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REACTOR POWER SYSTEMS FOR MANNED EARTH ORBITAL APPLICATIONS

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REACTOR POWER SYSTEMS FOR MANNED EARTH ORBITAL APPLICATIONS

by

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ABSTRACT

This paper presents design requirements resulting from integration of reactor power systems (10 to 30 kWe) with a manned Earth orbital space station designed for a five year mission duration; included are pertinent conclusions on design of the basic reactor power systems and their effect on the overall mission and space vehicle. The power conversion concepts investigated include the SNAP-8 type reactor in combination with the SNAP-8 and SNAP-2 mercury Rankin systems, Brayton cycle, and direct radiating and compact converter thermoelectric systems.

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 the various reactor power concepts.

Requirement projections resulting from this study indicate that a 20-kWe power level best satisfies the power demand of a second generation ORL application; 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.

Based on integration of the reactor power system with the MORL, modification or redefinition of mission parameters and systems are identified. These include (1) orbit altitude optimization for low-inclination and polar orbit missions; (2) resizing of the control moment gyros and modification of the reaction control system; (3) increased laboratory length to provide environmental control and life support radiator area to reject the entire power load; (4) selection of a 5.5-kWe, Pu-238 Brayton cycle system as the standby/emergency power source; and (5) redefinition of launch vehicles and launch systems.

Significant conclusions include: (1) reactor power systems are potentially compatible with manned missions, (2) compatibility is independent of the specific power conversion concept with the integration weight being approximately 10,000 lb for all concepts, and (3) replacement of the reactor power system is required and feasible although it has a major effect on reactor design.

ACKNOWLEDGMENT

The authors acknowledge the support of Langley Research Center personnel in performance of the NASA funded study from which this paper results; in addition the Douglas Aircraft Company had subcontractor support during the study from : (1) Atomics International, Division of North American Aviation, Inc.; (2) Westinghouse Astronuclear Laboratory, Westinghouse Electric Corporation; (3) Von Karman Center, Aerojet-General Corporation; and (4) AiResearch Manufacturing Company of Arizona, Division of the Garrett Corporation.

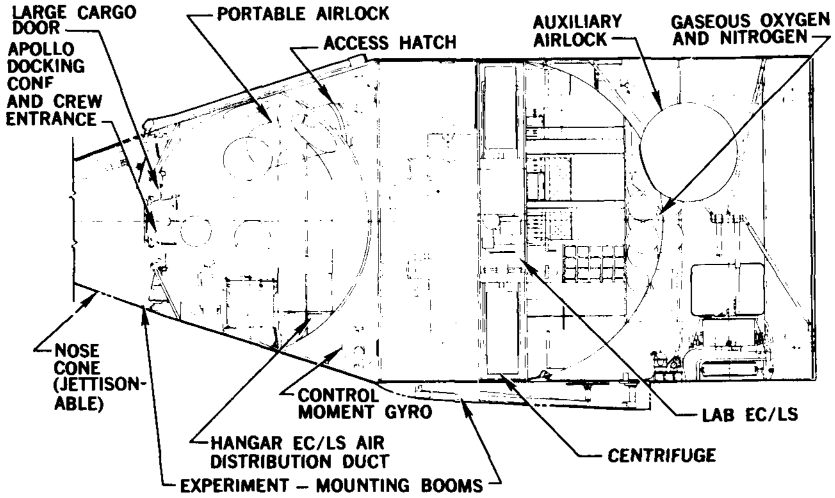
INTRODUCTION

Assessment is required of the need for nuclear power systems to meet the constantly increasing power demands and the progressively more ambitious objectives being set for manned space exploration. The most effective and timely use of nuclear power systems to meet these requirements depends primarily upon a realistic appraisal of nuclear power technological development, considering specific requirements, constraints, and mission criteria applicable to manned orbital programs.

Logical evolution of the nation's space goals includes development of an Orbital Research Laboratory (ORL) which is not only an end in itself but also provides a test/development bed for manned planetary programs. The primary power system of such an orbital laboratory must be flexible and exhibit growth potential for expanded Earth-orbital research programs and for lunar and interplanetary missions; it is indicated that reactor power system has this potential.

The purpose of this study, performed under Contract NAS1-5547 for the NASA Langley Research Center, was to select reactor power system (RPS) concepts that could meet effectively the constantly increasing power demands for ORL missions with a postulated 1974 to 1977 launch date.

The Manned Orbital Research Laboratory (MORL) illustrated in Figure 1, representing a specific Earth-orbital application of well-advanced design studies, was chosen as a representative mission for assessing 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 developing realistic and meaningful guidelines for such reactor technology programs.



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BASELINE MORL

FIGURE 1

Detailed study objectives included the following:

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 (Table 1) which influence manned Earth-orbital mission requirements.

The significant effects of reactor power system integration on the mission, space station design and associated subsystems are described in this paper.

Table 1

SELECTED REACTOR POWER SYSTEMS

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

MISSION REQUIREMENTS

Pertinent mission requirements dictated by the RPS application are as follows:

1. Radiation protection.
2. Compatibility with launch and logistics vehicles and operations.
3. Reactor system shutdown and startup.
4. Mission operations compatible with RPS installation.
5. Reactor system disposal.

RADIATION PROTECTION

The primary design problem was attenuation of the reactor source radiation dose to a level compatible with MORL personnel exposure limits and with minimum weight penalty. This is accomplished through use of shadow shielding and deployment of the RPS 125 ft from the ORL. Separation distance is essentially the same for all RPS's based on an optimization which included reaction control system (RCS) propellant consumption required for maintenance of the spacecraft orbit and attitude control to the required 0.1° accuracy (Figure 2).

All MORL experimentation-associated extravehicular activity (EVA) and orbital operations are accommodated by an 80-ft-diam dose plane at the aft end of the MORL. This 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. With separation distance optimized at 125 ft and an 80-ft dose plane diameter, a 35° shield cone angle and an associated radiation exclusion zone results (Figure 3).

All RPS structures, and/or pertuberances lie within this cone angle and minimize scatter radiation. Because deployable radiators were not adopted,

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SEPARATION DISTANCE OPTIMIZATION

TYPICAL CASE
· SNAP-8

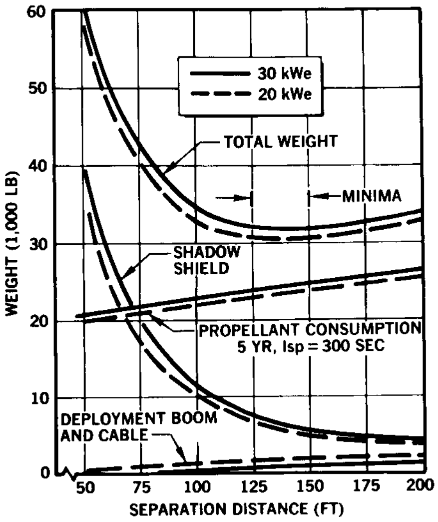

FIGURE 2

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RADIATION EXCLUSION ZONE

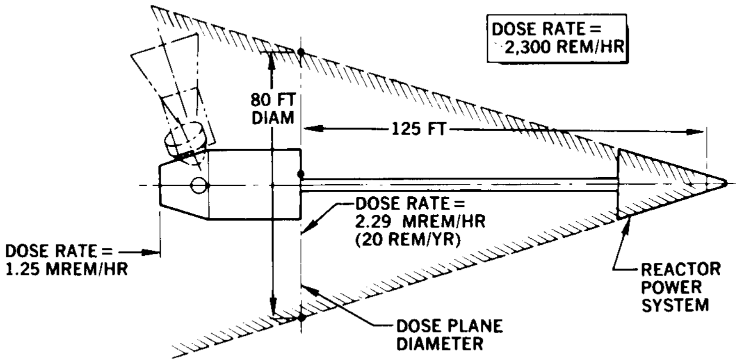

FIGURE 3

all RPS configurations are of the same geometric shape (35^o cones) with maximum diameters of 154 or 260 in. (compatible with the ORL and S-IVB) and with the external surface of the cone serving as both the principal structural support and the power conversion system radiator (Figure 4). 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 PCS components are located as far from the reactor as possible to minimize the radiation dose to crewman performing maintenance.

LAUNCH AND LOGISTIC VEHICLE COMPATIBILITY

Launch of the ORL/reactor power systems into orbit affects the RPS configuration. The RPS is stacked atop the MORL during initial unmanned launch into orbit by an upgraded Saturn IB launch vehicle (Figure 5).

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TYPICAL REACTOR POWER SYSTEM

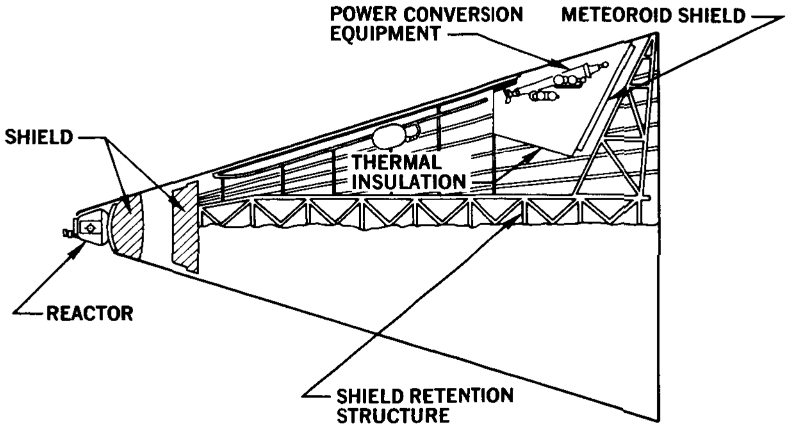

FIGURE 4

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REACTOR POWER SYSTEM LAUNCH ASSEMBLIES

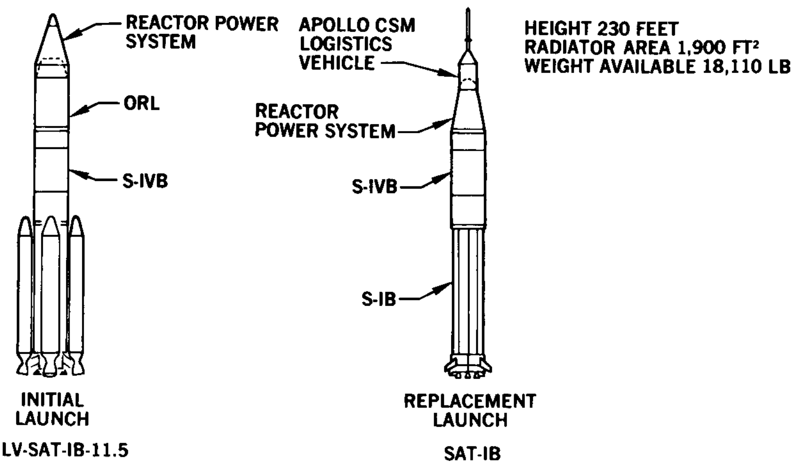

FIGURE 5

Because the dynamic conversion systems have an estimated lifetime of 2-1/2 years, they must be replaced at least once during the 5-year mission. The RPS must also be compatible with the manned replacement launch vehicle. Figure 5 depicts a replacement reactor power system launch assembly with an Apollo command and service module (CSM atop the power system; thus the PCS radiators must support the load of Apollo CSM as well as the reactor. To allow the configurations to exhibit commonality of design between the initial and replacement launch configurations, the replacement RPS sets design condition. It is highly desirable and almost economically mandatory that the RPS utilize the same launch vehicle and launch complex as the ORL logistics program; hence a product-improved Saturn IB is used for replacement launches and a 50°-inclination orbit into the baseline. The overall height of the Saturn IB/power system/Apollo is constrained by the structural capability of the Saturn IB in the flight condition; consequently, the length of the RPS and, hence, the radiator area, is limited. The payload available to the RPS is also limited by the Saturn IB payload capability. The reactor secondary shield is retained on the deployment boom during the replacement operation to minimize the replacement RPS weight.

SYSTEM STARTUP AND SHUTDOWN

The RPS must be designed for initial startup in orbit to meet launch safety criteria. Investigation of the ORL application has established preference for final deployment of the RPS configuration and in initial reactor startup after the station is manned, rather than remotely from the ground; thus reducing system complexity; power system startup is accomplished within 24 days of launch, following initial station manning.

Long-duration manned system applications require provisions for system shutdown. A total of 6 shutdowns and startups per year has been selected as the design basis, with an allowance of 4 shutdowns for a period of no longer than 5 days each for maintenance. During RPS shutdown, a standby power source must be provided to sustain vital life support services, as well as supply power to the RPS to indicate system status and maintain system flow and temperature levels within acceptable limits. In addition, 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.

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, but provision must be made for eventual reactor shutdown. The application of thermal shields, which are retracted during normal operation, provide for the eventuality (Figure 6). 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), the properties of which are presented in Figure 6, appears to offer excellent potential for

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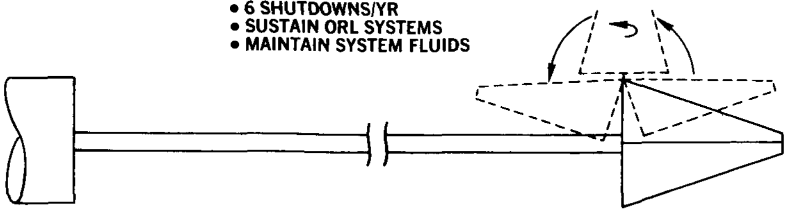
REACTOR POWER SYSTEM-SHUTDOWN & STARTUP

REQUIREMENTS
- 6 SHUTDOWNS/YR
- SUSTAIN ORL SYSTEMS
- MAINTAIN SYSTEM FLUIDS



ALTERNATE
LOW FREEZING TEMPERATURE FLUID
(NaK - Cs)

- EUTECTIC COMPOSITION = 3.1 Na, 24.1 K, 72.6 Cs
- FREEZING POINT = −108°F
- BOILING POINT = 1330°F
- SPECIFIC HEAT = 0.1 BTU/LB-°F (100 to 600°F)

FIGURE 6

this service, further test experience and development of properties of this fluid are required prior to its selection for this purpose.

OPERATIONS COMPATIBLE WITH RPS INSTALLATION

An articulating boom (Figure 7) 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 PCS components, the deployment boom is sized sufficiently large to allow passage of personnel in space suits.

The artificial-g mode of station operation (Figure 8) requires modification in the selected reactor configuration deployment boom design to facilitate retention of the spent S-IVB stage as a counterweight for spin deployment of the ORL. To avoid significantly increased shielding requirements and a

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DEPLOYMENT SYSTEM

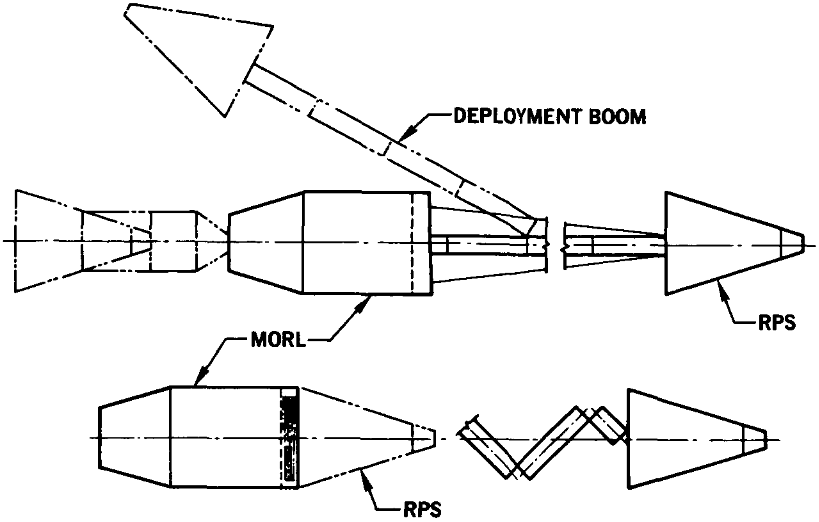

FIGURE 7

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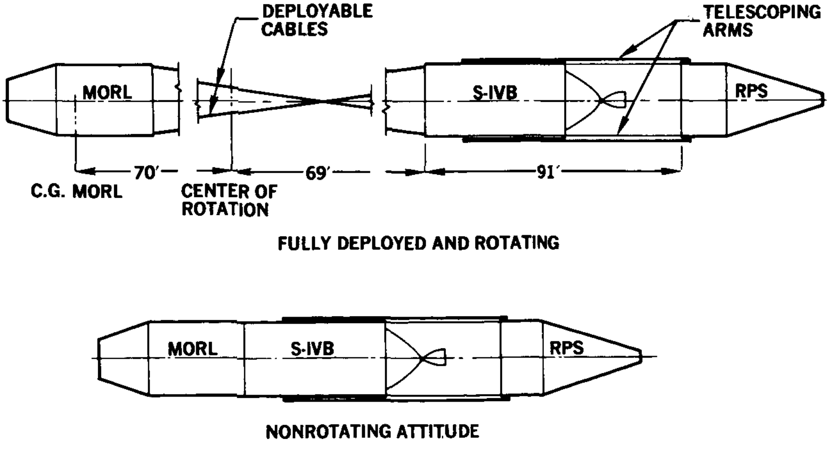
ARTIFICIAL G CONFIGURATION



FULLY DEPLOYED AND ROTATING

NONROTATING ATTITUDE

FIGURE 8

more complicated replacement system deployment operation, the RPS 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 of the forward end of the ORL and rotate the configuration to the operating position. This deployment system desgin is not well suited to retention of the secondary shield when the initial reactor power system is replaced. Moreover, access to the RPS for maintenance is significantly more difficult because extravehicular passage around the S-IVB is necessary.

RPS DISPOSAL

Final disposal of the RPS (Figure 9) is accomplished by a cluster of three solid rockets attached to the support structure of theRPS. For purposes of the present study, provisions are made for either placement into higher

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REACTOR POWER SYSTEM DISPOSAL

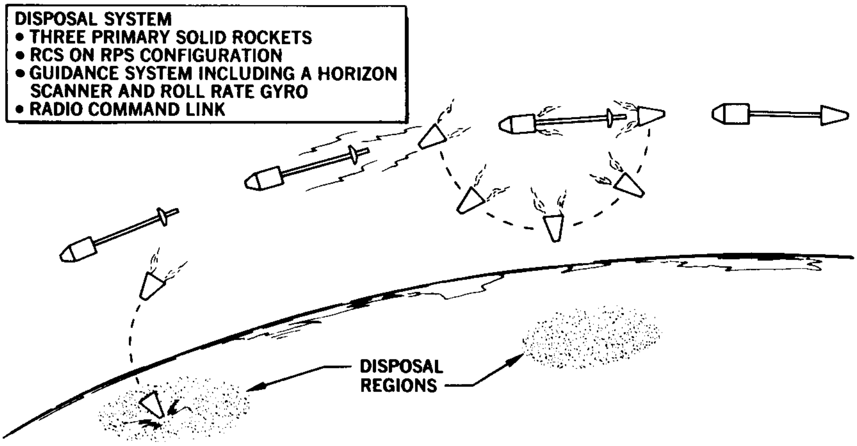

FIGURE 9

orbit or re-entry of the RPS into a designated area, adhering to the following sequences: separation of the RPS from the ORL by thrusting the ORL and the RPS configuration and the associated RCS's until a separation distance determented 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 to provide pitch and roll attitude information, and a roll rate gyro to provide yaw attitude information. To attain the correct attitude for deorbit and thrust initiation, attitude command 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.

MISSION INTEGRATION PARAMETERS

The principal MORL subsystem and mission requirements affected by RPS application are as follows:

1. Crew size and power utilization.
2. Standby/emergency power source.
3. EC/LS system radiator.
4. Stabilization and control system.
5. Launch vehicles and launch facilities.

The results presented while specifically related to affects on the ORL design are generally applicable to any prolonged manned Earth-orbital missions.

CREW SIZE AND POWER UTILIZATION

It was assumed that a reactor power system would not be considered for use with an early-generation space station which might require approximately 10 kWe and that an isotope (Pu-238) Brayton cycle (PBC) system or a solar cell/battery system would be prime candidates for this service.

Full utilization of the laboratory potential created by application of the 20- and 30-kWe reactor power systems allow an ORL having a 9-man crew and using a completely closed oxygen cycle. Electrical power requirements for the MORL mission can be grouped into housekeeping, orbit keeping, and experimental loads. A load analysis typical of 20-kWe application is shown in Table 2. The electrical systems used for the 20- and 30-kWe RPS applications are based on operating the RPS 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.

A 9-man crew, 2 of whom are cross trained in reactor operations and an EC/LS with closed-cycle H_20 and 0_2 subsystems is assumed for the 20- and 30-kWe power levels. The EC/LS heat rejection requirements for the 30-kWe

TABLE 2

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BASELINE LOAD ANALYSIS
(WATTS)

REQUIREMENT	AC	56 V (± 28 V) DC
GUIDANCE & CONTROL	1,169	236
COMMUNICATION & DATA ACQUISITION	325	1,142
EC/LS	2,718	2,790
DISPLAY, CONTROL, INSTRUMENTATION	–	311
LOGISTIC VEHICLES & MAINTENANCE	827	–
LIGHTING & MISCELLANEOUS	268	–
PROPULSION	920	–
TOTAL HOUSEKEEPING LOAD (CONDITIONED)	11,412	

TOTAL HOUSEKEEPING LOAD (SOURCE)	13,700
EC/LS ELECTRICAL LOAD (UNCONDITIONED)	3,300
EXPERIMENTAL LOAD (UNDEFINED)	4,500
TOTAL	21,500
CONTINGENCY @ 10%	2,150
TOTAL LOAD	23,650
SUPPLIED FROM EMERGENCY SOURCE (4.6 KW CONDITIONED)	5,500
STATION POWER AVAILABLE	29,150

system exceed the area available on the ORL requiring a 14-foot MORL extension thus it is concluded that the 30-kWe power level is best adopted to a growth version of the ORL, which could more readily apply the higher power and accommodate the associated power dissipation capabilities.

STANDBY/EMERGENCY POWER SOURCE

The standby system provides the ORL with only sufficient power to satisfy minimum station- and orbit-keeping requirements while the reactor power system is inoperative; this requires a capability of 41. 75 days of continuous operation at a gross power level of approximately 5. 5 kWe. The 41. 75-day duration. Figure 10 is predicated on the maximum time required to replace the reactor power system assuming two launches are required to achieve successful replacement and only two launch pads are available for replacement launch operations. The cumulative duration for which the standby

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STANDBY/EMERGENCY POWER SYSTEM OPERATING TIME

DESIGN CONDITION: REPLACING REACTOR POWER SYSTEM

	MAX DURATION (DAYS)	
1. REACTOR POWER SYSTEM FAILURE		
FIRST ATTEMPT		
2. REPLACEMENT SYSTEM LAUNCH	11.75	
COMPLETE REPLACEMENT DEPLOYMENT REPLACEMENT SYSTEM STARTUP	5.0	
SECOND ATTEMPT		
3. PAD REFURBISHMENT		31
REPLACEMENT SYSTEM LAUNCH		5.75
COMPLETE REPLACEMENT DEPLOYMENT REPLACEMENT SYSTEM STARTUP		5.0
SUCCESSFUL REPLACEMENT – 1ST ATTEMPT	16.75	
SUCCESSFUL REPLACEMENT – 2ND ATTEMPT		41.75

FIGURE 10

system must be designed is variable, but when system replacement and six reactor power system shutdowns per year are considered, the result is 75 days. Candidate standby power sources considered were an isotope Brayton 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 weights 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 isotope system 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 RPS is operating. However, the following three system complexities result: (1) 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%, (2) complexity deriving from the need for a supplementary isotope heater to supply 2.7 kW of thermal energy to the EC/LS system during standby periods, (3) unavailibility of standby power until after solar panels are deployed subsequent to a reactor system failure. Table 3 summarizes the criteria evaluated in selecting a standby power system.

The isotope Brayton 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 eliminated simplifying extravehicular maintenance and drag penalties; and (3) the system is invulnerable to space radiation damage. This power system has the further advantages of supplying thermal energy to the EC/LS during standby intervals and of supplying peak electrical loads during normal vehicle operation.

TABLE 3

M-31148

STANDBY/EMERGENCY POWER SYSTEM SELECTION

MAXIMUM SINGLE DURATION REQUIREMENT: 5.5 KW for 41.75 DAYS

	FUEL CELLS (H_2-O_2, 41.75 DAYS)	SOLAR CELL/ BATTERY	ISOTOPE (PU-238)
LAUNCH WEIGHT (LBS)	7,750	3,500	2,700
SYSTEM AVAILABILITY	MINOR DEVELOPMENT	DEVELOPMENT	ASSUMES BASELINE ORL DEVELOPMENT
INTEGRATION ADVANTAGES	• ORIENTATION INSENSITIVE • NO EXTERNAL APPENDAGES	• SELF SUFFICIENT • SOLAR CELL RELIABILITY	• ORIENTATION INSENSITIVE • NO EXTERNAL APPENDAGES • SUPPLIES THERMAL ENERGY TO EC/LS • SUPPLIES PEAK POWER LOADS
INTEGRATION DISADVANTAGES	• LONG TERM STORAGE • CRYOGENIC REFRIGERATION • LACKS FLEXIBILITY	• OPERATIONAL INTERFERENCE • MULTIPLE DEPLOYMENT • DRAG PENALTY	• RADIATOR AREA • RADIATION ENVIRONMENT

Selection of the standby PCS design parameters included an overall analysis and optimization of the heat source and radiator requirements with respect to performance, weight, and physical size, and resulted in selection of a turbine inlet temperature of 1,640°F and a compressor inlet temperature of 65°F. Design requirements for individual components were evolved from cycle optimization within the envelope defined by these basic parameters. The selected system fuel block is designed to produce a thermal power output of 21 kW. A thermal radiation mode of heat transfer from the fuel block to the power conversion system replacement simplifies installation and increases reliability. Hermetic containment of the working gas avoids physical connections between the heat source and the power conversion equipment which would have to be broken for PCS replacement.

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. Because of the low radiating temperature (approximately 50°F) any increase in power source rating has a pronounced effect on the required radiator size and, in turn, the capability of the ORL to accommodate this surface area.

The total heat load that must be rejected by the EC/LS system radiator is comprised of:

1. Reactor power system gross (unconditioned) output power.
2. Standby power system which is in operation concurrently with the reactor.
3. EC/LS system heat loads supplied by direct thermal means.
4. Metabolic production (500 Btu/man-hour).

Because the EC/LS radiator must be sized to dissipate the full output power rating of the reactor power system, the control parasitic loads (reactor and Brayton) is installed in the EC/LS cooling system; this maintains a relatively constant load on the EC/LS radiator and prevents undesirable temperature fluctuations.

Table 4 shows the total heat loads which must be dissipated in the EC/LS radiator for the individual reactor power systems. 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 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. An equivalent sink temperature of $-28^{\circ}F$ is selected to provide a conservative design basis. Under these conditions, the heat influx would exceed the design value for about 25 min. (of a 90 min. period) during the 50°-inclination orbit.

TABLE 4

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EC/LS RADIATOR COOLING REQUIREMENTS

(KWT)

EC/LS RADIATOR COOLING LOADS	10 kWe SiGe-T.E.	20 kWe PbTe-T.E.	20 kWe SNAP-2	20 kWe BRAYTON	30 kWe SNAP-8
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
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 DISSIPATED HEAT	15.2	35.4	33.5	33.5	44.5

Under the ORL baseline operating conditions, the EC/LS system radiator fluid inlet temperature averages 107°F and the outlet temperature 35°F resulting in a surface radiating temperature of approximately 50°F. The fluid inlet temperature is limited by 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. Figure 11 shows the comparative effects of equivalent sink temperature and EC/LS radiator fluid inlet temperature on the surface areas as a function of the heat load.

The total available surface area on the baseline ORL 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 11 it is apparent that additional surface area is required to accommodate the 20- and 30-kWe RPS 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 lower when using an equivalent sink

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EC/LS SYSTEM RADIATOR CHARACTERISTICS

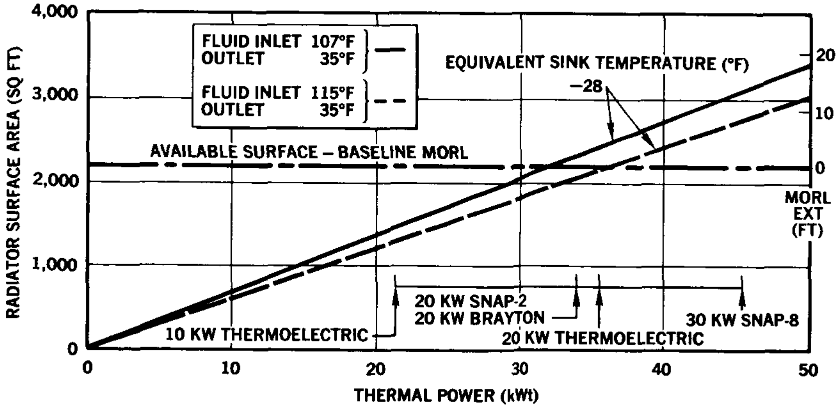

FIGURE 11

temperature of -28°F and EC/LS radiator fluid inlet temperature of 115°F. An allowance of 350 sq ft, in addition to the surface area requirements shown in Figure 11, must also be included for the radiator of the isotope Brayton-cycle standby power system associated with these designs.

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 RPS. Accommodation of the 30-kWe SNAP-8 system (3,100 sq ft) would require an ORL elongation of approximately 14 ft.

Based on the design criteria and ORL reactor power system requirements of this study, the maximum reactor power system power levels which can be accommodated by the Saturn V within weight and height limitations are presented in Figure 12. The limiting criterion for the Saturn V is a height of 380 ft, corresponding to the LUT crane height of Launch Complex 39 at Kennedy Space Center. Design condition for the Saturn V is the initial launch

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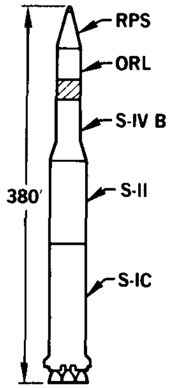
MAXIMUM POWER LEVEL ACCOMMODATION



POWER SYSTEM	MAXIMUM POWER LEVEL, KWe (SATURN V)
THERMOELECTRIC	30
BRAYTON	39
SNAP-2	47
SNAP-8	48

- DEPLOYABLE EC/LS RADIATOR NOT CONSIDERED
- 260 IN. STATION DIAMETER
- ALL LOAD REJECTED THROUGH EC/LS
- INITIAL LAUNCH DESIGN CONDITION

FIGURE 12

configuration (the Saturn V, ORL, and RPS). Both the RPS 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. Because deployable EC/LS radiators were not considered in this study, the additional EC/LS radiator area is obtained by increasing the ORL length. 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 and the ORL length at the higher power levels is significant; for example, 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 ORL.

STABILIZATION AND CONTROL

The functional and performance requirements of the stability and control system result from various mission events concerned primarily with injecting and maintaining the MORL in its prescribed orbit and for experimental program needs. The specific mission events and functions which must be supported by the stability and control system (SCS) include: (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 need 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's provide primary actuation because of the efficiency resulting from their capability to counter cyclical disturbance torques with a minimum of RCS propellant. The RCS supplies external torques for desaturating the CMG and handles events requiring high torque capability.

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

Long, slender configurations such as the MORL/RPS are subject to gravity-gradient torque when in the inertial orientation. Because the vehicle is rotated from the horizontal by a force proportional to the cross product of inertia. Aerodynamic drag is another significant disturbance producing both orbit decay and disturbance torques, which are primarily cyclical and can be countered by the CMG without the expenditure of propellant. Orbit keeping, however, requires the expenditure of considerable propellant. Figure 13 summarizes the disturbances, orientations, components and accuracy requirements of the stability and control system.

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MORL STABILIZATION & CONTROL

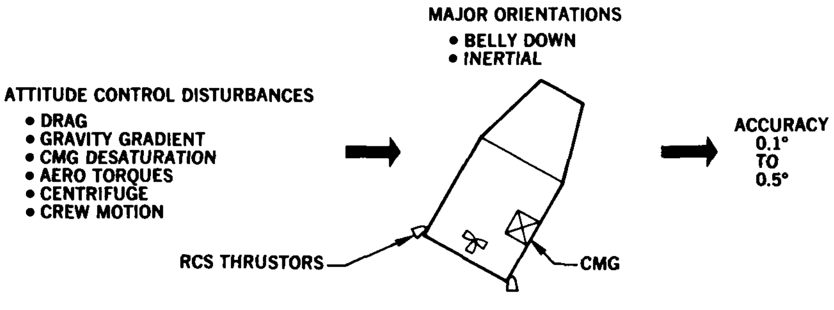

FIGURE 13

Design criteria used in the control analysis include the following:

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 with 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. Altitude control accuracy of a ± 0. 1° will accommodate approximately 94% of the precise Earth oriented and inertial experiments, the remaining experiments are gimbaled to obtain the desired accuracy.
8. Maneuvers performed with the CMG.
9. Alternate use of a chemical bipropellant RCS system (NTO/NMH) 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/RPS configuration. Use of the baseline MORL RCS system was discarded because the reactor power system located 125 ft from the ORL resulted in inordinate propellant requirements. A gravity-gradient SCS concept allowed the RPS and the deployment boom to act as a pendulum relative to the MORL; that is, the RPS is oriented along the local vertical during inertial orientations to eliminate gravity gradient torques was discarded as unduly complex. 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 as shown in Figure 14. The MORL RCS provides orbit keeping and desaturation of the roll CMG. Proper application of the orbit-keeping thrust 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's while the spacecraft is inertially oriented for experimentation. Thrustors are mounted radially to

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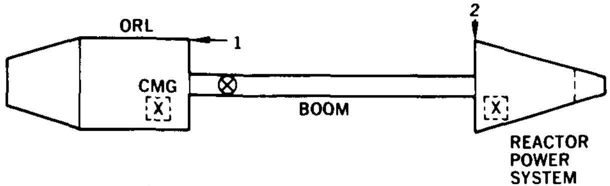
SELECTED REACTION CONTROL SYSTEM



ALL MANEUVERS PERFORMED BY CMG

BASELINE MORL
(164 NMi)

- 1972 – 300 LB/MO
- 1980 – 725 LB/MO

- RESIZED CMG – ADDITIONAL 1200-1500 LB
- ADDITIONAL RCS – BIPROPELLANT (100 LB THRUSTERS) – ~ 320 LB/MO
- ALTERNATE RCS – RESISTOJET – ~ 200 LB/MO

FIGURE 14

take advantage of the long moment arm without which propellant consumption during the inertial orientation would be excessive.

Selection of an orbital altitude above 164 nmi resulted from the optimization shown in Figure 15. For 20 logistic launches, total 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; experimental benefits accruing from a subsynchronous orbit are considered to offset this payload penalty.

The baseline MORL CMG must be resized for the ORL/RPS configuration to accommodate the large gravity-gradient torques which occur during the inertial orientation. Table 5 indicates the CMG weights for the various ORL/RPS configurations. CMG weight attributable to the reactor power system can be determined by subtracting the baseline MORL CMG

ORBIT ALTITUDE OPTIMIZATION M-31139

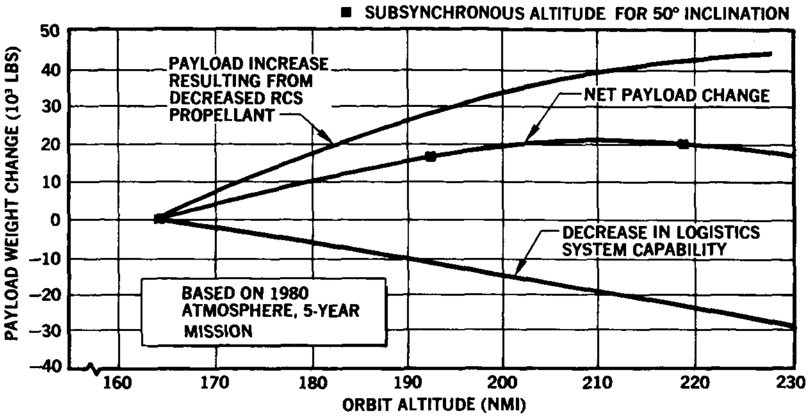


FIGURE 15

weight (628 lb) from the total CMG weights indicated in the first column. Four CMG designs are presented for each ORL/RPS 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 for unrestricted maneuver capability where the CMG is sized to accommodate all 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 ORL/RPS is taken as a reference point. The last weight column indicates 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. For a CMG replacement time of 1 year, CMG maneuvering with 1-g centrifuge capability results in a weight saving

Table 5

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	992	
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	

with 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 year, the weight advantage of the CMG maneuvering mode becomes more pronounced; consequently a CMG size to provide unrestricted maneuver capability was selected.

Launch Vehicles and Launch Facilities

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 RPS 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 use of 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 as the principal design constraints. Commonality of design between the integral and replacement launch configurations was also required with the result that the replacement system configuration sets the design condition. The selected configurations are sufficiently flexible to accommodate reasonable growth. Figure 16 shows the basic configuration types selected for each reactor power system.

The three types of launch conditions considered with the ORL/RPS are the following:

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

Three launch vehicles were identified as candidates for three launch conditions and are presented in Figure 17 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

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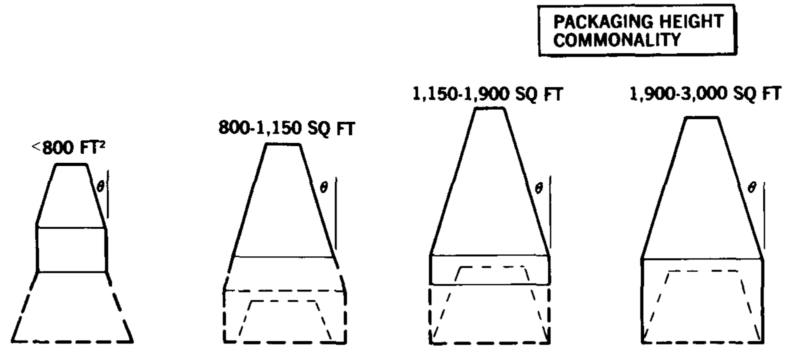
REACTOR POWER SYSTEM CONFIGURATIONS



kW	SYST	AREA
20	SNAP-2	757

kW	SYST	AREA
10	T/E	1,068
30	SN-8	1,075
20	BR	1,150

kW	SYST	AREA
20	T/E	1,891

SATURN V LAUNCHED CONFIGURATIONS

FIGURE 16

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CANDIDATE LAUNCH VEHICLES

	PAYLOAD CAPABILITIES (LBS) (50° INCL., 218 NM)	WEIGHT AVAILABLE (LBS)
• PRODUCT IMPROVED SAT IB	37,580	18,110
• MLV-SAT IB-11.5	69,000	41,000
• SAT V	~235,000	~207,000

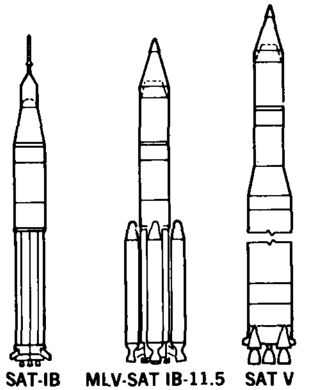

FIGURE 17

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.

An integral launch of the ORL and the initial RPS is selected in preference to separate system launch followed by assembly in orbit from considerations of reliability, cost, and relative operational complexity. On the basis of MORL/RPS weight, the MLV-SAT-IB-11.5 is selected as the integral launch 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, as shown in Table 6.

Significant in the entries shown in Table 5 are the power system weights which vary from 24,700 lb for the 20-kW, SNAP-2 system to 34,800 lb for

TABLE 6

MORL REACTOR POWER SYSTEM WEIGHTS

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(WEIGHT 1,000 LBS)

CYCLE	THERMOELECTRIC		SNAP-2	BRAYTON	SNAP-8
POWER LEVEL (KWe)	10 SiGe	20 PbTe	20	20	30
POWER SYSTEM	27.3	34.0	24.7	26.0	34.8
INTEGRAL* LAUNCH	62.2	69.3	57.8	60.4	71.0
REPLACEMENT* LAUNCH	15.6	22.6	14.7	16.4	21.0
REPLACEMENT LAUNCH HEIGHT (FT)	220	231	226	220	220
SEPARATE* LAUNCH	21.7	30.1	20.7	22.0	30.1

*INCLUDES STANDARD 20% CONTINGENCY

PAYLOAD AVAILABLE: INTEGRAL LAUNCH = 69.0, RESUPPLY AND SEPARATE LAUNCH = 18.1

the 30-kW, SNAP-8 system. Approximately 10, 000 lb are attributable to integration weights which are not necessarily an integral part of the power systems as shown in Table 7. Of note is the fact that all of the integration weights are approximately 10, 000-lb independent of power systems and, more importantly, of power level.

The product-improved Saturn IB is selected as the launch vehicle for replacement RPS launch for economic reasons. All replacement RPS 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 RPS's 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 RPS, launch vehicle height becomes a limitation.

TABLE 7

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REACTOR POWER SYSTEM INTEGRATION WEIGHTS

CYCLE	THERMOELECTRIC		SNAP-2	BRAYTON	SNAP-8
POWER LEVEL (kWe)	10 SiGe	20 PbTe	20	20	30
SHIELD RETENTION & DEPLOYMENT BOOM	2,720	3,450	2,254	2,150	2,350
STANDBY POWER	2,957	1,676	1,676	1,676	1,676
ELECTRICAL SYSTEM ON MORL	3,012	2,524	3,500	2,950	4,493
CMG PENALTY (LB)	1,182	1,568	1,452	1,190	1,560
RCS PENALTY	867	1,436	943	885	1,289
MORL EXTENSION & FAIRING	30	384	384	384	384
TOTAL (LB)	10,768	11,038	10,209	9,235	11,752

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 RPS launch assemblies essentially meet this limitation. In the replacement RPS 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 an RPS 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, corresponding to the crane height limitation of the LUT used in Launch Complex 39 operations. An RPS 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°.

The use of Launch Complex 34 at KSC for the integral launch of the ORL/RPS 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 ORL 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 ORL logistic launch vehicle to be the same product-improved Saturn IB used for the replacement RPS. If another launch complex is used for the replacement launch vehicle and routine ORL logistic operations are still based at Launch Complexes 34, 37A, and 37B, the cost of the replacement launches would increase significantly.

CONCLUSIONS

Integration of RPS's with a manned Earth-orbital space station, using the MORL concept as an example, has resulted in definition of ORL/RPS combinations useful at 10-, 20-, and 30-kWe power levels. Pertinent conclusions on design of both the reactor power systems and the overall mission and space vehicles include:

1. All of the RPS's investigated can be integrated effectively with the MORL to satisfy all laboratory and mission objectives, and will provide potential for increased capability.
2. RPS compatibility with the ORL is essentially independent of the PCS concept requiring a vehicle integration weight of approximately 10,000 lb for all concepts.
3. To meet the ORL 5-year mission objective, capability for RPS replacement is definitely required and is considered feasible.
4. Early mission consideration is mandatory to insure RPS development compatible with a manned Earth-orbital application.
5. The RPS's investigated are not competitive for use on a first generation space station requiring approximately 10 kWe; these RPS's will begin to become competitive with Solar Cell/Battery and Isotope Brayton systems at about the 20 kWe level which will be required for a second generation space station using closed cycle H_2O and O_2 subsystems.
6. The integrated RPS designs evolved are generally applicable to all manned Earth-orbital missions of extended duration. However, design differences involving reliability/lifetime extensions are mandatory for consideration of a RPS to accomplish manned interplanetary missions.