain constant pressure conditions.

In the case of a local-g environment, it is necessary to locate the mercury pump below (with respect to the gravity field) the condenser to avoid loss of NPSH because of the hydrostatic head. The lube-coolant pump must also be located below both the turbine alternator and mercury pump when local-g operation is encountered because the lube-coolant fluid dynamic slingers are designed to operate against a fixed back pressure, which must be maintained with ±0.5 psi to obtain proper coolant flow rates. In addition, the turbine alternator and mercury pump bearing reliabilities are somewhat degraded for extended mission durations when operated in an artificial-g mode.

The SNAP-8 system was evaluated for a net alternator output of 59.1 kWe (50.0 kWe at the bus). This power level is obtained with a system mass flow rate increase of 15% from the baseline system design, a 64.4% turbine efficiency, and application of power factor improvements. The 50-kWe power system radiator area requirements are 1,049 sq ft for the HRL and 370 sq ft for the LCL. The EC/LS heat load is 69.0 kW requiring 4,200 sq ft of radiator surface. These radiator area requirements can be satisfied by using a modified, cylindrical MORL (260-in. diam, no conical section) with a cylindrical extension to accommodate the EC/LS radiator. This results in a Saturn V launch height of 389 ft. The total integral launch weight with a 20% contingency is 77,761 lb. The replacement launch weight with shield retention and a 20% contingency is 26,604 lb.

5.2 SNAP-2 MERCURY RANKINE POWER CONVERSION SYSTEM

5.2.1 System Weight

The 20-kWe SNAP-2 system configuration has the lowest weight and radiator surface area requirements of the systems investigated in this study. An integral launch weight of 57,783 lb, and a replacement system launch weight of 14,730 lb, with secondary shield retention on the deployment boom, are within the selected launch vehicle capabilities, including 20% system weight contingency. If the shield is fixed, the replacement system launch weight provides 17% contingency. The system design satisfactorily meets all specified integration requirements. However, a degree of installation and operational complexity is introduced by the multiplicity of CRU's to achieve lifetime and reliability objectives for the selected systems.

5.2.2 Lifetime and Reliability

The selected 20-kWe SNAP-2 system consists of 14 CRU's to achieve a 2-1/2-yr system lifetime, requiring the operation of 5 CRU's for each 1-1/4-yr interval, and a total of 4 standby units. By an increase in component lifetime from 1-1/4 to 2-1/2 yr with constant failure rate, the total number of CRU loops can be reduced from 14 to 10 and the number of radiator condensers from 7 to 5 for the equivalent system reliability. The system arrangement and installation requirements are thereby simplified. A corresponding reduction in radiator surface area from 757 to 540 sq ft results. The application of a scaled-up combined rotating unit, capable of delivering 10-kWe net output power, would further reduce the installation complexity.

The SNAP-2 system was evaluated with respect to wearout failure modes to confirm the selection of a 1-1/4-yr component lifetime and to indicate the potential for 2-1/2 yr of operation. (Refer to Task Area III, Table 6-6, Douglas Report No. DAC-57932.) All of the identifiable failure modes appear to allow this increased lifetime capability, based on present test experience. These test results extrapolate to a CRU lifetime potential exceeding 22,000 hr. Based on continued materials testing, the application of filters and/or separators for corrosion product removal, and the relatively conservative selection of the cycle boiling temperature (935°F), it appears that 2-1/2-yr component lifetime can be achieved.

The scaled-up combined rotating unit investigated in this study is based on present SNAP-2 mercury Rankine technology. Studies of known wearout modes on present CRU's show that the higher power unit would have an even longer operational life and reliability.

The SNAP-2 system state point selection represents a conservative design basis. A nominal reactor coolant outlet temperature of 1,200°F is selected, in comparison with 1,300°F for the remaining power conversion systems studied. The corresponding boiling temperature of 935°F, superheat of 250°F, and turbine exhaust pressure of 9 psia yield a cycle efficiency of 8.4%. A 100°F increase in boiling temperature would raise cycle efficiency to about 10.5%. However, the lower temperature selected enhances reliability and lifetime potential by a reduced corrosion rate and increased design margin.

5.2.3 Performance/Flexibility

Operation in either a zero-g or artificial-g environment is accomplished by the orientation of the radiator-condensers and by locating the CRU's and regulator tanks at the subcooler-vapor interface of the condensers. However, with this arrangement, the potential for maintenance is limited.

Growth capability to higher power levels (approximately 30 kWe) generally is not limited by system weight, radiator surface area requirements, or reactor thermal power limitations. However, based on the present 5.6-kWe CRU design, the total number of units to meet reliability and lifetime requirements may be excessive with respect to component arrangement, installation, and operation complexity. Therefore, the uprated 10-kWe CRU design appears to be better suited for power levels over 20 kWe.

5.3 BRAYTON-CYCLE POWER CONVERSION SYSTEM

5.3.1 System Weight and Radiator Area

The integral launch weight of the 20-kWe system with the MORL is 60,405 lb, including a 20% weight contingency, as compared with the MLV-Sat IB-11.5 payload capability of 69,000 lb to the baseline 50°-inclination, 218-nmi circular orbit. Therefore, a 34% increase in reactor power system weight, sufficient for the application of a 30-kWe system output power rating (66,376-lb integral launch weight), can be accommodated within the launch vehicle payload capability. The weight of the 20-kWe replacement system configuration is 16,438 lb, including a 20% weight contingency, if the secondary shield is retained on the MORL deployment boom, or 20,098 lb if the complete shield is launched with the power system. The product-improved Saturn IB payload capability of 18,110 lb provides a 10% growth margin with secondary shield retention, but requires a reduction in the weight contingency from 20% to approximately 8% for the fixed shield configuration. The replacement 30-kWe system launch weight (21,564 lb, with secondary shield retention on the boom) also exceeds the capability of the selected launch vehicle if a 20% weight contingency is applied.

Three principal system design areas offering the potential for a significant reduction in system weight and radiator area are as follows:

1. Working Gas Selection--An optimum Xe-He working fluid to replace argon results in a 20% reduction of power conversion module weight.

2. Turbomachinery Efficiency--The selected system design is based on a compressor efficiency of 83%. However, it is expected that an increase in efficiency to about 87% can be obtained with an intensive 2-yr development program. This performance improvement results in an 11% power conversion module weight reduction and a 14% radiator area reduction.

3. Component Lifetime--The use of an inert gas as the working fluid and of gas bearings for the dynamic components provides the Brayton cycle with no identifiable performance degradation or wearout pattern. Consequently, this cycle appears to be capable of high reliability and long life. In this study, a component lifetime of 1-1/4 yr was specified for all dynamic systems to assure a practical design based on the current status of system development effort. However, it is reasonable to expect that the Brayton turbomachinery will exceed this operating capability and may provide the potential for 2-1/2 yr of service.

Based on application of the improvements in working gas, compressor efficiency, and redundancy, the overall reactor power system weight is reduced by 2,750 lb and the replacement system launch weight with fixed shield becomes 17,018 lb, including a 20% weight contingency. This value is within the selected replacement launch vehicle capability.

Application of the specified cycle improvements mentioned above includes a reduction from nine to six power conversion modules to produce rated power for the system lifetime. On this basis, the 30-kWe system is within the capability of the selected replacement launch vehicle if the secondary shield is retained on the deployment boom.

An alternative method of reducing the overall system launch weight involves individual power conversion module replacement during the mission. The selected system design provides only four fluid lines to each module, two from the NaK-gas heat exchanger to the heat source, and two to the associated radiator loop. The ability to replace the individual modules depends on the feasibility of cutting and reconnecting these liquid lines, with no leakage or entrance of foreign matter, and refilling the affected section. If this procedure is proved feasible, considerable latitude would exist in the number of PCS modules installed in the initial launch configuration, and a programmed replacement reactor power system launch would be eliminated.

5.3.2 Downgraded System Performance

The Brayton-cycle PCS was also evaluated on a more conservative basis, i.e., the compressor efficiency was reduced from 83% to 80%, and the turbine efficiency was reduced from 90.1% to 87%. These changes increased the integrated reactor power system weight by 2,000 lb and increased the radiator area from 1,150 to 1,600 sq ft. This assessment of the system design under degraded performance conditions indicated that a practicable design can be effectively integrated despite the conservative basis of the imposed conditions.

5.3.3 Performance/Flexibility

The radiator surface area (1,150 sq ft) required for the selected 20-kWe system design meets all of the integration limitations. However, an increase in system size to 30 kWe results in a 1,725-sq ft surface area requirement, which corresponds approximately to the replacement launch height limitation of 230 ft for the product-improved Saturn IB. Any further increase in launch height would be expected to require additional stiffening of the Saturn IB stage and interstages.

The Brayton-cycle efficiency of 18% resulting from the specified operating conditions is sufficiently high to provide significant growth in output power capability within the present reactor thermal power limitations. Application of a common 10-kWe power conversion module design provides flexibility in the selection of output power rating and redundancy requirements with a minimum of development effort. Moreover, the use of a single-phase working fluid is particularly well-suited to the attainment of prolonged component lifetime and high reliability. The principal system integration limitation involves the radiator surface area requirements.

Although the 20- and 30-kWe systems radiator area requirements can be accommodated within the constraints of this study, a further increase in system size is limited, based on the selected launch vehicles.

5.4 THERMOELECTRIC POWER CONVERSION SYSTEMS

Both of the thermoelectric systems satisfactorily meet the MORL integration requirements, with the exception of the replacement 20-kWe thermoelectric system launch weight, which exceeds payload capability of the selected replacement launch vehicle. Because of the inherently high reliability and anticipated prolonged lifetime capability of the thermoelectric converters, the design of these systems is predicated on a 5-yr system lifetime, equivalent to the MORL mission duration. Consequently, the system logistics requirements are simplified in comparison with the dynamic system designs.

5.4.1 System Weight and Radiator Area

The most promising means of decreasing system weight for both the 10-kWe SiGe direct radiating and 20-kWe PbTe compact converter system concepts include possible reduction in the installed redundant capacity and an improvement in overall efficiency. For the PbTe converters, an eventual reduction in the degradation allowance also appears to be possible. Optimization of the support structure for the SiGe converter configuration represents another potential source of weight reduction for that system.

A reexamination of the system weight-radiator surface area relationships on which the converter cold-side temperature selections were based provides a means of adjusting the operating temperature to favor either of these parameters, depending on which is the more limiting. For example, in the SiGe direct radiating system design, a 20% reduction in radiator area (from 1,068 sq ft to about 860 sq ft) is obtained by increasing the average cold-side temperature from 550° to 650°F, with a system weight increase of approximately 800 lb. However, under the particular integration requirements of this study, such a reduction in surface area is not warranted, because a surface area of approximately 1,150 sq ft would be available in any event to provide a configuration base diameter of 260 in., corresponding to S-IVB and MORL dimensions. In the PbTe compact converter system design, the radiator area/system weight relationship imposes a significantly higher weight penalty than the SiGe design for a nominal reduction in radiator area as cold-side temperature is raised above 550°F.

The thermoelectric converter efficiency directly affects both system weight and radiator area. Based on a reactor operating temperature limitation of 1,300°F, the converter average hot-side temperature is limited to about 1,150°F. The loss of 150°F in available hot-side temperature reduces efficiency of both PbTe and SiGe converters, and further design optimization of the systems could prove worthwhile in reducing system heat losses, reducing the temperature drop across the heat exchanger, reducing series and shunt thermal losses in the generators, and reducing the fluid temperature differential. However, because the possible gains in converter efficiency appear to be of an incremental nature within the temperature limits of the application, the assurance of a highly reliable design is viewed as being significantly more important than the weight or radiator area gains achieved by such means.

The redundant capacity provided in the 20-kWe PbTe system design amounts to approximately 27%. In addition, the actual power output (22.5 kWe) is about 12% higher than the specified 20-kWe level. Based on the converter reliability goals specified for this study, the overall reactor power system reliability exceeds the requirements. Although the reliability goals require substantiation in the continued development of this system concept, it is reasonable to expect some reduction in the redundant capacity and the required number of converter loops as a result of this further work. The potential weight saving obtained by reducing the redundancy and adjusting to the specified power level decreases the number of converter loops from 14 to 12 providing a 20-kWe output power level with 22% redundant capacity and a net system weight reduction of about 1,600 lb. A corresponding radiator area reduction of about 250 sq ft would also be obtained. These changes would be reflected in a replacement launch weight of about 16,600 lb, which is within the selected launch vehicle capability, but with a weight contingency of only 9%.

The 10-kWe SiGe direct radiating system provides a 20% redundant capacity. By reasoning similar to the above, a reduction in system redundancy may be warranted on the basis of further system development. However, the associated weight reduction is not high, amounting to only approximately 400 lb for a change from 20% to 10% redundant capacity.

5.4.2 Maintenance/Replacement

The PbTe tubular converter module design provides the potential for individual module or four-pack replacement. Although the present design would require disconnecting NaK lines, it may be possible to employ a concentric reentrant tube to supply heat to the inner diameter of the tube and to fit the other diameter within a jacket through which heat would be rejected. The maintainability and replaceability of the SiGe direct radiating converters are significantly limited by the inherent design arrangement. However, accessibility to the converters could be increased if the selected structural support arrangement, consisting of a continuous shell surface inside the converter array, is replaced by an open construction, consisting of longitudinal members and circumferential ring stiffeners.

From the presently specified study criteria and limitations, a SiGe direct radiating thermoelectric system of approximately 15-kWe capacity can be accommodated, as limited by the replacement system launch weight. If an upgraded replacement launch vehicle is used, a system of approximately 19-kWe capacity can be accommodated by the selected integral launch vehicle.

The selected PbTe thermoelectric system produces a 22.5-kWe output power level. The launch weight and height constraints adopted for this study prevent an increase in the system size. For the design investigated, a deficiency of 4,500 lb exists in providing the desired 20% weight contingency for the replacement launch. Further system growth would require the selection of an alternative launch vehicle.

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Section 6

REACTOR POWER SYSTEM DEVELOPMENT REQUIREMENTS

The activities required for the development of a flight-ready reactor power system for a manned Earth-orbital application can be divided into four major phases that culminate in a vehicle launch. These phases, in chronological order, are (1) reactor power system technology readiness, (2) subsystem design and testing, (3) prototype testing, and (4) vehicle integration and testing. The vehicle integration and testing phase includes prelaunch checkout of the reactor power system at KSC immediately prior to launch.

The technology readiness phase, which precedes the Authority to Proceed (ATP) date of the mission vehicle, initiates power system research and technology efforts in critical areas and carries these efforts to sufficient depth prior to ATP to provide an increased confidence in the design approach. Therefore, it is assumed that all of the design changes that are of primary importance for the technology readiness phase are incorporated in the various system designs prior to delivery of subsystems to the prime contractor for prototype testing. The subsystem design and testing are undertaken to verify component and subsystem performance. The purpose of prototype system tests is to verify the design integrity of the integrated subsystems. The purpose of the vehicle integration testing is to evaluate the functional interactions between the power system, the MORL vehicle, all other subsystems, and the ground support equipment in the launch and simulated orbital environment. A building-block approach is employed throughout all testing, whereby successful completion of component and subsystems tests are required prior to initiation of the more complicated series of integrated tests.

A summary of the complete development plan is presented in Figure 6-1. A period of 18 months is allowed for technology readiness; 66 months is allowed for the reactor power system and vehicle development phase. The plan shown permits revisions of detailed drawings and specifications to incorporate design feedback from development tests before commitment to flight units is made. Those power systems that are in a more advanced state of development will require shorter time for both phases. Summarized herein are the reactor power system development requirements including: technology readiness, prototype system tests, and vehicle integration tests. Subsystem design and testing was presented for a typical case in the Task Area IV report, Technology Planning (Douglas Report No. DAC-57942).

6.1 REACTOR POWER SYSTEM TECHNOLOGY READINESS

The technology readiness development phase which precedes the ATP data consists of research and technology efforts in critical areas to provide assurance that a highly reliable power system can be developed for specific mission requirements with a minimum of development risk to the overall vehicle development program. Design improvements for the SNAP-8 reactor,

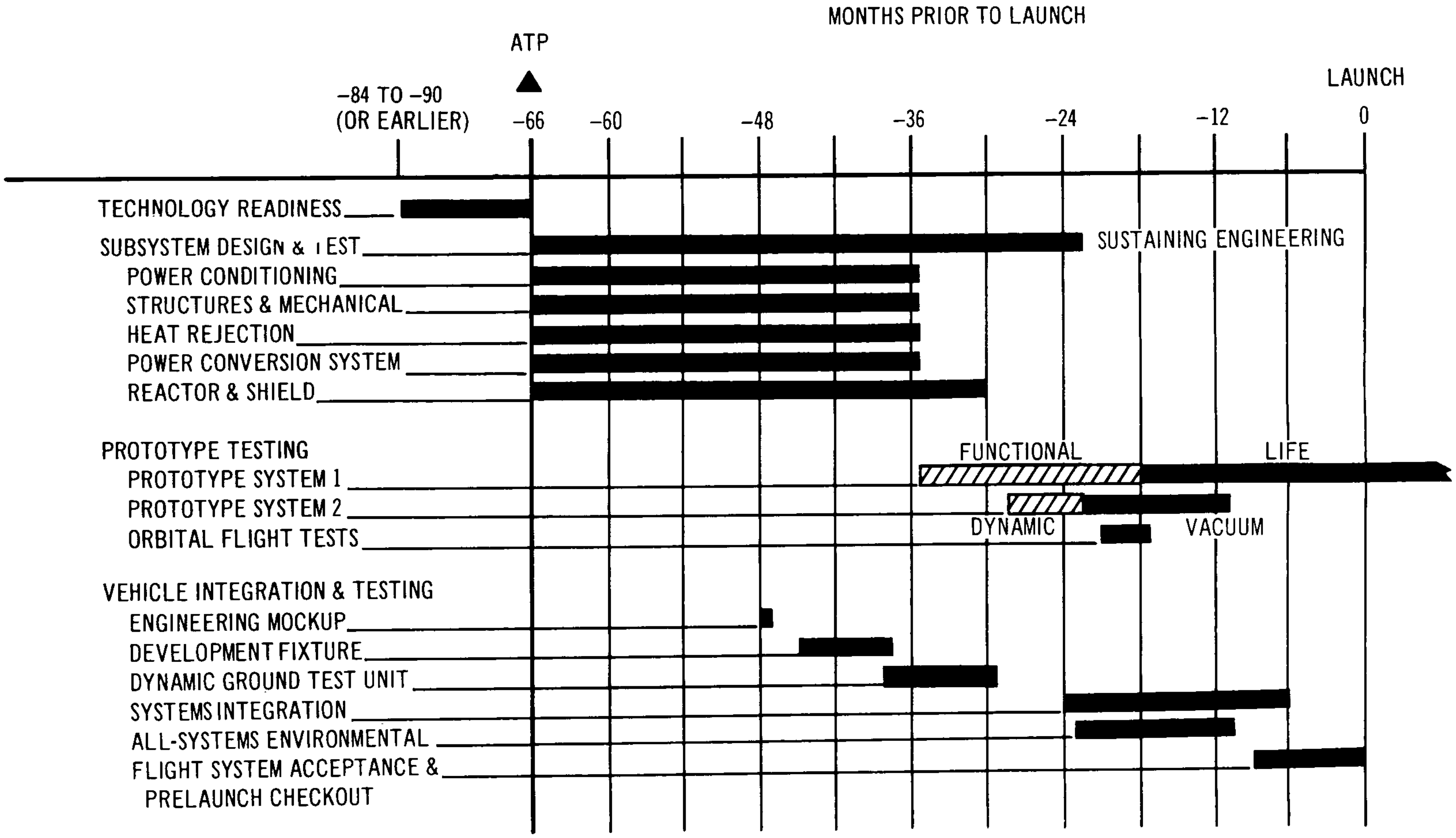

Figure 6-1. Reactor Power System Development Plan

shield, and the four conversion systems necessary to meet the MORL mission requirements are identified below as either required system changes or potential system improvements. Required system changes should be given immediate consideration such that on-going technology programs can be applied toward manned Earth-orbital applications. Potential system improvements will improve the overall power system performance but do not restrict application of the particular system, as presently conceived, for manned Earth-orbital applications.

6.1.1 Reactor and Shield

6.1.1.1 Reactor/Reflector Assembly (Required System Change)

The study results indicate that a core consisting of 349 SNAP-8 fuel elements could meet the MORL mission lifetime requirements for 5 yr. It was also found desirable to increase the number of active control drums from three to eight to enhance the reliability of the active control system and to taper the beryllium reflector and control drums to reduce shield weight. The single new development requirement is the need for incorporating additional burnable poisons in the MORL reactor to achieve an adequate control margin for the 5-yr lifetime. Analyses have indicated the feasibility of achieving a lifetime exceeding 5 yr, with respect to reactivity, by increasing the burnable poison loading in the core. Several suitable poison materials were identified.

6.1.1.2 Primary Coolant Loop (Potential System Improvements)

The desirability of utilizing a compact primary NaK loop for most man-rated reactor systems to minimize shield weight has been confirmed. Further study of thermoelectric pump designs, such as the spring-loaded TE element contacts, modified radiator configuration, and the two-stage TE elements, to permit installation in the hot leg is recommended.

6.1.1.3 Shielding (Required System Change)

The materials selected for the MORL radiation shadow shield are lithium hydride and depleted uranium alloyed with molybdenum (U-Mo). Extensive fabrication and test experience has been accumulated for lithium hydride neutron shields, but this experience does not include the large sizes required for the MORL system. Thus, previous fabrication development work on U-Mo as a fuel material for power reactors ensures the feasibility of building gamma shields of this material; but some development work may be required to fabricate the large diameter secondary gamma shield.

Rigorous analysis and specially designed experiments would also be required to optimize the shield design and confirm its effectiveness. Nuclear verification of the complete shield design would be difficult to achieve on the ground because of scattering limitations. Therefore, special tests of partial shields may be required to reduce uncertainties in shield effectiveness to a tolerable level. However, nuclear radiation effects and thermal-mechanical characteristics of the shield assembly could be confirmed by including the shield assembly in nuclear ground qualification tests of the reactor system.

6.1.2 SNAP-8 Mercury Rankine System

6.1.2.1 Boiler Redesign (Required System Change)

Location of the boiler within the shield gallery results in the possibility of introducing activated primary NaK into the power conversion system and introducing mercury into the primary coolant system in the event of a boiler tube leak. Of four possible methods of alleviating or eliminating this potential failure mode, redesign of the boiler to preclude a tube leak is considered to be the principal system change recommended for the technology readiness phase.

6.1.2.2 Effects of Zero-G and Artificial-G Operation and Multiple Restart Capability (Required System Change)

The ultimate feasibility of boiling and condensing in the zero-g environment remains one of the critical potential problem areas. In addition, multiple restart capability is also affected by operation in a zero-g environment. Further study and perhaps model testing of boiling and condensing, and fluid evacuation and refilling operations for system restart are recommended. A more detailed analysis of the effects of operation in an artificial-g environment is also recommended.

6.1.2.3 Redundant Systems Switchover and Performance (Required System Change)

The use of redundant systems requires development of equipment for malfunction detection, load sharing, and load transfer for both automatic and manual control. This work should include the detailed development of a restart system with provisions for draining, filling, and inventory control, and suitable for multiple PCS restart operations. The design and application of isolation and loop transfer valves to service a multiple PCS installation should also be studied, including an evaluation of the locations at which local manual and/or remote valve operators should be used. Instrumentation sensors for leak detection, such as conductivity cells or radiation detectors, should be evaluated for application in the detection, diagnosis, and correction of system malfunctions.

6.1.2.4 Lube-Coolant Fluid Radiation Tolerance (Required System Change)

The design flexibility of the SNAP-8 system for manned applications is limited by the radiation tolerance level of the lube-coolant fluid. Methods of alleviating this potential problem area should be evaluated during the technology readiness phase.

6.1.2.5 Static Deterioration (Required System Change)

A study of static deterioration is recommended with the objectives of identifying possible changes to the baseline design and of providing for periodic startup and shutdown.

6.1.2.6 Intermediate Loop (Potential System Improvement)

Application of an intermediate NaK-to-NaK loop is recommended for manned applications. The advantages of an intermediate loop are (1) reduced system weight, (2) improved boiler accessibility, (3) minimum adverse effects of boiler tube leakage, and (4) added system flexibility for zero-g and artificial-g operation, because the condenser and boiler can be installed at the same elevation.

6.1.2.7 Component and System Lifetime (Potential System Improvement)

High reliability and long system lifetime may be achieved by improved component reliability and lifetimes, installed redundancy, resupply of power systems, on-board maintenance, or a combination of all these concepts. Technology readiness studies of these items are therefore recommended.

6.1.3 SNAP-2 Mercury Rankine System

6.1.3.1 Redundant Systems Switchover and Performance (Required System Change)

The present SNAP-2 design possesses restart capability. However, use of 14 CRU's for the selected system requires development of equipment for malfunction detection, load sharing, and load transfer for both automatic and manual control.

6.1.3.2 Effects of Zero-G and Artificial-G Operation, Multiple Restart Capability and Static Deterioration (Required System Change)

The ultimate feasibility of boiling and condensing in the zero-g environment remains as one of the critical potential problem areas. In addition, multiple restart capability is also affected by operation in a zero-g environment. Further study and perhaps model testing of boiling and condensing, and of fluid evacuation and refilling operations for system restart are recommended. A more detailed analysis of the effects of operation in an artificial-g environment is also recommended.

A study of static deterioration is recommended with the objectives of identifying possible changes to the baseline design and of providing for periodic startup and shutdown.

6.1.3.3 Study of 10-kWe CRU Rating (Potential System Improvement)

While a detailed design of the 10-kWe CRU was not conducted, this design was evaluated in sufficient depth to indicate that this higher rated unit could be designed to be as reliable as, or more reliable than, the currently developed CRU-V machine. Further study of a 10-kWe CRU is, therefore, recommended.

6.1.3.4 Improved Boiler Design (Potential System Improvement)

The subject study has indicated the need for a compact boiler configuration both to reduce the gallery height and to provide a highly reliable NaK-to-mercury containment interface. Further study of alternate boiler designs is recommended.

6.1.4 Brayton System

6.1.4.1 Gas-Foil Bearing Development (Required System Change)

The tests required to substantiate gas-foil bearing design include determination of the amount of preload required to ensure stable operation in a zero-g environment, determination of the ability to withstand launch loads, and startup and shutdown tests.

6.1.4.2 Rice Alternator (Potential System Improvement)

Design studies and layouts should be prepared during the technology readiness phase to verify the capability of the Rice alternator design to remove heat from the region of the windings.

6.1.4.3 Xe-He Mixture (Potential System Improvement)

Evaluation of the optimum Xe-He gas mixture to replace argon as the working fluid should be accomplished in the technology readiness phase to determine its applicability to the flight system.

6.1.5 Thermoelectric Power Conversion System

6.1.5.1 Converter Performance, Reliability, and Lifetime (Required System Change)

Continued development effort should be directed toward the improvement in converter performance through minimization of parasitic losses, reduced degradation, segmentation of the couples, and application of alternative materials. The systematic identification and evaluation of failure and wearout modes are especially important factors in the development programs. Because the manned system application imposes a multiple restart requirement, a determination of the performance and integrity of the converters under thermal cycling conditions should be emphasized in this work.

6.1.5.2 Redundancy (Potential System Improvement)

A promising method of decreasing system weight is reduction in installed redundancy. However, such a reduction requires substantiation of the reliability and lifetime goals established for the converters through continued development effort.

6.1.5.3 Direct Radiating Converter Structural Optimization (Potential System Improvement)

The structural support for the direct radiating converter configuration represents a large fraction of the total system weight, because of the additional stiffening required to prevent possible converter damage under dynamic loading conditions. Further study of thermoelectric system structural supports is recommended.

6.1.5.4 Compact Converter Module Replacement (Potential System Improvement)

The installed redundancy may be reduced if converter module replacement is feasible. A more detailed investigation is warranted in view of the possible design simplification involved.

6.1.6 Ancillary Recommendations

The technology readiness recommendations that are common to all reactor power systems are as follows: (1) on-board maintenance, (2) maintenance of inactive system fluids in a liquid state, (3) facilities requirements, (4) aerospace safety, (5) impact of on-board radiological control facility, (6) deployment concepts, (7) leak detection and control, and effects of fluid leakage, (8) radiator design and fabrication, (9) standby power system interface with the primary power system, (10) orbital test requirements, and (11) study of reactor decay heat removal during power system shutdown periods. The first two items are considered potential system improvements for all of the power conversion systems. The remaining nine items are recommended as required study areas.

6.2 REACTOR POWER SYSTEM PROTOTYPE TESTS

Three complete prototype systems are required; they are (1) prototype system No. 1 (functional test unit), (2) prototype system No. 2 (environmental test unit), and (3) a flight test qualification unit.

6.2.1 Prototype System No. 1 (Non-Nuclear and Nuclear)

Initial performance tests consist of separate functional testing of a simulated energy source (electric heaters), heat rejection subsystem, single PCS or static conversion unit, and the control and conditioning subsystem. Multiple PCS or static conversion units are assembled with the simulated energy source, heat rejection subsystem, and power conditioning system into an integrated system test assembly midway through the first prototype tests to verify functional operation of the entire system. Subsequently, the reactor is installed and the entire power system is operated to demonstrate lifetime capabilities.

6.2.1.1 Separate Subsystem Checkout and Single Loop Tests (Non-Nuclear)

Initial testing or prototype system No. 1 is conducted on a single PCS and initially consists of separate functional checkouts of the simulated energy source (electric heaters), heat rejection subsystem, PCS, and the power control and conditioning system. The first subsystems to be functionally operated include the heat rejection loop and refrigeration unit to verify operating pressures, temperatures, flow rates, and heat rejection capacity. At the completion of the functional tests of the simulated energy sources and heat rejection subsystems, these units are integrated with a single conversion system and a dummy load bank for continuing functional tests of the rotating machinery or thermoelectric converters. Startup and shutdown procedures for closed-loop operation are verified. The combined rotating unit is operated to obtain overall performance and cycle and component efficiencies.

The power conditioning equipment is assembled with the integrated test unit in place of the dummy load bank; the tests are then continued using a step-by-step procedure. For example, the parasitic load control is tested for stability, dynamic response, and response at the lowest and highest power levels by applying a sudden transfer of power to and from the parasitic load. Malfunction testing includes simulated component failures.

6.2.1.2 Multiple Loop and Lifetime Tests (Non-Nuclear and Nuclear)

The proposed building block approach is typified by assembling a second PCS to prototype system No. 1 for further non-nuclear system performance tests. The system performance of multiple systems is determined, including load sharing capability, fault protection performance, stability under transient load conditions, multiple system startup and shutdown, malfunction detection, off-limit testing, and the capability of the power system director to transfer the load from one system to the other. The operation of the status display and warning system, emergency power system interlocks, essential load bus control logic, and transfer from the normal to the emergency power supply are verified.

Prototype system No. 1 is also utilized for an extended period of lifetime and reliability demonstration with the reactor installed. The lifetime demonstration unit will serve two functions: (1) provide long-term reliability data, and (2) serve as a test module that is capable of simulating system failures that may occur on the in-orbit MORL vehicle. Therefore, corrective action for unforeseen system failures may be determined by duplicating the failure on the continuously running lifetime demonstration unit. The lifetime demonstration system will initially utilize a simulated energy source (electrical heaters) and at a given point in time will utilize a flight-type nuclear reactor.

The multiple loop tests require initiation of technology readiness studies of: (1) manual and automatic multiple system startup and shutdown, (2) malfunction detection, (3) load transfer and load-sharing capability for alternate primary systems, (4) load transfer to emergency system, and (5) test facilities, including a vacuum chamber equipped for operating reactor power system for long durations. A study of the required vacuum chamber facilities should include: (1) local shielding requirements, (2) effects of scatter, and (3) correlation of test conditions with expected orbital conditions such as differences in separation distance, shielding, and means of heat rejection.

6.2.2 Prototype System No. 2 (Non-Nuclear)

Prototype system No. 2 is used to verify the integrity of the overall system while subject to dynamic and vacuum environments. The initial test results are used to make mandatory system changes prior to the start of the MORL all-systems environmental test program. The environmental tests are conducted in two phases: (1) vibration testing using electric heaters, and (2) vacuum chamber tests using electric heaters. All tests are non-nuclear.

6.2.2.1 Vibration Tests

The capability of the static converter or rotating equipment, radiator tube mounting and coatings, and reactor and shield mountings and coatings to withstand the vibration and shock loads is evaluated. The harmonic frequencies of the installed systems are determined. The reactor power system is not required to operate during the vibration testing.

6.2.2.2 Vacuum Chamber Tests (Simulated Energy Source)

A specially designed energy source, making use of electrical heaters mounted within the reactor vessel, and a radiation shield identical to the flight unit are used for the early vacuum chamber tests. The calculated system thermal balance is verified and a complete temperature map is obtained by simulating the heat sink temperatures in the vacuum chamber. The simulated reactor and shield temperatures and heat exchanger temperatures are monitored. The complete radiator is not installed within the vacuum chamber for those systems that required surface areas too large for feasible installation.

The tests are used to (1) determine temperature distribution through the shield, power conversion system, and radiator loops; (2) determine the thermal expansion of the shield, supports, and the heat leakage to the MORL structure; (3) evaluate the system capability to supply variations in the electrical loads in the simulated orbital environment; (4) establish tolerances of temperature-sensing elements; (5) evaluate the performance of leak-detection equipment; and (6) determine the effects of rapid changes in altitude, similar to the orbital pressure variations experienced during launch, on thermal insulations.

A study of the vacuum chamber facilities required, including facilities to simulate heat rejection for those systems that require radiator areas too large for feasible vacuum chamber installation, is recommended.

6.2.3 Flight Test Qualification

The need for a separate flight test depends to a large extent on the conversion system selected and on those subsystem tests that may be performed on Apollo-class launches. For example, the stability of gas bearings for the Brayton system, or boiling and condensing phenomena for the Rankine systems, may be firmly established through orbital subsystem testing prior to implementation of a reactor system development for MORL. A flight test is generally defined as the final proof of design of a qualified system for a specific mission application. If it is assumed that the major reactor subsystems are thoroughly tested in orbit, then the need for a full-scale, integrated system flight test is based on evaluating subsystem interactions and on a subjective need for a final proof of design of an integrated system. The need for a reactor flight test requires further investigation.

A study of the requirements for major subsystem and complete system orbital testing of conversion systems is recommended.

6.3 VEHICLE INTEGRATION AND TEST REQUIREMENTS (Non-Nuclear)

The reactor power systems are mated with full-scale, ground-test, MORL vehicles for integration and qualification tests which parallel the reactor power system prototype tests. The spectrum of MORL and MORL/reactor power system tests is: engineering mockup, development fixture, dynamic ground test unit, systems integration unit, and all-systems environmental unit. After completion of the all-system environmental test, final design modifications are made to the flight system. This is followed by assembly and subsequent transport to KSC where the MORL and reactor power system undergoes prelaunch checkout.

As presently conceived, the integration and qualification tests do not include operation of the reactor but utilize a simulated energy source. However, the requirements for, or the benefits derived from, the use of an operating reactor for MORL qualification tests merits further study.

6.3.1 Engineering Mockup, Development Fixture, and Dynamic Ground Test Unit

The engineering mockup is a full-scale wooden structure that simulates the MORL vehicle and its installed subsystems and is used to demonstrate the adequacy of access for installation ease and maintainability and to verify installation clearances.

The purpose of the development fixture is to check the physical compatibility of subsystem design configurations early in their development and to develop feasible maintenance procedures and techniques. The operation of the deployment boom and separation mechanisms are verified during the development fixture test program.

The dynamic ground test unit is used to verify that the MORL structure is compatible with critical mission environment and load requirements. Mode shapes are measured for each mode, transfer functions are obtained, and phase and amplitude measurements are derived.

6.3.2 Systems Integration Unit

The purpose of the integration testing is to permit engineering development and design evaluation of the MORL and to ensure that the MORL is compatible with its ground support equipment. Data gathered in these activities is used to develop the corrective changes which will provide a high level of confidence in the success of the operational flight program. Evaluations are made of the crews' capability to perform on-board maintenance and repair, and maintenance procedures are developed. The power system startup, shutdown, and switch-over procedures established in the prototype system tests are functionally verified. The performance of leak-detection and control equipment are analyzed and demonstrated.

A study of the feasibility of on-board maintenance, multiple system startup, leak detection and control, and multiple system startup and shutdown is recommended.

6.3.3. All-Systems Environmental Unit

The all-systems environmental unit is a complete MORL laboratory with operational flight systems and equipment. Special on-board metabolic simulators are required during unmanned test operations. A complete set of support equipment includes servicing, handling, and checkout GSE; a logistics vehicle simulator; and bench maintenance equipment. The power system includes a simulated energy source rather than a nuclear reactor. The environmental test is used to evaluate the operational MORL configuration under simulated launch and orbital mission environmental conditions. The test program includes: (1) launch simulation, (2) orbital mission simulation, (3) thermal investigation, (4) system failure inducements, (5) emergency operation, and (6) manned operation.

All laboratory systems are operated; however, the engines are not fired. On successful completion of manufacturing and integration systems checkout, the laboratory test unit is subjected to the mechanical vibration and the acoustical noise of the launch environment. The laboratory test unit is then installed in a large-diameter space chamber to thoroughly evaluate its operation in a simulated space environment.

With the exception of the lifetime/reliability tests, the successful completion of the all-systems environmental test program results in a fully qualified flight rated unit. Acceptance and prelaunch checkout of the first flightweight unit, immediately prior to launch, is the final verification of power system performance prior to orbital operations.

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Section 7

CONCLUSIONS AND RECOMMENDATIONS

Integration of reactor power systems with a manned Earth-orbital space station, using the MORL concept as an example, has resulted in definition of Orbiting Research Laboratory (ORL)/reactor power system combinations useful at 10-, 20-, and 30-kWe power levels, and the pertinent conclusions and recommendations on design of both the reactor power systems and the overall mission and space vehicles.

The characteristics of the MORL incorporating a 10-, 20-, and 30-kWe reactor power system are compared to the baseline 11-kWe MORL, using an isotope system as the prime power source, in Table 7-1. Summarized are the MORL design parameters, reactor power system design parameters, integrated MORL/reactor power system associated weight constraints, power system technology readiness requirements, and total system weights. The power systems are grouped according to power level to facilitate comparisons between the various system designs and integration constraints, and between a specific reactor power system design and the baseline MORL.

7.1 CONCLUSIONS

The study objectives presented in the Introduction have been satisfied by a systematic design analysis and integration of five basic reactor-power conversion concepts, including the SNAP-8-type reactor in combination with the SNAP-8 and SNAP-2 mercury Rankine, Brayton, and the direct radiating and compact converter thermoelectric systems. It is concluded that all of the reactor power systems investigated can be effectively integrated with the MORL to satisfy all laboratory functions and mission objectives, and to provide potential for increased capability and growth accommodation in the laboratory.

The selected reactor power system configurations are characterized by the following criteria and requirements:

1. Application of a shadow shield, an 80-ft dose plane diameter at the MORL, and a reactor-MORL separation distance of 125 ft. The configuration boundary is limited by a 35° shadow cone to avoid radiation scatter outside this zone.
2. Utilization of the Saturn IB class launch vehicles for the baseline mission, imposing a weight and overall height limitation on the reactor power system configurations.
3. Conformance with the physical dimensions of the MORL and the S-IVB stage, and adaptability to the Apollo CSM for manned replacement system launches.

Table 7-1

COMPARISON OF REACTOR POWER SYSTEM CHARACTERISTICS

	Baseline MORL	Direct Radiating Thermoelectric System	Compact Converter Thermoelectric System	SNAP-2 Mercury Rankine System	Brayton System	SNAP-8 Mercury Rankine System
Power level at load, kWe	8.8 (11 at source)	9.8	22.5	20	20	30
Orbit	164 nmi, 50° inclination 164 nmi, 90° inclination	218 nmi, 50° inclination; 218 nmi, 90° inclination				
	19,350 nmi, 28.3° inclination					
Initial launch configuration	MORL/Saturn IB	Reactor power system, MORL, MLV-Saturn IB-11.5, unmanned				
Replacement launch configuration, replacement interval	None (on-board spares)	Not scheduled		Reactor power system, manned Apollo Command and Service Module, product improved Saturn IB, replacement interval 2-1/2 yr.		
MORL/power system separation distance, dose plane diameter, dose rate	10 Rem/yr	Separation distance, 125 ft; dose plane diameter, 80 ft; dose rate, 20 Rem/yr.				
Crew size	6 to 9 men	6 men	9 men			9+ men
EC/LS system	Open cycle O_2 subsystem; closed cycle H_2O subsystem		Closed-cycle H_2O subsystem, closed-cycle O_2 subsystem			
EC/LS radiator area, sq ft	822	1,275	2,150			2,750
Standby power system	Batteries	Solar cell/battery	Isotope Brayton System			
Standby power system radiator area, sq ft	920 (primary source)	---	350			
Total EC/LS and standby power system radiator area, sq ft	822	1,275	2,500			3,100
Required extension of MORL length to accommodate EC/LS and standby power system radiator area	Baseline MORL length, 44 ft; 2,150 sq ft radiator area available	-	5.2			14
CMG system						
Total weight	628	1,810	2,196	2,080	1,818	2,188
Additional CMG weight compared to baseline MORL	--	1,182	1,568	1,452	1,190	1,560
Reactor control system (147-day maximum resupply interval)		Two separate RCS systems required; one on-board MORL; one on power system structural assembly.				
Total weight of tanks, supports and propellants	1,306	2,173	2,742	2,249	2,191	2,595
Additional weight compared to baseline MORL	--	867	1,436	943	885	1,289
Reactor disposal system	None	Solid propellant engine, guidance system, liquid propellant vernier control engines; total weight, 511 lb				
Maintenance of inactive system fluids in liquid state during reactor shutdown intervals			Auxiliary loop provided during startup interval following removal of thermal shields.			
Total thermal shield weight	Not applicable	1,095	1,484	570	844	698
Power system radiator requirements						
Total area, sq ft	920	1,068	1,891	757	1,150	1,065
Radiator configuration	Tube and truss core sandwich structure	Direct radiator, titanium truss core support	Tube and fin radiator, capable of supporting reactor power system throughout launch environment.			
Energy source	Pu-238	349 element core, SNAP-8-type reactor				
Thermal power level, kWt	42	422	622	313	152	414
Shield configuration and materials	Shadow shield canned lithium hydride and stainless steel	Shadow shield with equipment gallery; two depleted uranium alloy gamma shields, two canned natural lithium hydride neutron shields.				
Shield gallery equipment	None	Heat exchanger and primary loop components		Heat exchanger/boiler, primary loop components and auxiliary startup loop		
Power system component/system life	Spares provisioning	Potential of 5-yr component life		1-1/4 yr component life; 2-1/2 yr system life		
Total number of power conversion systems	2	Not applicable	Not applicable	14	6	3
Number of active power conversion systems to supply load for each 1-1/4 yr	2			5	2	1
Total number of redundant systems for 2-1/2 yr system life	2 plus spares provisioning	20% redundancy	27% redundancy	4	2	1
Turbine inlet or converter hot side temperature, °F	1,640°	1,150°	1,150°	1,155°	1,250°	1,298°
Condenser, converter cold side, compressor temperature, °F	65°	550°	550°	610°	200°	575°
Overall system efficiency, %	21.5	2.33	3.62	6.41	13.15	7.43
Technology readiness						
Required system changes or study areas	Pu-238 fuel production and facilities Fuel capsule material studies Fuel block studies Fuel capsule/fuel compatibility Fuel block, heat exchanger, and radiator emissive coatings Insulation studies Study of Xe-He gas mixtures	Converter performance Reliability and lifetime verification	Overall system in early development compared to direct radiating thermoelectric system Converter performance Reliability and lifetime verification	Effects of zero-g, artificial-g, and multiple restart capability Static deterioration Redundant systems switchover and performance	Gas foil bearing development	Boiler redesign Redundant systems switchover and performance Effects of zero-g, artificial-g, and multiple restart capability Static deterioration Lube coolant fluid radiation tolerance
Potential study areas and system improvements	Re-entry of fuel block Gas bearing technology Alternator design High temperature measurements	Reduced redundancy Structural optimization	Reduced redundancy Converter module replacement	10-kWe CRU Improved boiler design	Rice alternator heat removal Xe-He gas mixture	Intermediate loop component/system life
Total power system and associated launch weight	4,967	27,308	33,981	24,699	25,983	34,826
Integral MORL/power system and associated launch weights (with 20% contingency)	32,100	61,994	69,262	57,783	60,405	71,016
Replacement launch, reactor power system weight with 20% contingency and retention of a portion of radiation shield	Not applicable	15,648	22,606	14,730	16,438	21,011

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4. Integral launch of the initial reactor power system with the MORL, unmanned, using the MLV-Sat IB-11.5 launch vehicle. Integral launch is preferred to separate reactor power system launch and subsequent orbital assembly because of increased reliability, lower cost, and reduced operational complexity.

5. Commonality of the integral launch and replacement system launch configurations to minimize development effort.

6. Minimization of replacement system launch weight for accommodation on a product-improved Saturn IB launch vehicle by permanently retaining the secondary shield of the initial system configuration on the deployment boom. Replacement system launch is the limiting case with respect to allowable height and weight.

7. Utilization of the same launch vehicle for replacement system launch and MORL logistics requirements to minimize cost and to avoid excessive restacking and launch response time.

The following specific conclusions are divided into two categories: (1) to reflect the influence of a manned Earth-orbital application, typified by the MORL on the reactor power system design, and (2) to establish the effects of a reactor power source on an ORL mission.

7.1.1 Influence of Manned Earth-Orbital Application on Reactor Power Systems

The most pronounced impact of MORL application on the reactor power systems is the required development of man-rated system designs for prolonged service in a space environment. The lifetime and reliability associated with unmanned applications are not generally sufficient to meet manned mission requirements. Moreover, reactor shielding must be increased to provide adequate biological protection of laboratory personnel. Maximum flexibility to meet the operational requirements and reliability of an extended mission dictates provision of system shutdown and restart capability, and the means to sustain life support services during the shutdown intervals. The presence of man also requires the provision of system maintainability and manual control functions in development of the system designs.

These requirements have been explored in the individual system designs investigated. The principal effects resulting from this work are summarized in Table 7-2 and discussed subsequently. Conclusions relating to the principal functional areas common to all systems are presented initially, followed by those conclusions which are unique to the reactor and particular conversion system designs investigated.

7.1.1.1 General Conclusions

Reliability and Lifetime

1. To meet the MORL mission objectives, the reactor power systems are designed for a full-power reliability goal of 0.95 over the system lifetime. This reliability level is attained by the application of installed redundancy and the capability for reactor power system replacement during the 5-yr mission. While maintenance can

Table 7-2

PRINCIPAL EFFECTS OF MANNED EARTH-ORBITAL APPLICATION ON REACTOR POWER SYSTEMS

General

Installed redundancy to attain reliability/lifetime.
System maintenance potential.
Intermediate loop for increased accessibility.
Increased component lifetime advantages.
In-space startup and shutdown requirements.
Standby/emergency power source.
Shutdown system protection.
Reactor disposal provisions.
Reactor-MORL separation and deployment system requirements.
Modified deployment for artificial-g mode.

Reactor and Shielding

Single reactor design selection.
Shadow shield concept selection.
Shield retention capability.
Allowable radiation dose rate specification.

Power Conversion Systems

System design selection.
Redundancy basis and requirements.
Boiler design (SNAP-8 and SNAP-2).
Single-shaft turbomachinery selection (Brayton)
10-kWe module size selection (Brayton)
Intermediate loop advantages
Radiator-condenser selection (SNAP-2).
Indirect radiator selection (Brayton).
Artificial-g mode adaptation (SNAP-8 and SNAP-2).
Lube-coolant marginal radiation tolerance (SNAP-8).
Uprated CRU design application (SNAP-2).
Growth accommodation.

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contribute to increased reactor power system reliability, only a minimum of preventive and corrective maintenance, primarily associated with the electrical systems located in the MORL, is assumed in specifying system redundancy requirements. This approach is taken because of uncertainties in the extent to which maintenance can be performed in space, and to minimize conflicts with the laboratory experimental program arising from allocation of manpower to maintenance tasks.

2. Further effort is needed to evaluate the feasibility and net utility of system maintenance operations on a case basis and to determine the special maintenance equipment required to facilitate such maintenance.

The power conversion system components have been arranged near the aft end of the configuration to provide maximum accessibility and to minimize the radiation dose to crewmen performing maintenance.

3. The application of an intermediate NaK loop between the primary system and power conversion system generally is desirable to provide the flexibility in component location to facilitate maintenance. It also provides positive means of preventing direct intermixture of primary and power conversion system fluids in the event of heat exchanger tube leakage.

4. Attainment of a 5-yr system lifetime would eliminate the need for a scheduled system replacement for the MORL application. Achievement of this goal may not be practicable for the dynamic systems studied; however, provision of a 2-1/2-yr system operating life can minimize reactor power system replacement requirements for extended orbital applications and provide compatibility with typical interplanetary flyby missions.

   The dynamic power conversion systems can be provided with sufficient redundancy to meet reliability objectives over a 2-1/2-yr system lifetime within acceptable limits of weight, surface area and design complexity. However, a significant reduction in installed redundancy and a consequent simplification of system design can be attained if component lifetime can be increased from the presently specified goal of 1-1/4 yr without increasing the failure rates. Because of the inherently high reliability and anticipated prolonged lifetime capability of the thermoelectric converters, the thermoelectric system designs can be based on a 5-yr lifetime within practical limits of redundant capacity, and a scheduled replacement system launch can thereby be eliminated.

System Startup, Shutdown, and Disposal Capability

1. The reactor power systems must be designed for initial startup in orbit to meet launch safety criteria. Investigation of the MORL application has established a preference for final deployment of the reactor power system configuration and initial reactor startup after the station is manned, rather than remotely from the ground; this reduces complexity and improves reliability. Accordingly, the reactor power system startup is accomplished within 24 days of launch, following initial station manning.

2. Long-duration manned system applications require provisions for system shutdown. A total of 6 shutdowns and startups per year, with an allowance of 4 shutdowns for a period of no longer than 5 days each for maintenance, has been selected as the design basis.

3. During reactor power system shutdown, a standby power source must be provided to sustain vital life support services, as well as to supply power to the reactor power system to indicate system status and maintain system flow and temperature levels within acceptable limits. Integration of reactor and standby power sources is required to effectively accommodate laboratory electrical and thermal loads during

normal operation and to ensure provision of the average power demand and proper load control.

4. The fluids within the radiator and system components must be maintained in a liquid state and at a suitable viscosity during system shutdown periods. Continued operation of the reactor up to 10% of rated power prevents freezing and permits limited access for maintenance at tolerable radiation dose levels. Provision is made for reactor shutdown and the application of thermal shields, which are retracted during normal operation, to maintain an acceptable fluid temperature during the shutdown period.

5. An alternate operational mode utilizing a radiator fluid that has a sufficiently low freezing temperature to preclude the need for thermal shields is the preferred ultimate design. Although a eutectic mixture of sodium, potassium and cesium (NaK-Cs) appears to offer excellent potential for this service, further test experience and development of properties of this fluid are required prior to its selection for this purpose.

6. Provisions are made for reactor disposal at the end of lifetime according to acceptable safeguard requirements. Capability for reactor disposal by either re-entry and deposit into the ocean or placement into higher orbit can be provided. Three solid rockets permanently attached to the reactor configuration and a guidance and control system coupled to a radio command link are used for this purpose. The higher orbit disposal method requires disposal rockets designed for greater impulse, with resulting greater weight, and is considered less desirable.

Configuration Design

1. The integration requirements specified result in a high degree of commonality of the system configurations. All selected configurations are of the same conical geometry (35° cone angle) with maximum diameters of 154 or 260 in., and with the external surface of the cone serving as both the principal structural support and as the power conversion system radiator. The conical section is extended by a 154- or 260-in.-diam cylindrical section if required to provide additional radiator surface.

2. The power conversion system radiator is used as a common structural support for the entire configuration, which includes the Apollo CSM mounted atop the reactor configuration for replacement system launch. An aluminum fin and stainless steel tube radiator structure, using the tubes for longitudinal support and circumferential ring stiffeners, is selected in preference to a truss core sandwich construction for all systems except the 10-kWe thermoelectric system, on the basis of radiator area and weight comparisons.

   The converter-radiator cannot be used for structural support in the 10-kWe direct radiating thermoelectric system configuration. A system of longitudinal load-carrying members and circumferential rings proved to be the most desirable based on static structural analysis and converter accessibility.

The relatively low natural frequency of the individual converters requires additional ring stiffening to the extent that this method of support becomes heavier than the truss core structure. Accordingly, a truss core structure, fabricated of titanium to withstand the elevated temperature environment, is used for the direct radiating system.

3. The MORL-reactor separation distance has been optimized as a function of the dose plane diameter, reactor power system support structure, and RCS propellant required to maintain stability and control requirements of the laboratory. The selected separation distance is 125 ft, based on an 80-ft-diam dose plane at the aft end of the MORL, which accommodates all MORL experimentation and associated extravehicular activity. The optimum MORL-reactor separation distance is relatively insensitive to total weight for distances greater than 100 ft; consequently, the use of a larger reactor power system would make little difference in the selected separation distance. As the separation distance decreases below 100 ft, the shield weight increases dramatically, approaching a 4π shield weight for a 50-ft separation distance.

4. An articulating boom, consisting of multiple hinged sections, is provided to accomplish deployment of the initial and replacement reactor power system configurations, and to maintain the 125-ft separation distance throughout the mission. To simplify access to the power conversion system components, the deployment boom is sized sufficiently large to allow passage of personnel in space suits.

5. The artificial-g mode of station operation requires a modification in the selected reactor configuration deployment boom design to facilitate retention of the S-IVB for spin deployment of the MORL. To avoid significantly increased shielding requirements and a more complicated replacement system deployment operation, the reactor power system configuration is deployed behind the S-IVB, in preference to a location between the MORL and the S-IVB. For this purpose, two telescoping deployment arms, pivoted on the outside surface of the S-IVB, are used to engage the reactor configuration at the forward end of the MORL and rotate the configuration to the operating position. This deployment system design is not well suited to retention of the secondary shield when the initial reactor power system is replaced. Moreover, access to the reactor power system for maintenance is significantly more difficult because extravehicular passage around the S-IVB is necessary. Further detailed study is required to assure the most favorable design under these conditions.

Reactor and Shielding

1. A single SNAP-8-type reactor design with 349 fuel elements, a nominal 600 kWt capability at 1,300°F coolant outlet temperature, and a potential operating lifetime of 5 yr can effectively accommodate the operating characteristics and unique features of the various power conversion systems. This lifetime is feasible with the use of a burnable poison selected from identified candidates which exhibit favorable lifetime characteristics. Operational reactivity control is obtained by

eight operating control drums which are tapered to provide a minimal shadow cone envelope for the shadow shielded configurations. If a 4π or 2π shield is used, resultant higher reflector temperatures necessitate application of alternate external reflector and control drum materials.

2. A shadow-shielded configuration is capable of satisfying all MORL requirements and has been adopted for all systems in this study. A dual shield design with an intervening gallery sized to accommodate primary system components has been applied to attenuate primary and secondary radiation sources and to minimize total shield weight. Application of 2π shielding would provide increased operational flexibility and/or design simplification through possible elimination of the deployment boom at a significant increase in weight.

3. Maintenance of replacement reactor power system configuration weights within the selected launch vehicle capability, dictates a secondary shield design which is separable from the reactor/PCS to allow its retention. Similar provisions are even more critical for 2π and 4π shield configurations.

4. An allocated radiation dose of 20 Rem/yr from the reactor source is chosen, based on the allowable personnel radiation exposure levels specified for the MORL and consideration of additional radiation flux from space radiation and standby power sources. Because the variation in allowable dose rate from the reactor generally has a smaller effect on shield weight than the other principal shield design parameters (such as separation distance, cone angle and gallery height), there does not appear to be a strong incentive to increase the allowable dose rate from the reactor.

7.1.1.2 Power Conversion System Results

SNAP-8 Power Conversion System

The selected baseline 30-kWe SNAP-8 system design to meet a 2-1/2-yr system lifetime consists of 3 independent 30-kWe power conversion subsystems, 3 associated boilers installed in the shield gallery, and 2 sets of heat rejection and lube coolant radiator tubes. This design can be satisfactorily integrated with the MORL; however, the integral and replacement system launch weights are marginal for the selected launch vehicles.

Specific conclusions are as follows:

1. The use of complete power conversion subsystem redundancy is preferred to individual component redundancy to minimize the number of switching valves required by the design. Preliminary analysis of the baseline SNAP-8 system design indicates that the installation of three complete power conversion subsystems (including three boilers), and two sets of heat rejection and lube coolant loop radiator tubes meets overall system reliability and system lifetime requirements.

2. Since the most probable source of boiler failure involves tube leakage, installation of multiple boilers to meet reliability requirements also

requires boiler design modification to preclude mercury leakage into the primary NaK.

3. The use of an intermediate NaK loop provides the following system advantages: (1) prevention of both direct leakage of mercury into the primary NaK loop and primary NaK leakage into a shutdown mercury loop; (2) reduced shield gallery height resulting in lower shield weight; (3) accessibility to the boilers for potential maintenance; and (4) compatibility with the MORL artificial-g mode without additional valving.

4. The MORL artificial-g mission mode has minimal effect on the operation of a SNAP-8 system provided with an intermediate loop because the liquid-vapor interfaces of the condenser and boiler are installed at the same elevation. However, for the baseline SNAP-8 system (boiler installed in shield gallery), the induced gravity field requires higher absolute pressure at the boiler inlet. The addition of a pressure control valve in the boiler feedline may be required to avoid an overall reduction in boiler performance and the possibility of wet vapor at the turbine inlet.

5. The use of lube coolant fluid to cool the canned rotor centrifugal primary pumps located in the shield gallery is suspect with 2-1/2-yr radiation exposure.

6. The SNAP-8 system design can be uprated to approximately 50-kWe net output power capability with relatively minor system modifications. The increase in system weight (amounting to approximately 4,200 lb) requires an increase in launch vehicle payload capability which could be readily accommodated by the Saturn V. However, provision of the additional EC/LS system radiator surface on the MORL required to dissipate the total output power capacity results in an integral launch height of 389 ft, which exceeds the 380-ft height of the launcher-umbilical-tower crane. Use of this configuration would require facility modifications.

SNAP-2 Power Conversion System

The selected 20-kWe SNAP-2 system consists of 14 combined rotating units (CRU) of 5.6-kWe gross output power capability. A total of 5 active and 2 standby CRU loops are supplied for each 1-1/4-yr operating period to achieve an overall reactor power system reliability of 0.95 with a 2-1/2-yr system lifetime. An alternative design using uprated 10-kWe CRU's requires only 6 installed CRU loops to meet the same objectives. The selected system design satisfactorily meets all specified integration requirements.

Specific conclusions are as follows:

1. The 20-kWe SNAP-2 system configuration has the lowest weight and radiator surface area requirements of the systems investigated in this study (14,490 lb and 757 sq ft).

2. Although the provision of individual component redundancy was investigated, the application of completely separate, redundant CRU

loops is preferred to minimize valving associated with the former concept. A total of 14 CRU loops (of which 5 are required to produce 20 kWe) are installed to meet reliability and lifetime objectives. The selected cycle state points and the component design basis are relatively conservative, indicating potential for an increase in component lifetime to be feasible. An increase to 2-1/2 yr would allow the installation of only 10 CRU loops, thereby significantly reducing system design complexity.

3. Comparative evaluation of the radiator-condenser and an indirect radiator for waste heat rejection clearly indicates the radiator-condenser to be preferable because of its surface area and reliability advantages. To attain a competitive surface area, a significantly more complex dual loop indirect radiator would be required.

4. The annular boiler design proposed for SNAP-2 is a relatively compact design, well suited to multiple-loop application; it precludes the intermixture of mercury and NaK in the event of boiler tube leakage and effectively eliminates the need for an intermediate loop.

5. Application of the system to both zero-g and artificial-g modes of operation requires installation of approximately half of the PCS modules at the forward end of the configuration. Although the potential for maintenance of PCS modules in this location is limited, the redundancy provided is sufficient to meet reliability and lifetime objectives without reliance on such maintenance.

6. An alternate SNAP-2 system design is based on the use of two operating combined rotating units (CRU) of 10-kWe capacity and results in the use of fewer modules to meet lifetime and reliability objectives. A total of 6 uprated CRU's can provide the equivalent output and reliability to 14 CRU's of the present design. Attainment of a 2-1/2-yr component lifetime would reduce the total number of uprated CRU's to 4.

7. The 10-kWe CRU design provides the most favorable prospect for system growth above 20 kWe. Preliminary evaluation indicates that nine 10-kWe CRU's can be installed within present integration limitations to produce an output power of 30 kWe while meeting the specified overall system reliability of 0.95.

Brayton-Cycle Power Conversion System

The selected 20-kWe Brayton-cycle system consists of six 10 kWe, single-shaft modules using argon as the working fluid, an intermediate NaK loop between the primary and gas loops, and a segregated radiator using NaK as the coolant. The system design can be effectively integrated with the MORL in accordance with the specified mission requirements, limitations and launch vehicle capabilities.

Specific conclusions are as follows:

1. Application of the Brayton-cycle PCS results in the highest thermal performance (18% cycle efficiency) of all the designs investigated.

The radiator surface area requirement of 1, 150 sq ft for the 20-kWe system is within the limits which can be effectively integrated into the various launch vehicle payload assemblies.

2. Based on comparative evaluation of the high frequency (850 Hz) single-shaft and 400 Hz two-shaft turbomachinery concepts, the single-shaft design is preferred on the basis of increased flexibility, reliability, and facility of system integration. However, either design can be successfully developed for manned Earth-orbital application with a comparable level of performance, and expectancy of meeting reliability goals and growth potential.

3. The use of a single basic 10-kWe power conversion module design to satisfy a range of power levels by multiple installation is preferred over use of a module uniquely designed for a discrete power level. The 10-kWe module design provides increased flexibility, reduced development effort for multiple power level applications, and increased part power reliability.

4. The use of an intermediate loop results in negligible performance penalty, while providing a high degree of system flexibility for manned mission application by facilitating the placement of power conversion modules in an accessible location behind the shield. This design provides a reduced shield weight through reduction in gallery height, smaller liquid line penetrations of the shield, and a close-coupling of gas loop components which minimizes gas pressure drop.

5. A radiator with NaK coolant is preferred to an integral radiator using gas coolant, providing lower weight (smaller liquid tubes require less armor), reduced gas pressure drop, and higher confidence in the predicted value of gas pressure drop. For this application, NaK is superior to FC-75, the fluid used in the baseline MORL Pu-238 Brayton cycle and EC/LS radiators because of the higher operating temperature (413°F at the radiator inlet).

6. An increase in system output power capability to approximately 30 kWe can be accommodated within the surface area limitations of the selected launch vehicles; an increase in replacement system launch payload capability is required. An increase in component lifetime from 1-1/4 yr to 2-1/2 yr, which appears feasible for the Brayton cycle, would reduce the number of installed PCS modules and system weight within the capability of the selected logistics vehicle.

Thermoelectric Power Conversion System

The 20-kWe thermoelectric system developed in this study uses lead telluride (PbTe) tubular converter modules arranged in 14 loops serviced by individual radiators. Seven intermediate NaK loops connect the primary system and the converter loops. In normal operation, 6 of the 7 intermediate loops, and 12 of 14 converter loops and associated radiator loops are required to produce a net power output of 22.5 kWe.

The selected 10-kWe thermoelectric system applies the advanced silicon germanium (SiGe) direct radiating converters, arranged in 6 loops on the surface of the conical configuration. Five of the six loops are required to produce a net output power level of 9.8 kWe.

Both thermoelectric systems satisfactorily meet the MORL integration requirements. Principal attributes of the thermoelectric systems are the high reliability and prolonged lifetime potential inherent in the completely static design.

Specific conclusions are as follows:

1. The SiGe direct radiating system represents a more advanced stage of development than the PbTe compact converter system in view of the SNAP-10A flight test experience and continuing development efforts. Therefore, the SiGe direct radiating design is the most likely candidate of any of the systems studies for early mission application.

2. The PbTe compact converter is also under active development and represents a low development risk in relation to projected application requirements in the 10- to 20-kWe power range.

3. The direct radiating thermoelectric system design provides the simplest fluid system arrangement of all the conversion systems studied because the SiGe converters are provided with integral radiating surfaces. However, the direct radiating design is inseparable from the overall configuration surface to which access is limited. With the application of an intermediate loop, the compact converter design provides a greater potential for maintenance and possible converter module replacement than the direct radiating design.

4. Verification of specified reliability goals through continued converter development should facilitate a reduction in the presently recommended redundant capacity (20% direct radiating, 27% compact converter) which an attendant decrease in weight and radiator area requirements.

5. An increase in direct radiating system capability to about 13.5 kWe can be provided using the same configuration by raising the radiating temperature from 550° to 650°F, thereby decreasing specific radiator area; the resulting weight increase is within the capability of the selected launch vehicles (18, 100-lb limit for replacement system launch). A capability of approximately 20 kWe could be provided by using a configuration equivalent to that of the compact converter system, although an increase in reactor size to deliver approximately 900 kWt would be required. An increase in replacement system launch weight capability and possibly an increase in integral launch capability would also be required.

6. The selected compact converter system design produces a net output of 22.5 kWe. The system configuration is marginal for replacement system launch to provide the nominal 20% weight contingency.

7.1.2 Influence of Reactor Power System Application on the MORL

The principal MORL subsystem and mission requirements which are affected by reactor power system application are as follows:

1. Standby/emergency power source.
2. EC/LS system radiator.
3. Crew size and power utilization.
4. Radiation environment.
5. Stabilization and control system.
6. Launch vehicles and launch facilities.

The conclusions presented in this section are specifically related to effects on the MORL design in the above areas; these conclusions are generally applicable, with relatively minor adaptation, to any prolonged, manned Earth-orbital missions.

7.1.2.1 Standby/Emergency Power Source

1. Based on an evaluation of candidate standby power sources, a Pu-238 Brayton-cycle (PBC) system design, basically identical to the system incorporated in the baseline MORL design, has been selected as the standby/emergency power source for the 20- and 30-kWe reactor power system applications. The standby/emergency power system is required to provide 5.5 kWe for a continuous period as long as 42 days during replacement of the reactor power system. Although both the PBC system and a solar cell/battery system have the capability for indefinite operating periods without resupply, the PBC system is preferred because of the independence of this system from MORL orientation, its supplementary capability in handling laboratory peak loads and supplying essential EC/LS thermal load requirements, and its minimal interference with the experimental program. Availability of the PBC system for this mission is postulated on its use as the prime power source in the baseline MORL mission.

2. A 10-kWe reactor power system application assumes unavailability of an isotope Brayton system for early MORL missions probably because of safety/fuel availability considerations; accordingly, the PBC system must be assumed to be unavailable as a standby source. On this basis, a solar cell/battery system is selected because of its low weight and the ability to operate for indefinite periods without resupply. This choice dictates retraction of the solar panels during normal reactor operation to minimize RCS propellant consumption.

7.1.2.2 EC/LS System Radiator

1. The EC/LS system radiator must reject all of the heat generated in the laboratory, including metabolic heat and essentially all electrical power. The usable net radiator surface of 2,150 sq ft on the baseline

MORL is sufficient to accommodate the output power of the 10-kWe thermoelectric system which requires only 1,275 sq ft. For the 20- and 30-kWe reactor power system applications, the selected PBC standby power system radiator area (350 sq ft) must also be accommodated. The combined standby power system and EC/LS radiator area requirements (up to 2,500 sq ft) for all 20-kWe system designs are satisfied by a 5.2-ft extension to the MORL cylindrical length. A deficiency of approximately 600 sq ft of surface exists, even with the 5.2-ft vehicle extension, when using the 30-kWe SNAP-8 system; further vehicle extension of 9 ft would be required for this case.

2. The EC/LS radiator area requirements are generally applicable, within reasonable limits, to any large manned Earth-orbital application under the equivalent orbital conditions, and amount to approximately 60 sq ft/kWt rejected, plus standby system radiator allowance if required.

7.1.2.3 Crew Size and Power Utilization

1. The 10-kWe power system design is compatible with a 6-man MORL and an EC/LS system design using a closed-cycle water subsystem and open-cycle oxygen subsystem. With the assumed application of a solar cell/battery standby system at this power level, insufficient power is provided by the reactor power system to allow use of a completely closed-cycle life support system.

2. A crew of 9 to 12 men can be accommodated on the MORL for prolonged periods, based on a consideration of the volume and facilities available. Within the physical limitations of a permanent 9-man crew and adaptability of the basic laboratory subsystem designs, a power system capacity up to about 20 kWe can be justified; it will provide increased laboratory capabilities in satisfying experimental program objectives.

7.1.2.4 Radiation Environment

1. A radiation exclusion zone bounded by an 80-ft-diam dose plane at the aft end of the MORL is sufficient for all projected experimentation, EVA, docking, and stowage requirements.

2. Optimization of reactor and vehicle shielding for space radiation, standby power system, and reactor radiation sources results in an allocated radiation dose of 20 Rem/yr from the reactor.

7.1.2.5 Rendezvous

1. The selected radiation exclusion zone permits rendezvous of logistic vehicles without requiring reactor shutdown. Based on an evaluation of the maximum credible accident associated with docking phase operations, it is concluded that the logistic vehicle will not pass within a 2-nmi radius prior to docking phase alignment and will not exceed the boundaries of the radiation exclusion zone while in the docking phase.

7.1.2.6 Stabilization and Control

1. The MORL stabilization and control requirements can be satisfied when using a deployed reactor power system configuration. However, the baseline MORL CMG must be resized and the RCS must be modified. The CMG is modified to provide unrestricted maneuver capability; the weight penalty for the resized CMG is approximately 1,200 lb for the 10-kWe thermoelectric and the Brayton systems, and 1,500 lb for the 20-kWe thermoelectric, SNAP-2, and the SNAP-8 systems. A second RCS system is provided on the reactor power system configuration; propellant requirements for the two bipropellant RCS's range from 7 to 107 lb/month greater than for the baseline MORL, depending on the particular reactor power system.

2. Propellant penalties have been minimized by adopting a new mission altitude of 218 nmi for the 50°-inclination circular orbit; this orbit provides a 3-day subsynchronous repeating orbital trace.

7.1.2.7 Launch Vehicles and Launch Facilities

1. An integral launch of the MORL and the initial reactor power system is selected in preference to separate system launch followed by assembly in orbit from a consideration of reliability, cost, and relative operational complexity. On the basis of MORL/reactor power system weight, the MLV-SAT IB-11.5 is selected as the integral launch vehicle for the baseline 50°-inclination, 218-nmi circular orbit. All integral launch weights are within the 69,000-lb payload capability with no weight contingency applied. However, when the standard 20% contingency is applied, the 30-kWe SNAP-8 system configuration clearly exceeds the payload capability and the 20-kWe thermoelectric system configuration is marginal.

2. The product-improved Saturn IB is selected as the launch vehicle for replacement reactor power system launch for economic reasons. All replacement reactor power system launch weights are within the 18,110 lb available payload with the exception of the nominal 20-kWe thermoelectric system (22.5-kWe output capability) and the 30-kWe SNAP-8 system, which require an increase of about 4,000 lb in payload capability. The weights of replacement reactor power systems have been minimized by retention of the secondary shield during the replacement operation.

   Because of the additional height resulting from the Apollo CSM stacked atop the replacement reactor power system, launch vehicle height becomes a limitation. Preliminary structural analysis indicates a height limitation of approximately 230 ft for the Saturn IB stage in the replacement vehicle assembly, precluding stage redesign and subsequent requalification. However, all replacement reactor power system launch assemblies essentially meet this limitation. In the replacement reactor power system configuration, the critical mode from a launch height standpoint, a maximum radiator area of 1,900 sq ft can be accommodated by a Saturn IB launch vehicle with a reactor power system and Apollo CSM, without structural modification of the Saturn IB stage and interstage.

3. The Saturn V is required for all launches into polar and synchronous orbits; the limiting height for the Saturn V payload assembly is 380 ft, which corresponds to the crane height limitation of the LUT used in Launch Complex 39 operations. A reactor power system radiator area limit of 3,300 sq ft is obtained using the Saturn V in the replacement system launch configuration, based on the present shadow cone angle of 35°.

4. The use of Launch Complex 34 at KSC for the integral launch of the MORL/reactor power system configuration using the MLV-SAT IB-11.5 launch vehicle is feasible, although modification of the complex is required. Because a separate launch vehicle or launch complex cannot be assigned to a replacement reactor power system launch, the routine MORL logistic vehicle, which is always in a launch-ready condition on either Launch Complex 37A or Launch Complex 37B, must be restacked with the replacement power system. This restriction, coupled with the requirement of minimum reactor power system replacement time, requires the routine MORL logistic launch vehicle to be the same product-improved Saturn IB used for the replacement reactor power system. If another launch complex is used for the replacement launch vehicle and routine MORL logistic operations are still based at Launch Complexes 34, 37A, and 37B, the cost of the replacement launches would increase significantly.

7.2 SYSTEM GROWTH ACCOMMODATION

Based on the design criteria and MORL/reactor power system requirements of this study, the maximum reactor power system power levels which can be accommodated by the Saturn IB and Saturn V within weight and height limitations are presented in Table 7-3. The limiting design condition for the Saturn IB is the replacement system launch configuration, which includes the product-improved Saturn IB, replacement reactor power system, and the Apollo CSM. The height of this configuration is limited to approximately 230 ft, corresponding to a reactor power system radiator area of 1,900 sq ft, precluding Saturn IB stage or interstage redesign. The payload available to the replacement reactor power system is 18,100 lb, considering retention of the secondary shield during the replacement operation. The limiting criterion for the Saturn V is a height of 380 ft, corresponding to the LUT crane height. Design condition for the Saturn V is the initial launch configuration (the Saturn V, MORL, and reactor power system), rather than the replacement launch because height is limiting. Both the reactor power system radiator area and MORL EC/LS radiator area increase as a function of power level, assuming the total load is rejected through the EC/LS radiator. Since deployable EC/LS radiators were not considered in this study, the additional EC/LS radiator area is obtained by increasing the MORL length.

As shown in Table 7-3, the maximum power levels that can be accommodated by the product-improved Saturn IB replacement launch are all constrained by weight, with the exception of the PbTe compact converter thermoelectric system, which is also constrained by height. If another Saturn-IB-type launch vehicle with greater payload capability is selected to eliminate the weight constraint, the following power levels (kWe) could be accommodated: (1) Brayton, 34; (2) SNAP-2, 50; and (3) SNAP-8, 59.

Table 7-3

POWER LEVEL ACCOMMODATION BASED ON VEHICLE HEIGHT AND WEIGHT LIMITATIONS

Power System	Saturn IB[(1)] (Replacement Launch)	Saturn V[(2)] (Integral Launch)
Thermoelectric	20[(2)]	30
Brayton cycle	25 to 30	39
SNAP-2	~31	47
SNAP-8	~30	48

NOTES:

- Configuration Constraints: (1) Weight (2) Area
- Deployable EC/LS radiators are not considered
- 260-in. laboratory diameter
- All load rejected through EC/LS radiator
- SNAP-2 design based on 10-kWe CRU rating

Power levels that can be accommodated by the Saturn V are all constrained by height. The 380-ft height limitation can be increased to 410 ft if the LUT crane is not used and the mobile service tower is appropriately modified. The effect of EC/LS radiator area, hence MORL length, at the higher power levels is significant; e. g., the SNAP-8 system at 48 kWe requires a MORL length increase of 30 ft over the baseline MORL length (44 ft). Increased power levels could be accommodated by using a deployable EC/LS radiator or by allocation of power output to experiments in which the power is continuously dissipated external to the MORL.

7. 3 RECOMMENDATIONS

The attainment of high reliability and extended operating lifetime are the most important objectives for the application of reactor power systems to both manned Earth-orbital and interplanetary missions. Therefore, the following recommendations resulting from this study are primarily oriented toward simplification of the integrated system design, improvement in design integrity, verification of system operation, and other means to enhance reliability or improve lifetime capability of the integrated reactor power systems.

7. 3. 1 Configuration Design

1. Consideration should be given to the use of Saturn V, or an upgraded Saturn IB capable of approximately 100, 000-lb payload capability, for the baseline mission integral launch because significant design simplification can be achieved through elimination of the deployment boom. This can be accomplished by relocating the reactor power

configuration in a position adjacent to the MORL interstage section which allows a separation distance of approximately 50 ft between the reactor and the deck of the living quarters. In the integral launch configuration, the MORL would be oriented with the hangar test area down and the reactor power system in fixed position atop the MORL. The increased shielding requirements (a 2π or 4π shield) would involve the application of active shield cooling, means to retain a large fraction of the shield during reactor power system replacement and reactor reflector design for an increased operating temperature. By retaining most of the shielding on the MORL, a Saturn IB class launch vehicle may be used for both replacement system launch and routine MORL logistic requirements. Further analysis is required to assess this design approach.

2. The use of a power conversion system radiator fluid having a sufficiently low viscosity and freezing point at the equilibrium temperatures encountered during system shutdown in the specified orbits would eliminate the need for retractable thermal shields. A NaK Cs eutectic having a freezing temperature of -108°F, heat transfer properties essentially equivalent to NaK, and satisfactory corrosion and material compatibility, has been considered for this purpose. Because of the potential simplification in the configuration design, it is recommended that the NaK Cs eutectic mixture be further developed for application as a radiator fluid. The heat transfer and thermodynamic properties at elevated temperature and the effects of radiation must also be further defined to determine the feasibility of applying this fluid in the primary coolant system.

3. As an alternate to the selected bipropellant RCS, a resistojet RCS could be applied to achieve substantially decreased propellant requirements. Further analysis is necessary to establish the specific advantages and magnitude of the gain.

4. An acceptable depository area for reactor disposal at the end of lifetime should be selected on the basis of safeguard review and analysis. The reactor disposal system should be further developed and integrated with the configuration design.

7.3.2 Reliability and Lifetime

1. System reliability analyses should be used to identify weak links in the reliability chain, estimate redundancy requirements to be considered in the detailed design, and compare alternate system concepts on an equivalent-reliability basis. Consistent reliability logic and computational approaches should be used for this purpose.

2. The preliminary reliability analysis did not consider component interactions, operational requirements and failure response characteristics of the system which may affect design integrity. Therefore, in the development of detailed system operating and casualty procedures, the capability for failure detection, isolation (if required), and startup of redundant capacity should be verified to assure that the specified level of reliability is attained.

3. Although reliability estimates should be based on system and component test experience where possible, it will not generally be feasible to obtain statistically representative reliability values within the practical limits of system development programs. Consequently, increased emphasis must be placed on identification of the principal failure modes through design review and testing, and a determination of the failure effects on system performance. A continuing systematic effort to eliminate or reduce the severity of failures to reliability-critical components should be implemented in present and future technology efforts on reactor power systems.

4. Redundancy requirements may be reduced for the dynamic systems if component lifetime can be prolonged without increasing the failure rate. Therefore, system development programs should include the analysis and testing of component wearout modes with the objective of extending the lifetime potential of principal components without sacrificing proved design features.

7.3.3 Reactor and Shielding

1. Effort should be directed toward development of a SNAP-8-type reactor capable of a 5-yr operating lifetime, power levels up to about 600 kWt at 1,300°F coolant outlet temperature, and shadow shield application, as typified by the 349 fuel element reactor design adopted for this study. Such a design provides the flexibility of application with a wide variety of power conversion concepts and power levels (up to approximately 30 kWe) in the range anticipated for manned Earth-orbital and interplanetary missions. The extended reactor lifetime provides desirable margin in reliability and performance capability regardless of generally shorter power conversion system lifetimes.

2. The possible increased operational flexibility and deployment boom elimination which result from the use of a 2π or 4π shielded arrangement warrant continued development of reactor reflector designs suitable for the attendant increase in ambient temperatures.

3. Study results confirm that shielding is a dominant factor in the overall reactor power system weight for manned applications. Preliminary layouts have established the approximate gallery size to accommodate primary system components for the various PCS systems, and indicated a significant effect of gallery size on total shield requirements. Further detailed arrangement studies and piping stress analyses are required to quantify these results. Development of dual shield material combinations and fabrication requirements, applied conceptually in this study, should be continued.

7.3.4 Power Conversion Systems

Further development programs for individual power conversion systems should include the areas of further development identified in this report to achieve technology readiness for manned mission application. The following recommendations uniquely apply to the individual power conversion systems.

7. 3. 4. 1 SNAP-8 PCS

1. The use of lube-coolant fluid to directly cool primary pumps in the shield gallery should be eliminated because the long-duration radiation tolerance of this fluid is marginal under the expected radiation environment.

2. A modified boiler design or intermediate loop application should be considered to avoid the possibility of mercury leakage into the primary system or primary NaK leakage into an idle power conversion loop.

7. 3. 4. 2 SNAP-2 PCS

1. An uprated 10 kWe combined rotating unit design can significantly reduce redundancy requirements in meeting a 20-kWe system output power level, and is adaptable to system growth to power levels of 30 kWe and higher. Further development of this CRU design should be considered for further system applications requiring power levels in this range.

7. 3. 4. 3 Brayton PCS

1. Optimization and testing of turbomachinery design to attain a compressor efficiency of approximately 87% (presently specified 83%) and a turbine efficiency of 90% is warranted by the improvement in cycle performance and radiator area requirements. Since such improvement appear to be reasonable for the projected application schedule, the design, fabrication, and testing of turbomachinery to demonstrate this performance should be considered.

2. The use of a helium-xenon gas mixture instead of argon as the cycle working fluid offers the potential for significant system weight reduction at comparable performance levels. Further investigation and testing are necessary to resolve existing uncertainties in the preferential leakage of helium.

7. 3. 4. 4 Thermoelectric PCS

1. PbTe compact converter design modification to facilitate converter assembly replacement without disconnecting liquid lines should be investigated because of the potential for a significant reduction in installed redundancy.

2. Continued effort should be directed toward the systematic identification and evaluation/correction of thermoelectric converter failure modes and limiting wearout modes to substantiate the high reliability and prolonged lifetime capability predicted in this study.

3. Structural design of the SiGe direct radiating system configuration should be further optimized on the basis of dynamic analysis.

7.3.5 Operations, Maintenance, and Test

1. Individual reactor power system design provisions for multiple startup, loop transfer, shutdown, and decay heat removal should be developed in greater detail to ensure acceptability of the designs for manned mission application. Although operating procedures outlined in this study demonstrate suitability of the basic systems, a considerably more comprehensive analysis of these procedures is essential to confirm their adequacy and identify additional design features to most effectively implement them. The startup procedure sequence associated with thermal shield removal, and the method of maintaining system flow and temperature control during shutdown are two such areas requiring further investigation. All operating procedures eventually should be verified by test on the complete system.

2. The qualifications and allocation of laboratory personnel should be evaluated to determine the effects of reactor power system maintenance on normal laboratory operations, the experimentation program, and work/rest cycles. A system checkout and maintenance plan should be developed for each power conversion system concept based on a consideration of the maintenance effects on reliability, difficulty of performance, maintenance equipment requirements, man's capabilities in space, and the interrelationships with normal laboratory operation. If power conversion module replacement is feasible based on such evaluation, the installed redundancy to meet reliability requirements may be reduced. Analysis of crew qualifications and allocation should be coupled with extravehicular capabilities definition in future human factors programs to ensure reactor power system applicability.

3. Development of reactor power systems for manned spacecraft application requires a comprehensive study to establish acceptance testing requirements through the successive stages of assembly of the reactor, power conversion system, and the overall configuration. Such a test program should include the specification of tests, checkout requirements, and test and support facilities to be provided at the launch site (KSC), as well as test operations conducted at contractor facilities. Because of the prolonged period of storage for the resupply configuration at KSC, delineation of periodic tests at the launch site to identify and correct possible component degradation is viewed as an especially important aspect of this program. Development of such a program should include active participation of the vehicle contractor in a Joint Test Group composed of representatives of the cognizant agencies to ensure coordination of tests at contractor facilities and at the launch site.

7.3.6 System Components

1. A thermoelectromagnetic pump design has been selected for the majority of reactor power conversion system applications in this study. However, further detailed evaluation and design analysis of pump requirements, unique to the particular conversion system, are considered necessary. Although the direct radiating thermoelectromagnetic pump developed for the SNAP-10A has been extensively

tested, the extent to which uprating of the design capacity or modification of the power source (as for example, an across-the-line design) effects the reliability should be determined. Further effort should be expended in comparing the attributes of the canned rotor centrifugal pump design and the thermoelectromagnetic pump design to further clarify the pump selection basis. Means of flow control during the reactor shutdown and startup operations are particularly important areas requiring further study.

2. Detailed design requirements of system valves have not been established in this study. In view of the general application of system redundancy to satisfy lifetime and reliability requirements and the provisions for multiple shutdown and restart operations, the location, design, and reliability of system valves which are required to satisfy loop transfer and isolation functions are especially important. A more detailed study to develop the detailed requirements and assess the feasibility and comparative reliability of candidate valve designs for this application is mandatory.

7.3.7 Interplanetary Usage Considerations

The integrated reactor power system designs evolved in this study are generally applicable to all manned Earth-orbital missions of extended duration. However, design differences will result from the application of these systems to manned interplanetary missions. Certain of the significant design changes which can be identified at this time are listed in Table 7-4. To attain the maximum benefit from the present study results and to positively identify the distinctions from the manned Earth-orbital application, it is recommended that further in-depth analysis of the reactor power system design requirements to accomplish manned interplanetary missions be performed.

Table 7-4

MODIFICATION OF EARTH-ORBITAL REACTOR POWER SYSTEM APPLICATION REQUIREMENTS FOR MANNED INTERPLANETARY MISSIONS

Reactor	1.	Verification of capability at required power level and lifetime
	2.	Possible reflector modifications to accommodate shield design changes
Shielding	1.	Modified shielding according to selected configuration and required shielded zone
	2.	Possible revision of allocated dose rate from reactor
Power Conversion System	1.	Power level to meet mission requirements
	2.	Possible modification to installed redundancy to meet reliability and lifetime objectives, inasmuch as resupply capability is eliminated
	3.	Increased maintenance capability
	4.	Reevaluation of partial power capability
	5.	Modified meteoroid criteria and sink temperature environment for radiator design
Configuration	1.	Reconfigure for mission module, re-entry, required staging
	2.	Structural capability for escape and re-entry phases
	3.	Modified orbital assembly and deployment
Lifetime and Reliability	1.	System lifetime at least 2-1/2 yr
	2.	Required increase in reliability because of elimination of resupply capability
Mission Module	1.	EC/LS modification to accommodate manpower and environment changes required by mission
	2.	Protection against space radiations (application of biowell)
	3.	Increased standby power source capability
	4.	Abort and re-entry design provisions
	5.	Instrumentation, telemetry, and exploratory equipments

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Appendix A

STUDY PLAN OUTLINE

STUDY AREA A--REACTOR POWER CONVERSION SYSTEM DESIGN SELECTIONS

A/1	Establish Guidelines and Design Criteria
A/1.1	Establish Reactor Design Criteria
A/1.2	Establish PCS Design Criteria
A/1.3	Establish MORL System Constraints
A/1.4	Establish MORL Mission Interfaces
A/1.5	Establish Power Utilization
A/2	Radiator Weight Tradeoff
A/3	Evaluate Reactor Shield-HX-Interface
A/4	Selection of System Designs
A/5.1 through A/5.5	PCS Design Selections
A/5.6	Unique vs Common Design Selections
A/5.7	Select Reactor Thermal Design
A/5.8	Select Shield Designs
A/6	Select System Concepts
A/7	Select Functional Requirements
A/8	Evaluate Growth Accommodation
A/9	Conduct Comparative Analysis
A/10	Recommend Preferred Nuclear Power System
A/11	Specify Development Criteria
A/12	Estimate 50-kWe System

STUDY AREA B--REACTOR DESIGN SELECTION

B/1	Set Operating Limits and Design Criteria
B/2	Establish Baseline Reactor Characteristics
B/3	Develop Reactor, Operational Capability, and Thermal Performance
B/4	Evaluate Reactor Reliability
B/5	Develop Primary Cooling System Design and Performance
B/6	Evaluate Reflector Design
B/7	Establish Preliminary Reactor, Shield, and Primary Cooling Arrangement
B/8	Compare Common vs Unique Reactor Designs
B/9	Select Reactor and Primary Coolant Designs
B/10	Assess Advanced Reactor Potential
B/11	Determine Temperature and Flow Control Program

STUDY AREA C--REACTOR INTEGRATION AND DESIGN ANALYSIS

C/1	Participate in Design Selections for Further Study
C/2	Develop Integration Reactor Shield and Primary Coolant System Arrangement
C/3	Analyze Performance During Fill and Startup
C/4	Develop Overall Reactor Control Requirements
C/5	Determine Reactor Response to Load Demand Changes
C/6	Determine Off-Design Performance
C/7	Evaluate Alternate Mission Performance
C/8	Develop Maintenance, Resupply, and Replacement Requirements
C/9	Develop Operating Requirements Characteristics
C/10	Specify Instrumentation, Control, and Display
C/11	Reliability Logic Diagrams
C/12	Outline Development Program and Schedule
C/13	Develop Technology Plan Information

STUDY AREA D--REACTOR SHIELDING DESIGN AND INTEGRATION

D/1	Evaluate Shield Materials
D/2	Analyze Basic Shield Configurations
D/3	Determine Sensitivity to Component Configurations
D/4	Determine Shield Cooling Requirements
D/5	Determine Arrangement and Integration Requirements
D/6	Assess Effects of Vehicle Interfaces
D/7	Select Representative Designs
D/8	Develop Arrangement and Structural Design
D/9	Specify Radiation Source Strengths
D/10	Determine Dose Rate vs Location
D/11	Estimate Fission Product Radiation Dose
D/12	Outline Development Program Schedule
D/13	Develop Technology Plan Information

STUDY AREA E--RADIATION EXPOSURE LIMITS, INTEGRATED VEHICLE SHIELDING, AND RADIATION EFFECTS

E/1	Specify Allowable Personnel Dose
E/2	Determine Space Radiation Environment
E/3	Perform Preliminary Reactor-Vehicle Shield Optimization
E/4	Assess Radiation Effects on Components

STUDY AREAS F, H, J, L--POWER CONVERSION SYSTEM DESIGN SELECTION

F--Thermoelectric
H--SNAP-2 Mercury Rankine
J--SNAP-8 Mercury Rankine
L--Brayton

F-H-J-L/1	Set Operating Limits and Design Criteria
F-H-J-L/2	Develop Candidate System Design and Performance
H-J/3	Evaluate Corrosion and Wear, and NPSH Requirements
H-J/4	Assess Boiling and Condensation Phenomena
F-H-J-L/5	Determine Parametric Radiator Performance

F-H-J-L/6	Evaluate Primary Heat Exchange Design
F-H-J-L/7	Determine Size and Weight Configuration of Candidate System
F/8	Evaluate PbTe and SiGe Performance and Design
L/9	Evaluate Alternate Turbomachinery Application
F-H-J-L/10	Assess Reliability of Systems
F-H-J-L/11	Evaluate Load Control and Power Dissipation
F-H-J-L/12	Determine Shield Cooling and Regenerate Heating Capability
F-H-J-L/13	Compare Common vs Unique System Designs
F-H-J-L/14	Select System Designs at Each Power Level
F-H-J-L/15	Assess Advanced System Potential
L/16	Assess Optimum Gas Mixture Application

STUDY AREAS G, I, K, M--POWER CONVERSION SYSTEM INTEGRATION AND DESIGN ANALYSIS

G--Thermoelectric
I--SNAP-2 Mercury Rankine
K--SNAP-8 Mercury Rankine
M--Brayton

G-I-K-M/1	Participate in Design Selection for Further Study
M/2	Select Alternator Design
G-I-K-M/3	Develop Radiator Design
I-K/4	Analyze Fill, Startup, Shutdown, and Restart
G-I-K-M/5	Perform Component Design Analysis
G-I-K-M/6	Develop Component Arrangement and Structural Design
I-K-M/7	Assess Bearing and Dynamic Seal Capability
G/8	Evaluate Circuit Failure Conditions
G-I-K-M/9	Specify System Transient Characteristics
G-I-K-M/10	Determine Electrical Characteristics Control Requirements
G-I-K-M/11	Determine Orbital Environment Effects
G-I-K-M/12	Evaluate Alternate Mission Performance
G-I-K-M/13	Develop Maintenance, Resupply, and Replacement Requirements
G-I-K-M/14	Develop Operating Requirements and Characteristics
G-I-K-M/15	Specify Instrumentation, Control, and Display
G-I-K-M/16	Prepare Reliability Logic Diagrams
G-I-K-M/17	Outline Development Program and Schedule
G-I-K-M/18	Develop Technology Plan Information

STUDY AREA N--PRELIMINARY DESIGN

N/1	Determine MORL Limitations
N/2	Determine Orientation Requirements
N/3	Establish Gross Layouts
N/4	Determine Preliminary Weights
N/5	Determine Launch Configuration
N/6	Integrate Radiators
N/7	Integrate With and Select Launch Vehicle
N/8	Perform Deployment Analysis
N/9	Establish Operations Effects
N/10	Iterate Designs
N/11	Specify and Select Configurations

STUDY AREA O--DESIGN INTEGRATION

O/1	Determine Component Arrangement
O/2	Integrate Radiators
O/3	Finalize Deployment
O/4	Design Support Structure
O/5	Modify Design for Radiation
O/6	Integrate Configuration
O/6.1	Determine Constraints
O/7	Launch Vehicle Compatibility
O/8	Select Deployment Distance
O/9	Establish Final Designs
O/10	Modify Design for Repair
O/11	Alternate Mission Design
O/12	Delineate Configuration
O/13	Determine Growth Capability
O/14	Assess 50-kWe Capability

STUDY AREA P--ELECTRICAL POWER SYSTEM DESIGN

P/1	Prepare MORL Load Analysis
P/2	Normalize Load Analysis to 10 kWe
P/3	Identify Load Growth Potential
P/4	Prepare 20- and 35-kWe Load Analysis
P/5	Develop Candidate System Configurations
P/6	Evaluate Comparative System Performance
P/7	Establish Reference System Designs
P/8	Evaluate Constant Load vs Partial Load Operation
P/9	Establish Reactor Control and Protective Functions
P/10	Develop Cable Requirements
P/11	Develop System Activation Operation and Shutdown Requirements
P/12	Integrate Standby/Emergency Power Source Requirements
P/13	Determine Operating Characteristics and Stability
P/14	Evaluate Fault Clearing Capability
P/15	Assess Principal Interface Requirements
P/16	Establish Location and Overall System Arrangement
P/17	Integrate Instrumentation, Control, and Display Requirements

STUDY AREA R--STANDBY/EMERGENCY POWER SOURCE

R/1	Determine Initial Standby Power Requirements
R/2	Determine Startup, Shutdown, and Emergency Power Requirements
R/3	Determine Peak Load Power Requirements
R/4	Compare Alternative Power Sources
R/5	Integrate Overall Standby/Emergency Source Requirements

STUDY AREA S--OPERATIONS, LOGISTICS, EXPERIMENTS, AND SUBSYSTEM INTERACTIONS

S/1	Determine Heat Dissipation Capability
S/2	Assess EC/LS Integration
S/3	Identify Potential Experiments
S/4	Examine Radiation-Experiments Effects
S/5	Evaluate Initial Startup

S/6	Assess Automatic vs Manual Control
S/7	Develop Nuclear System Operations
S/8	Evaluate Radiation Exposure
S/9	Assess Man's Capabilities
S/10	Determine Mission Sequencing
S/11	Develop Mission Operations
S/12	Evaluate Resupply and Replacement
S/13	Develop Alternate Mission Operations

STUDY AREA T--ATTITUDE CONTROL REQUIREMENTS

T/1	Determine Moment of Inertia
T/2	Determine Drag and Gravity Gradient
T/3	Establish Stability and Control Requirements
T/4	Assess Control System
T/5	Develop Preliminary Weights
T/6	Iterate Control Analysis
T/7	Determine Resupply Criteria
T/8	Determine Alternate Mission Requirements

STUDY AREA V--RELIABILITY

V/1	Assess Reactor-PCS System Reliability
V/2	Assess Vehicle Power System Operational Reliability
V/3	Prepare Reliability Flow Charts
V/4	Evaluate Power System Effects on Mission Reliability

STUDY AREA W--TECHNOLOGY PLANNING

W/1	Develop Operating Requirements Characteristics

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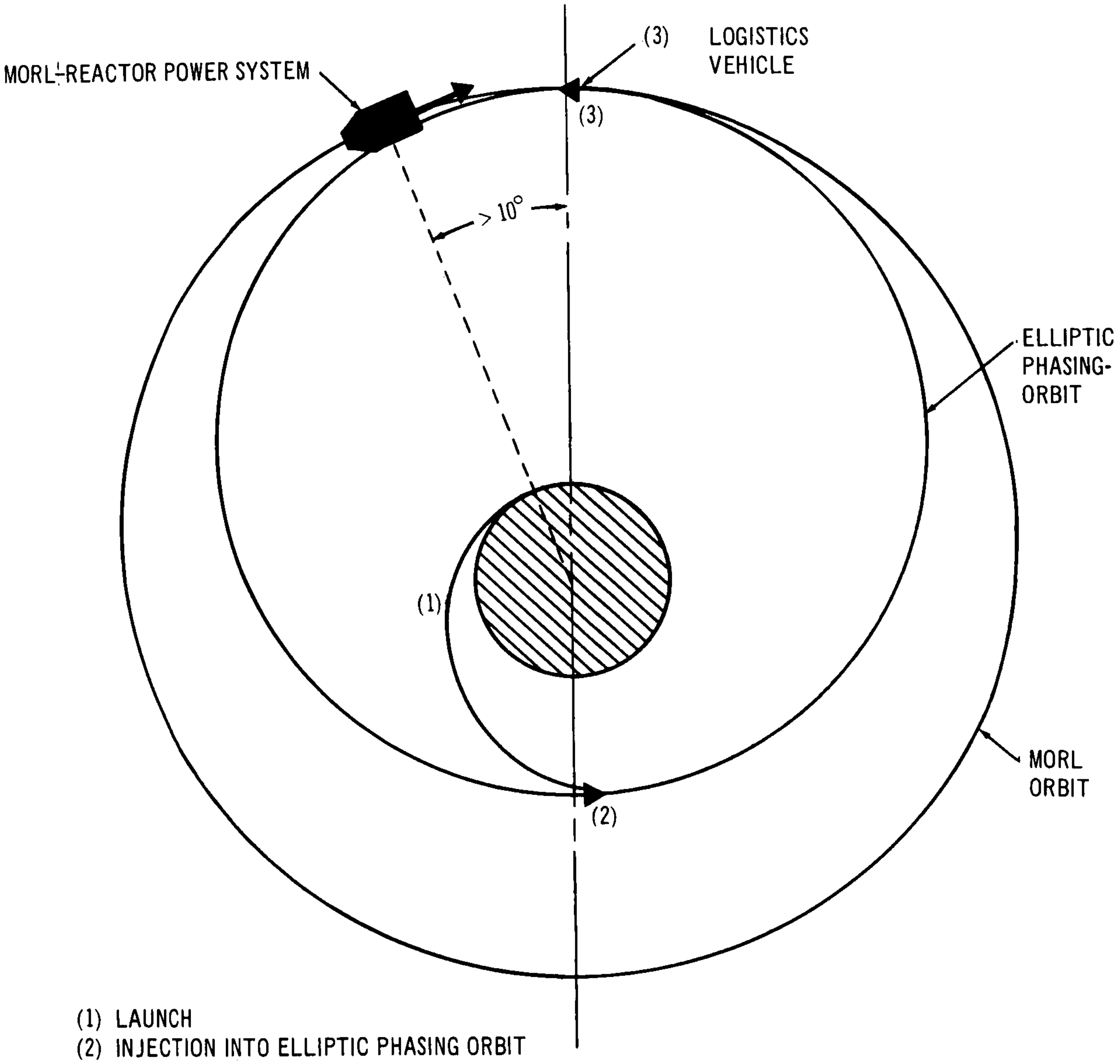
Appendix B
RENDEZVOUS

Certain requirements have been established for the rendezvous of a logistics resupply vehicle with the MORL-reactor power system configuration to ensure that the logistics vehicle crew will not be exposed to excessive radiation levels. These requirements define allowable relative positions of the MORL-reactor power system and logistics vehicle during rendezvous. During the closed-loop, braking, and docking phases of rendezvous, the logistics vehicle must enter and remain within a 35°, cone-shaped radiation exclusion zone referenced from the reactor deployed on the boom. When the logistics vehicle is outside this zone, the relative range must be sufficient to ensure acceptable radiation levels; for example, at a separation distance of 2 nmi, the dose is 320 mRem/hr.

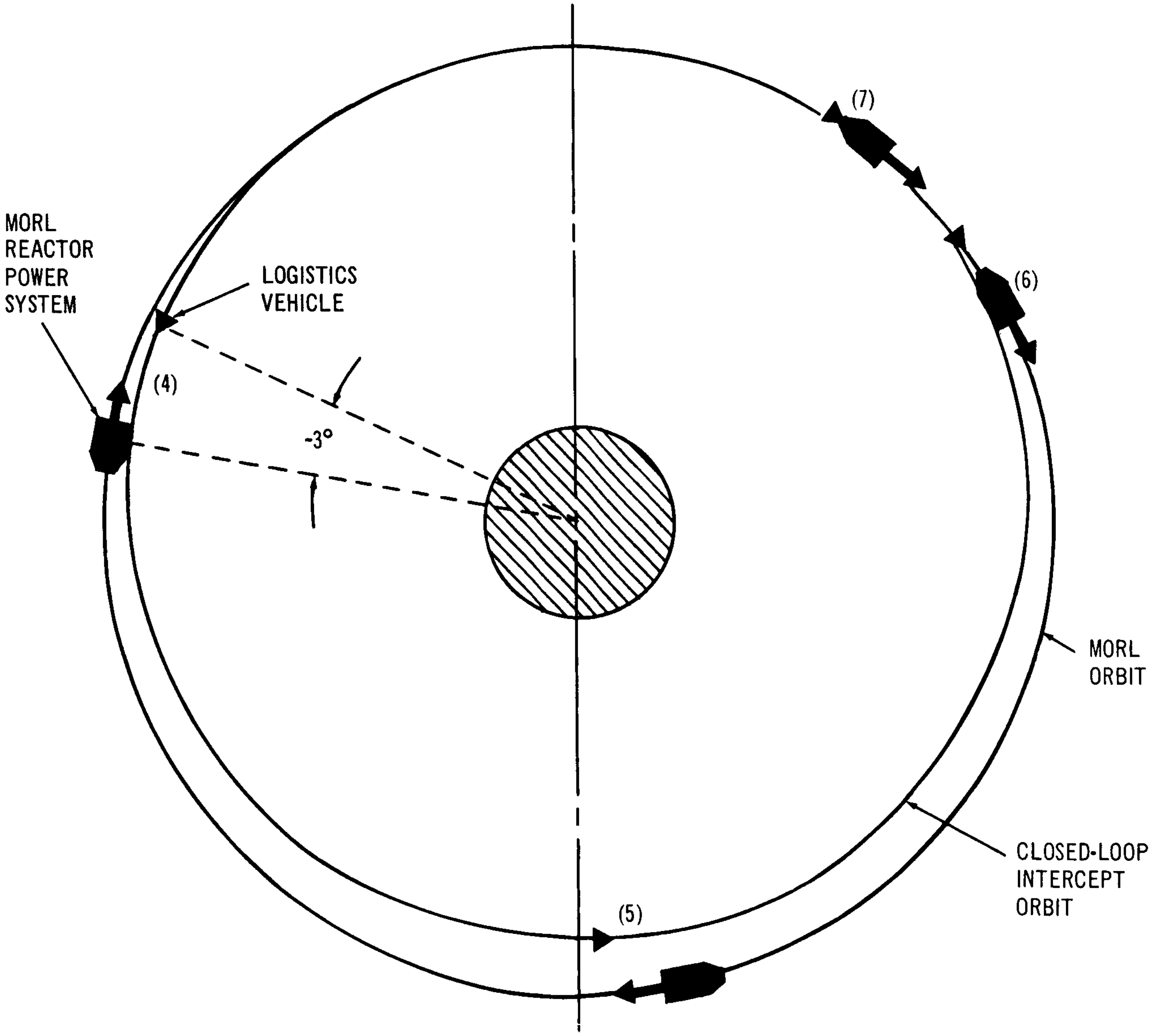
Prior to determining the feasibility of meeting the above requirements, a typical launch and rendezvous sequence for the logistics vehicle is defined. Figure B-1 shows the sequence prior to the first closed-loop correction. After the logistics vehicle is injected into the elliptic phasing orbit (Sequence 2), a ground-based orbit determination is initiated. All information necessary for injecting the vehicle into the gross intercept orbit (Sequence 3), which becomes the closed-loop intercept orbit when corrections are considered, is generated at ground-based facilities and relayed to the logistics vehicle. The injection, based on the ground-generated information, is accomplished by a guidance system aboard the logistics vehicle. The remainder of the rendezvous sequence is shown on Figure B-2. Closed-loop corrections (Sequence 4) are initiated after radar contact is established between the two vehicles and at the proper phasing angle. Additional corrections (Sequence 5) are applied until the logistics vehicle is in the correct position for initiation of the braking phase. The braking phase is initiated at a nominal range of 2 nmi and at a closing velocity of 8 to 10 fps. Docking is under the functional control of the pilot, who completes the maneuver based on visual information.

Two possible error sources which are not additive must be considered in meeting the above rendezvous requirements. They are errors in injecting the logistics vehicle into the gross intercept orbit, and radar and reference axes bias (instrumentation) errors encountered in the closed-loop phase. The mechanics of the previously described rendezvous technique are such that the propulsive corrections applied during the closed-loop phase obviate all errors resulting from injection into the gross intercept orbit (a parametric analysis of which is presented at the end of this appendix); consequently, the ability of rendezvousing within the 35° exclusion zone is dependent only on the closed-loop guidance instrumentation accuracy, that is, radar and reference axes bias errors. A goal for rendezvous accuracy that could be achieved under all circumstances was established at the end of the closed-loop phase and is described as follows: at a range of no less than 2 nmi, the logistics vehicle must be less than 90° below and less than 45° above the local horizontal. At



(1) LAUNCH
(2) INJECTION INTO ELLIPTIC PHASING ORBIT
(3) INJECTION INTO GROSS INTERCEPT ORBIT

Figure B-1. Launch, Phasing-Orbit and Intercept-Orbit Phases of Rendezvous



(4) FIRST CLOSED-LOOP CORRECTION
(5) ONE OF SEVERAL CLOSED-LOOP CORRECTIONS
(6) BRAKING AND DOCKING.
(7) LOGISTICS VEHICLE DOCKED.

Figure B-2. Intercept, Braking, and Docking Phases of Rendezvous this point the braking phase is initiated under manual control of the logistics vehicle crew. The logistics vehicle can be maneuvered along the 2-nmi radius until the logistics vehicle is aligned with the longitudinal axis of the MORL-reactor power system inside the 35° radiation exclusion zone. After this alignment is accomplished, final braking and docking is completed under functional control of the pilot. Perturbations about the longitudinal axis are minimal in the braking phase of rendezvous, as proved in simulation runs and the Gemini-Agena flights, with the result that the magnitude of these perturbations will never exceed the radiation exclusion zone.

Attainable closed-loop guidance accuracy is shown parametrically as a function of radar and reference axes bias errors on Figure B-3. The maximum trajectory dispersion is ± 0.7 nmi, referenced from the MORL-reactor power system longitudinal axis (local horizontal) at a distance of 2 nmi from the docking port. This dispersion is more limiting than the 2-nmi, 45°-above, 90°-below goal previously described, but the latter can be attained under all circumstances and consequently is taken as reference. The ± 0.7-nmi dispersion exceeds the radiation exclusion zone at 2 nmi by approximately 0.1 nmi; but, since the closing velocity is only 8 to 10 fps, the logistics vehicle can easily maneuver inside the radiation exclusion zone and align with the docking port. A typical closed-loop rendezvous trajectory prior to the braking phase is shown on Figure B-4. Relative range when the logistics vehicle is 90° below the MORL-reactor power system is 16 nmi, which is acceptable. The 45° above the MORL-reactor power system is not exceeded at any range. An out-of-phase error analysis was also conducted and indicated that the relative angle between the two orbits (MORL-reactor power system and logistics vehicle) can be maintained to within 1°, which is an acceptable value.

If the reactor is to remain at full power during rendezvous, the logistics vehicle must remain within the radiation exclusion zone under all circumstances while in close proximity to the MORL-reactor power system. If the logistics vehicle rendezvous propulsion system (reliability of 0.9994) or guidance and navigation system failed during the latter part of the closed-loop phase and a reactor intercept was indicated, logistics vehicle entry into the high radiation area surrounding the reactor can be avoided by aborting the resupply mission using deorbit propulsion. If the logistics vehicle systems failed during the braking phase, the reactor could be shut down and the MORL-reactor power system oriented in such a manner that the logistics vehicle would remain in the radiation exclusion zone until the separation distance is sufficient to negate any appreciable radiation dose. At this time, system repair is initiated. If the failure is not repairable, the resupply mission would be aborted using deorbit propulsion such that an excessive radiation dose would not be experienced.

Within the scope of this study it is concluded that sufficient guidance accuracy and system reliability, including such alternative techniques as deorbit propulsion, are associated with the described rendezvous technique such that rendezvous can be accomplished using only a shadow shield while the reactor is operating at full power.

A trajectory perturbation analysis was conducted with regard to errors resulting from injection into the gross intercept orbit (the closed-loop intercept orbit without corrections). Error sources resulting from uncertainties in ground-based tracking and computation (considered to be 35 error sources for

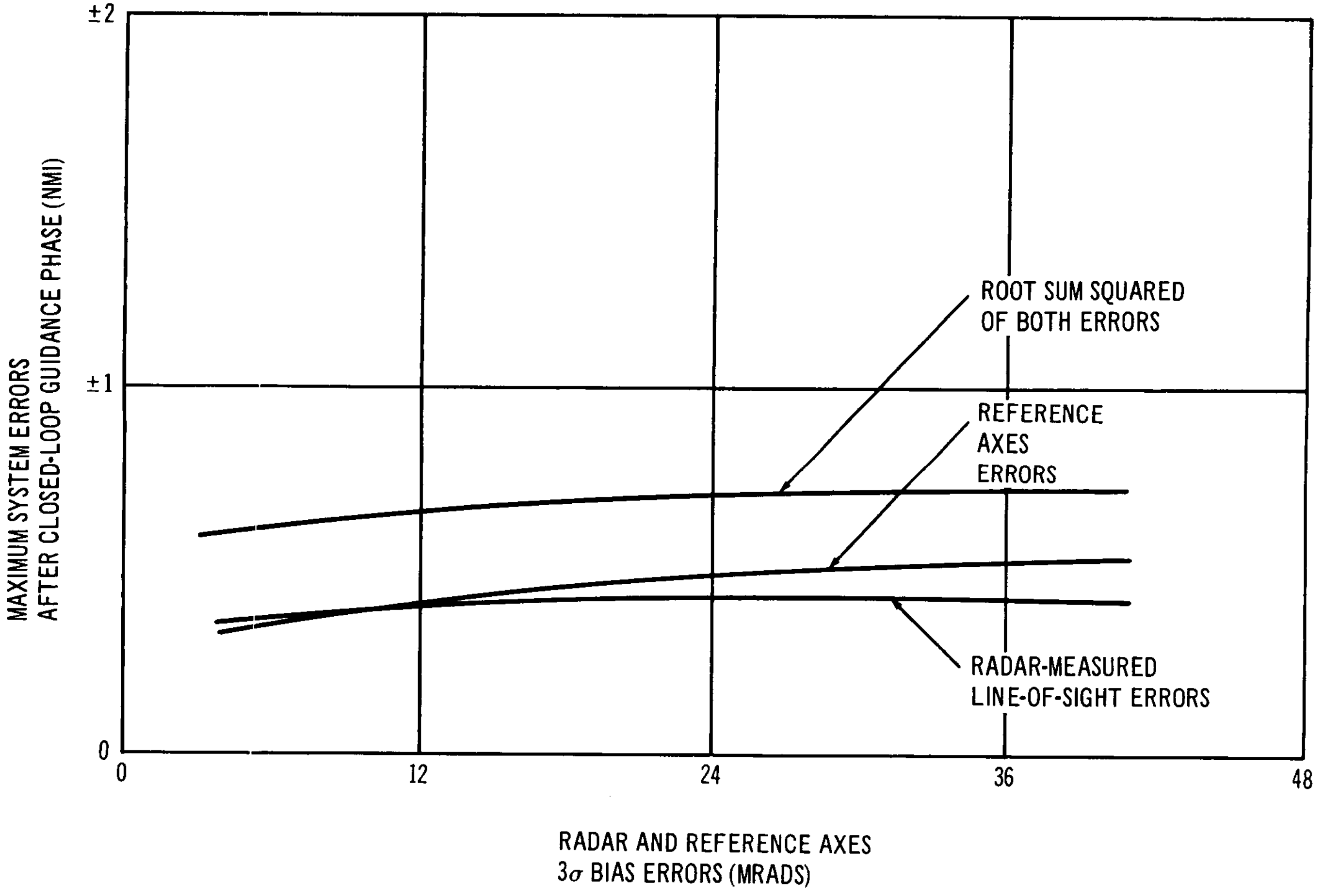


Figure B-3. Influence of System Errors on Closed-Loop Guidance Accuracy

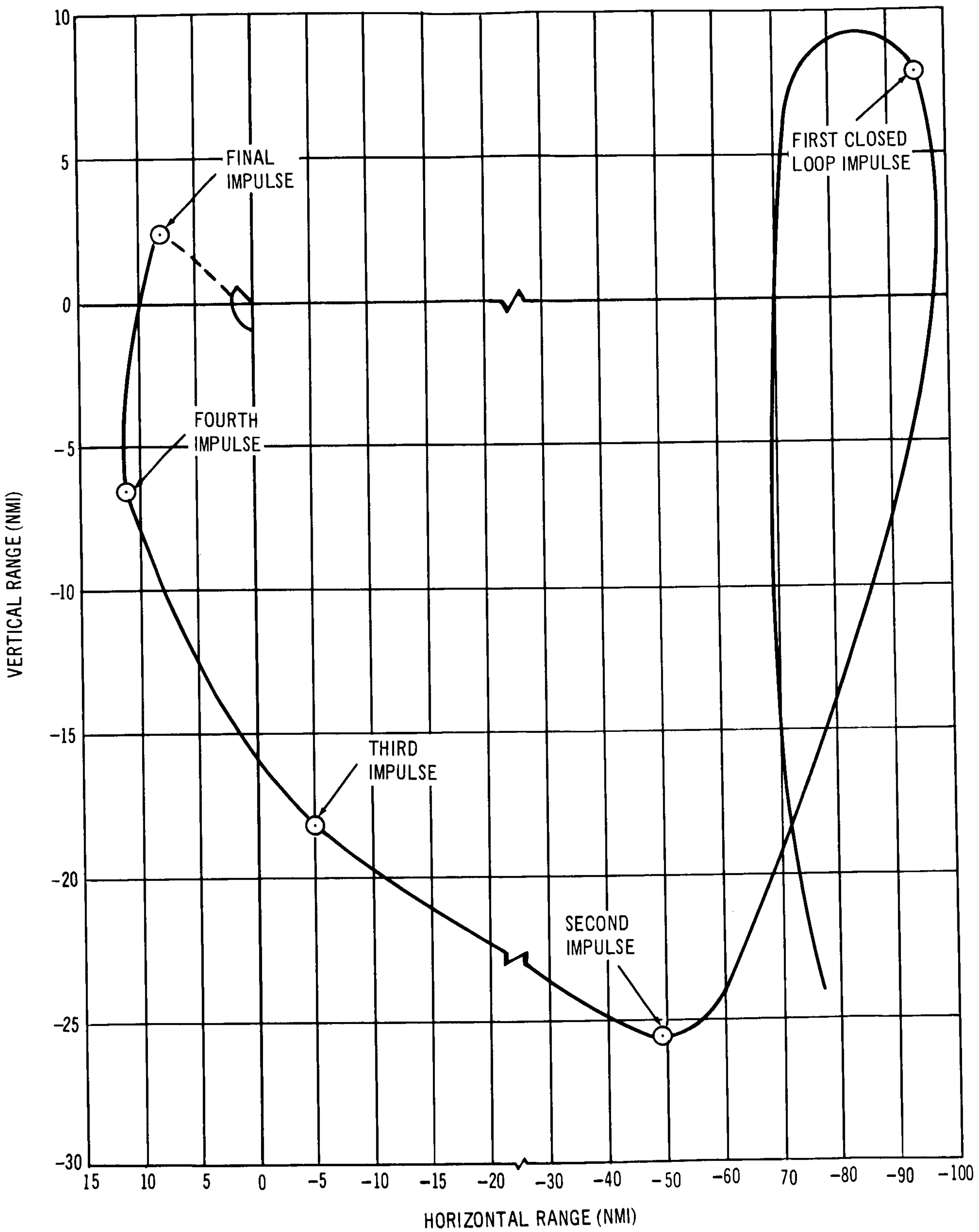


Figure B-4. Typical In-Plane Trajectory

the tracking time available) were initially considered; the results are presented in Figures B-5, B-6, and B-7. Presented is the range of the logistics vehicle with respect to the MORL-reactor power system in a rotating reference frame centered at the MORL-reactor power system. The reference frame rotates at the orbital rate of the MORL-reactor power system; therefore, the horizontal and vertical ranges are along the local horizontal and vertical referenced to the MORL-reactor power system.

As shown, all trajectories intercept the 2-nmi radius within the 45°-above, 90°-below goal. An additional error source, not attributable to ground tracking, relates to velocity error in injecting the logistics vehicle into the gross intercept orbit (Figure B-8).

The effect of all the above in-plane errors would result in intercept trajectory dispersions which would place the logistics vehicle outside the defined 2-nmi radius. However, as has been mentioned, the closed-loop phase negates these errors so that any trajectory dispersion is a function only of the closed-loop guidance instrumentation accuracy.

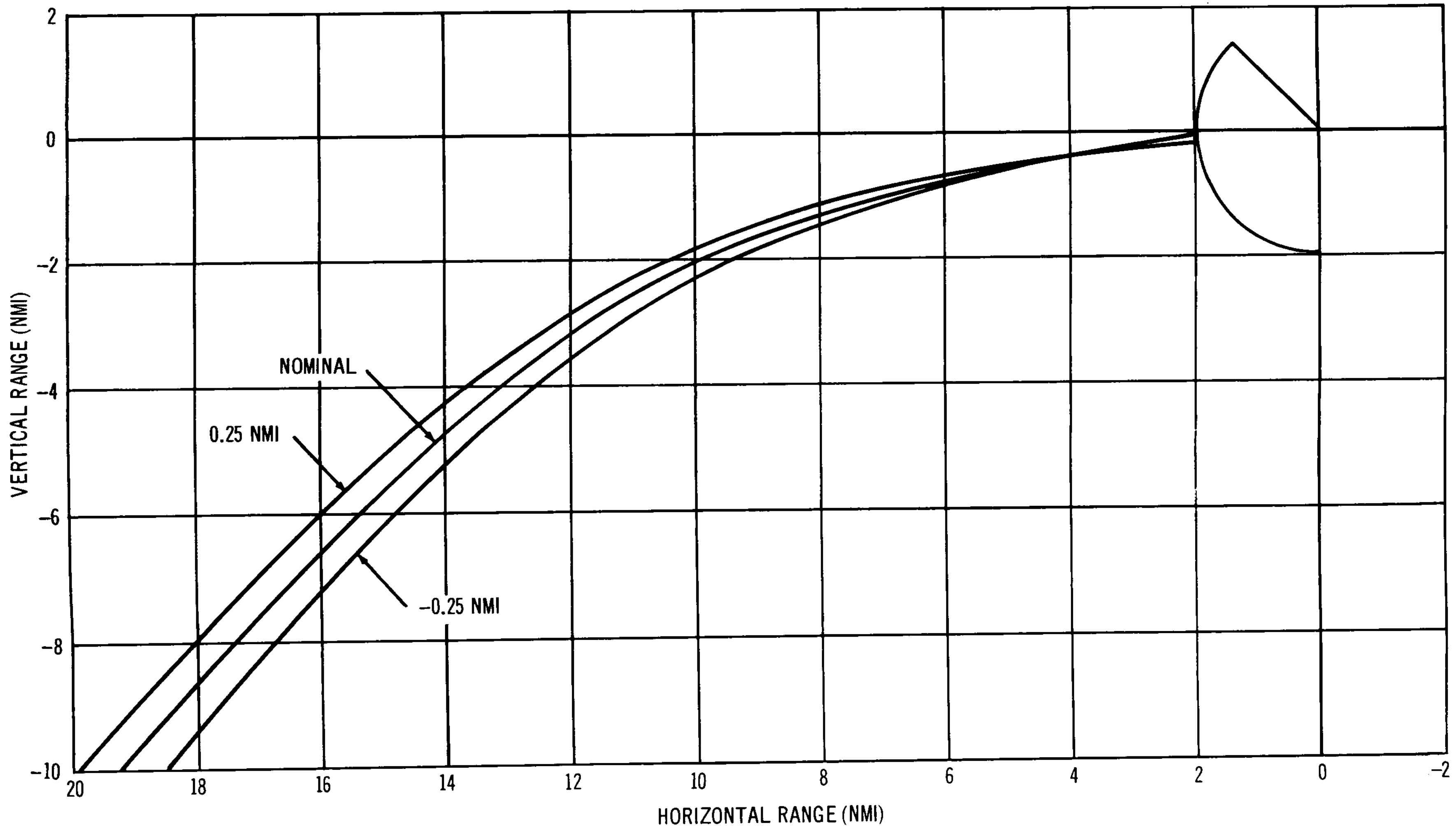


Figure B-5. In-Plane Trajectory Dispersions Caused by Errors in MORL Orbit Altitude

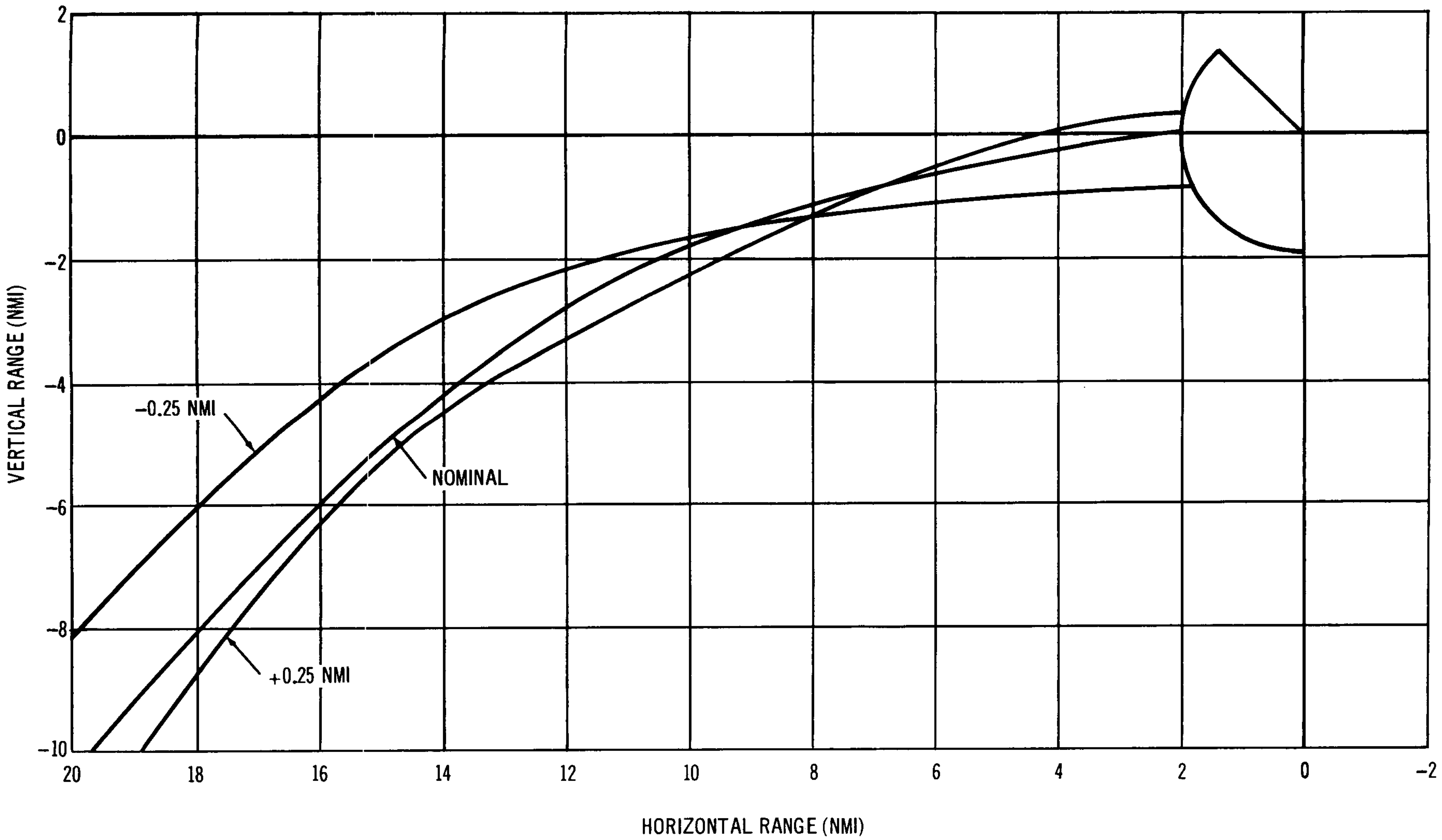


Figure B-6. In-Plane Trajectory Dispersions Caused by Errors in Logistics Vehicle Orbit Altitude

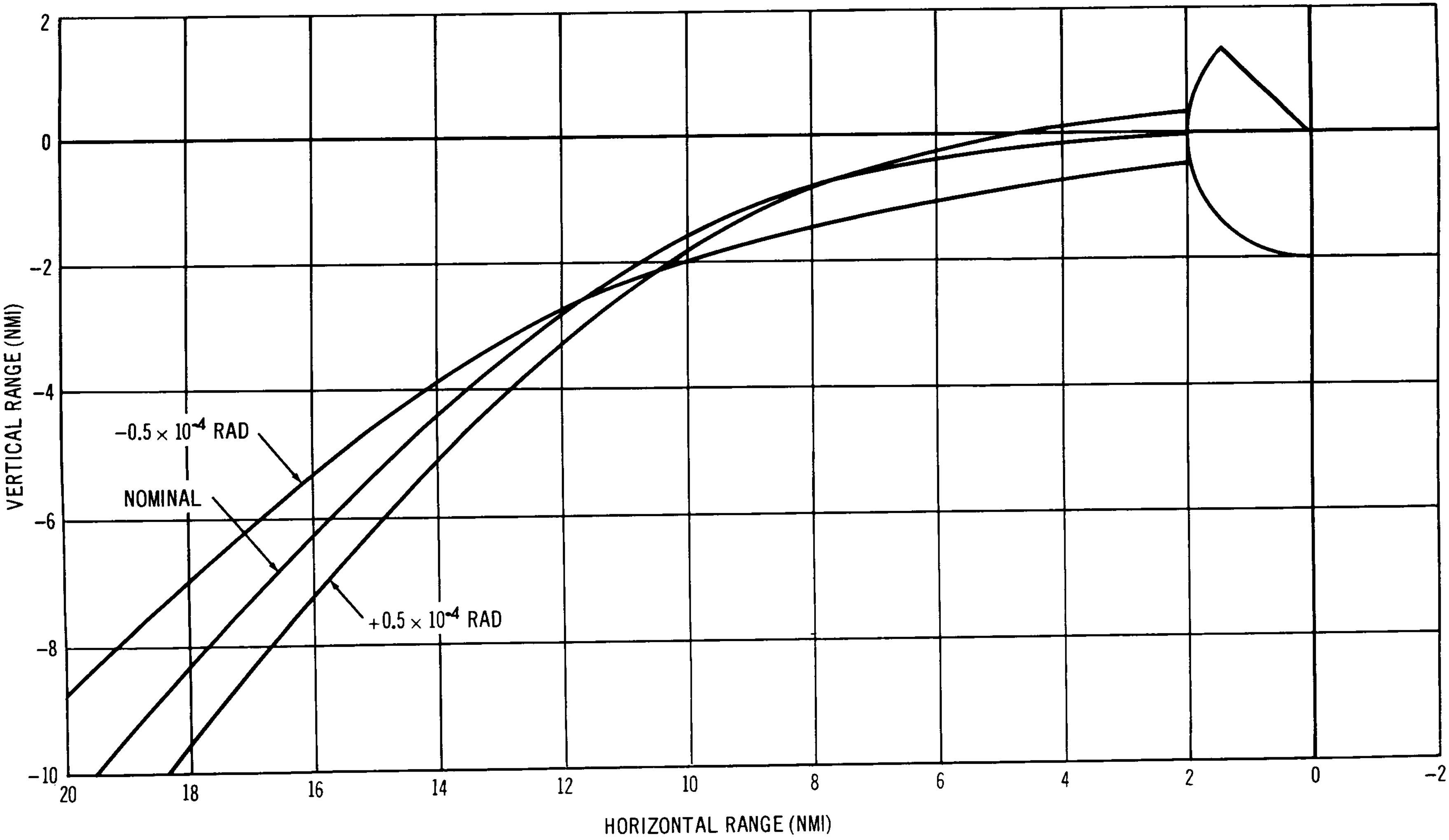


Figure B-7. In-Plane Trajectory Dispersions Caused by Errors in Relative Earth Angle

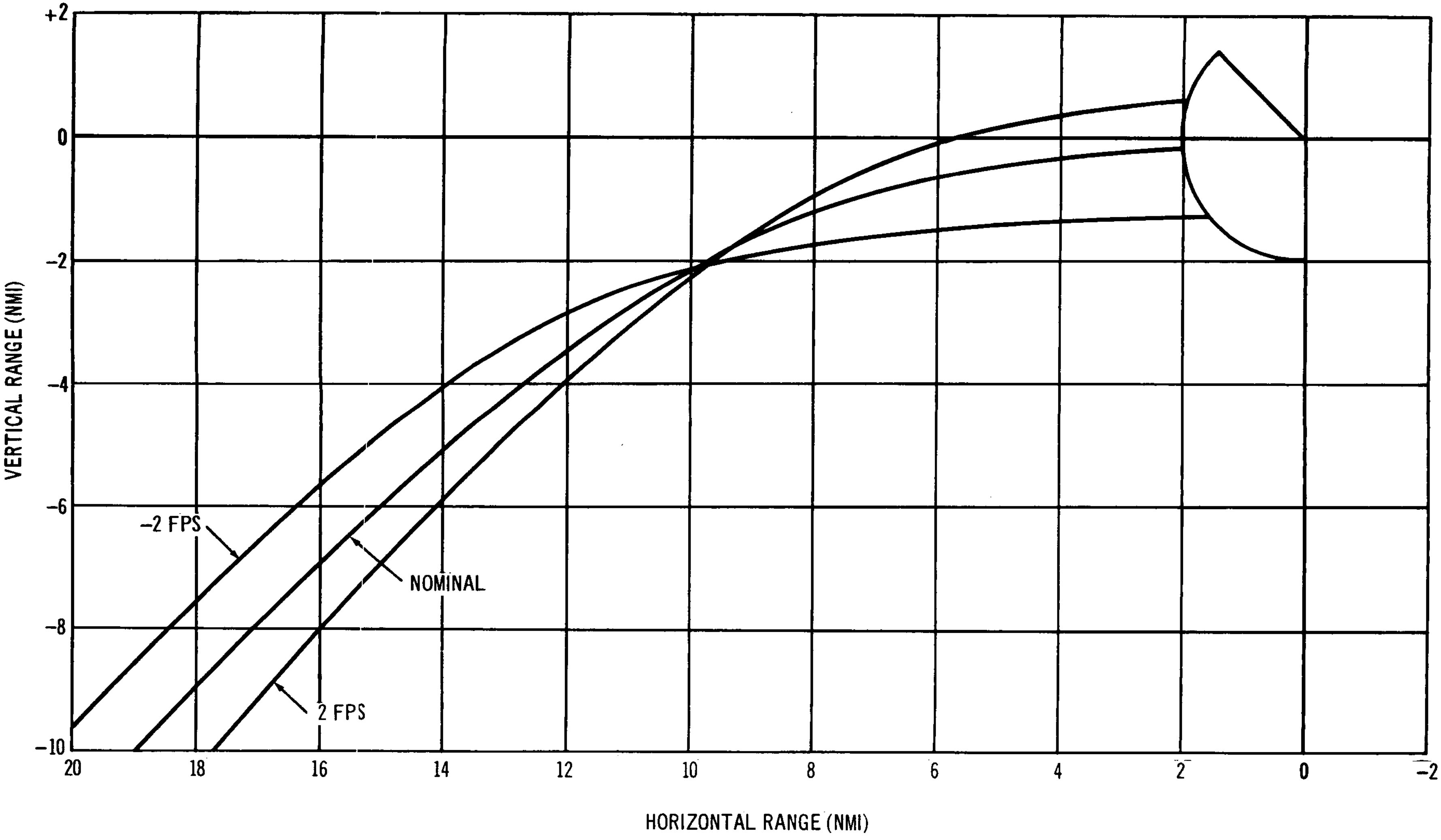


Figure B-8. In-Plane Trajectory Dispersions Caused by Error in Applying Injection Velocity