REFERENCE ZIRCONIUM HYDRIDE REACTOR
THERMOELECTRIC SYSTEM

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Frontispiece. Manned Orbital Workshop with 25-kw
Reactor — Thermoelectric Power System

AI-AEC-MEMO-12717

I. INTRODUCTION

This report presents the results of a nine-month engineering study of nuclear reactor — thermoelectric (TE) power systems. This general type of space power system is not new; a 500-watt (SNAP 10A) reactor — TE system was flight-tested in space in 1965. Since that time significant technological advances have been made with SNAP (zirconium hydride type) reactors and with TE converters. As of this writing the latest of a series of SNAP reactors (SNAP 8) has just gone critical and is entering a test program aimed at demonstrating over 10,000 hr of operation at 600 kw, 1300°F. Similarly the tubular lead-telluride TE converters being developed for the AEC by Westinghouse Astronuclear Laboratories (WANL) have demonstrated efficiencies 3 to 4 times higher than those used in the SNAP 10A system. The fabrication processes for this converter module have also been developed to yield good reproducible results, and endurance testing has exceeded 20,000 hr.

These advances, together with the results of several joint NASA/AEC application studies, have made it apparent that reactor — TE power systems utilizing the components developed to date would be attractive candidates for space missions in the 70's requiring power levels up to approximately 40 kwe. In late 1967, therefore, the Atomic Energy Commission started this reactor — TE system study at Atomics International (AI) to better define the design and performance characteristics of such a system.

The general guidelines provided by the AEC for this design effort were that the power system should utilize the reference zirconium hydride reactor coupled to a power-conversion system (PCS) incorporating lead-telluride tubular TE modules. WANL performed the design and analysis work on the TE converters and power-conditioning equipment under subcontract to AI.

Additional objectives set for this study are as follows:

- 1) Establish a conceptual design of a reference system suitable for adaption to either manned or unmanned space missions with a nominal power level of 25 kwe and a minimum lifetime of 20,000 hr.
- 2) Prepare parametric performance data over a suitable power range above and below 25 kwe to illustrate the trade-offs available between power, weight, area, temperature, etc.

- 3) Establish preliminary design and performance requirements for key system components to serve as a guide for ongoing and/or future development work.
- 4) Prepare or update conceptual designs of reactor — TE powerplants adapted for specific space missions, including manned orbiting workshops and manned lunar bases.

The conceptual design for a reference zirconium hydride reactor subsystem suitable for use with TE or other PCS's was also to be established parallel with the above system engineering work.

The results of the reactor — TE system engineering effort are presented in this report, in the same order as the objectives listed above. Details of the reference zirconium hydride reactor design are given in a companion document.^{(1)*}

The work reported herein was performed for the USAEC under Contract No. AT(04-3)-701, and was completed in June 1968.

*Superscript numbers in parentheses are for References at the back of this report.

II. SUMMARY

A. REFERENCE SYSTEM

The reference 25-kwe reactor - TE system design evolved in this study consists of the zirconium hydride reactor coupled by the primary-coolant loop to four parallel power-conversion sections. The reactor design is similar to the SNAP 8 reactor but has a slightly larger core and an internally cooled BeO reflector suitable for operation within an enclosed shield. These modifications are desirable for manned space applications.

Each of the four power-conversion sections includes a TE converter assembly, a NaK pump, and a heat-rejection loop (HRL). Each converter assembly contains 24 TE tubular modules structurally supported within a rectangular box and interconnected with coolant manifolds for proper flow distribution of the hot primary loop and the cold HRL's. The tubular modules are arranged in parallel "4-packs," each of which provides slightly more than 1 kwe at 56 volts, dc. Blocking diodes are used for each 4-pack to isolate possible short circuits to ground.

The NaK pumps are of the dc-conduction electromagnetic (EM) type. Each pump has three throats, two of which pump 1/4th of the total primary-loop flow and the third throat pumps one of the HRL's. A separate TE power pack consisting of three high-current modules connected in parallel provides the dc current to each pump.

Each HRL consists of a radiator section, an expansion compensator, and interconnecting piping and manifolds. The radiator design selected as a reference is of the conventional fin-and-tube type, with stainless-steel NaK tubes diffusion-bonded to aluminum fins and meteoroid armor. Alternate radiator materials and concepts offering potential performance improvements were also identified. The possible use of heat-pipes for the heat-rejection side of the PCS was also studied, but it is not now recommended due to inexperience with a suitable working fluid for the temperature range of interest.

A reference startup and control scheme was defined which uses reactor-outlet temperature as the control parameter during startup and electrical

current output during normal operation. No valves or moving parts other than the reactor control drums are required. A shunt-type voltage regulator which dissipates excess power to space through high-temperature resistance elements was selected for voltage and load control.

The major design and performance characteristics for the reference reactor - TE system are summarized in Table II-1. The reactor thermal power and coolant-outlet temperature are well within the capabilities of the reference ZrH reactor, and provide adequate margins for reliability, power growth, and/or compensation for possible system degradation. The unshielded system weight and radiator area correspond to a near-minimum weight design; the area can be reduced at the expense of increased weight. The specific weight of approximately 280 lb/kwe and specific area of 56 ft²/kwe represent a significant improvement over previous designs.

TABLE II-1
REFERENCE REACTOR - THERMOELECTRIC SYSTEM
DESIGN AND PERFORMANCE CHARACTERISTICS

Electrical power: (gross)	25.2 kwe
(regulated)	24.7 kwe
Voltage	56 volts dc
Reactor thermal power	583 kwt
Reactor-outlet temperature	1246°F
Average radiator temperature	563°F
Net efficiency (system)	4.24%
Unshielded weight	7000 lb
Specific weight	280 lb/kwe
Radiator area	1400 ft ²
Specific area	56 ft ² /kwe
Design lifetime	20,000 hr
System degradation allowance	10%

A number of system and component optimization and trade-off studies were made in the process of arriving at the reference design described briefly above.

Among these were (1) the optimization of the converter module dimensions, (2) system weight-area-and-temperature trade-offs, (3) evaluation of several converter-packaging alternates, (4) several iterations on the pump type and capacity, (5) comparison of two vs three loops in series, (6) reliability and weight trade-offs for two to eight parallel power-conversion loops and HRL's, (7) determination of near-optimum pressure drop and ΔT for both loops, (8) radiator materials, tube size, and spacing optimization, and (9) overall system reliability estimates for various system configurations and design alternatives.

Parametric studies were also performed to determine the system characteristics at higher and lower power levels, using a computer code developed for this purpose during the study. From 15 to 35 kwe, the unshielded system specific weight ranges from approximately 320 to 250 lb/kwe, respectively. The specific area for near-minimum weight remains in the range of 56 to 60 ft²/kwe, and the reactor thermal power ranges from 350 to 800 kwt.

B. POWERPLANT FOR ORBITAL WORKSHOP

Major emphasis in adapting the reference system for specific space missions was placed on establishing a conceptual powerplant design suitable for integration with the Saturn-V Orbital Workshop (OWS) concept, which is currently being studied by NASA under the Advanced Apollo Program. The power system design is essentially identical to the reference system except that the radiator area has been reduced slightly at the expense of a small weight penalty, and radiation-shield designs tailored for the mission have been included.

The frontispiece to this report illustrates the powerplant-OWS integration concept evolved after examination of several alternate approaches. The reactor power system is shown extended in its operational position; during launch or shutdown periods it would be retracted within the cylindrical structure which serves as an aerodynamic shroud, heat shield, support structure, and docking adaptor. The powerplant package is attached to (and can be disconnected from) the forward docking port of the multiple docking adaptor. The power system is designed so that with minimal modifications it can be launched integral with the OWS on a two-stage Saturn-V, or separately using either a Titan-IIIF or

Saturn-IB/Service Module combination. With the separate launch an unmanned rendezvous with the manned OWS would be required, using the Transtage or Service Module for this maneuver.

Both shadow and 4π radiation-shield designs were examined for an assumed dose limit of 20 to 30 rem/yr, which is small compared to the dose that is expected from natural, space radiation. The power-conversion equipment is located in a compact gallery within the shield. The shadow- and 4π -shield weight estimates are approximately 14,300 and 16,500 lb respectively, which brings the total powerplant weight (including power cables, deployment mechanisms, etc.) to approximately 22,300 to 24,500 lb, depending on the shield type. Thus the total, shielded power system specific weight is approximately 885 to 975 lb/kwe.

The estimated payload margins available for the separate launch and rendezvous mode (including allowances for the shroud, rendezvous propellant, etc.) are 6700 to 8900 lb with the Titan-III-F, and 1500 to 3800 lb with the Saturn-IB/service module. The margin available for the integral launch mode on a two-stage Saturn-V depends strongly on the final weight estimate for the OWS.

End-of-life (EOL) disposal of the reactor power system, if required for safety reasons, could be accomplished by undocking the powerplant and then using the manned Command and Service Module's (CSM) propulsion and guidance capability to either de-orbit the reactor into the ocean or park it in a higher long-lived orbit.

C. LUNAR BASE AND MANNED ORBITING RESEARCH LABORATORY (MORL) POWERPLANTS

Two reactor - TE powerplant designs evolved in previous joint NASA/AEC studies^(2,3) were updated to incorporate the design and performance changes available with the reference system. In both cases significant improvements were obtained with respect to system simplification, specific weight, and specific area. For the lunar base powerplant, for example, it now appears possible to increase the net power from 20.4 to 35.5 kwe, using the same constraints and criteria established in the previous joint study. For the MORL powerplant the weight and area reductions were 5 and 26% respectively, the total number of coolant loops was reduced from 22 to 5, and the reactor outlet-temperature was reduced approximately 50°F.

III. REFERENCE SYSTEM

A. SYSTEM DESCRIPTION

The reference ZrH reactor - TE System utilizes the nuclear reactor described in Reference 1 combined with a compact PbTe TE converter currently under development by Westinghouse to produce 25 kw of electrical power. The design uses two sets of heat-transfer loops in series, the primary loops and HRL's. A sodium-potassium liquid-metal alloy (NaK) is used in both loops. The arrangement of loops and components is shown schematically in Figure III-1. Detailed descriptions of components are provided in subsequent sections of this report.

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Figure III-1. Reference 25-kwe System Schematic

Three-loop systems were also considered early in the study. In this arrangement an intermediate set of loops with heat exchangers is placed between the primary and HRL's. The intermediate heat exchangers (IHX's) are somewhat more compact than the compact converters, and in orbital applications requiring a shielded gallery a small shield weight savings may thus be obtained. For the current 25-kwe design, however, the increase in weight caused by the intermediate loops more than offsets the shield-weight savings. For these reasons and because the two-loop arrangement is also less complex and more reliable it was selected. Any further growth of the system to use more of the reactor's power capability (>1200 kwt), however, could result in a three-loop arrangement being optimum.

The primary loops transport NaK, heated to 1246°F in the reactor, to the hot side of the TE tubular modules. NaK circulating in the HRL's provides the 573°F average cold junction of the modules and transports the rejected heat to radiators. The same schematic arrangement and system components are used in common for several different mission adaptations. As described later in this report, the mission adaptations, except for the radiator and shield, are primarily configurational changes.

The PCS utilizes four compact converters each having an independent HRL. Four parallel loops are also used in the primary system to simplify integration. The primary loops are not hydraulically independent, as they share the reactor vessel in common.

The selection of four parallel loops was based on a trade-off between weight, partial-power (one loop out) performance, complexity, and reliability. The penalty in going from two to four loops was 150 lb; from four to six was 200. The partial-power capability in a four-loop system is 80% of normal power assuming that the reactor-outlet temperature is increased to its full 1300°F capability to provide partial compensation for loss of the loop. This includes the penalty of flow reversal through the inactive NaK pump resulting from the postulated loop failure. (Flow check valves for this application were excluded by reliability considerations.) For less than four installed loops the partial-power capability fell to a level considered to be unacceptable for the probable requirements for most missions. An increase to many more than four loops, with the

added complexity and reduced reliability for full-power operation, could not be justified on the basis of the small increase in partial-power capability. Four loops was considered the best compromise for a typical application at the designated power level. With the components sized for this system, considerable growth can be accomplished by adding parallel loops without severely complicating the system.

Each of the four compact converters consists of 24 tubular TE modules. They are placed in a four-by-six array; each set of four is connected in series electrically for a 56-vdc electrical output. All modules are hydraulically in parallel. In the reference design the overall system efficiency is 4.24%.

The NaK pumps used in the reference system are the EM type utilizing a separate TE power supply. One pump is used in each of the four system quadrants. Each pump has three throats within the same magnet frame. Two throats are connected hydraulically in series to meet the primary-loop flow requirement. The third throat provides pumping of a HRL. The three pump throats are connected in series electrically to a special three-module TE power supply having a 220-mv 1500-amp output. The power supplies are mounted directly on the pump frames.

A total of eight NaK expansion compensators is used in the system. Four are used in the primary system and one in each of the four HRL's. All units are identical, of the double-sealed gas-backed bellows type, with a volume change capacity of 0.15 ft^3 . They maintain the system pressures at 20 psia under nominal operating conditions.

The radiator structure and shielding requirements for the system are dependent to a considerable extent on the mission adaptation. Trade studies considering heat-rejection temperature, TE performance, radiator area, and system weight resulted in the selection of 570°F average heat-rejection temperature and 1400 ft^2 of radiator as near-optimum values.

The radiator may be designed in a number of ways including finned tubes or heat pipes. The radiators may also be fixed or folding depending on vehicle-integration constraints and other considerations. A typical design adopted for the Saturn-V OWS application consists of a fixed 12-ft-diam structure to which

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Figure III-2. ZrH Reactor - Thermoelectric System,
Reactor/Gallery Arrangement

are attached 96 3/8-in.-diam NaK tubes. Aluminum fins with integral meteoroid armor are diffusion-bonded to the stainless-steel tubes. Each HRL provides NaK to one quadrant of the radiator cylinder. Each quadrant in turn is divided into three parallel flowpaths by means of headers and interconnecting piping to maintain the radiator pressure drop to a low value. The support structure for the finned tubes is a 0.010-in.-thick Ti shell-and-stringer structure with internal frames spaced at an average of 3-ft intervals. This radiator design concept is used for the weight summary provided later.

The shield structure, like the radiator, varies with mission adaptation. Fundamentally, the reference design consists of a molten-Pb gamma shield (encapsulated in a steel container) immediately surrounding the reactor, followed by a LiH neutron shield. Internal heat generation in the Pb gamma shield is radiated to the reactor vessel. The primary-loop components contain radioactive NaK and are sandwiched between the primary reactor shield and secondary shielding. In a typical manned application the secondary shield consists of a depleted uranium gamma shield followed by additional LiH neutron shielding. Descriptions of designs for specific missions are provided in Section V of this report. General shielding requirements, reactor/shield integration, and shielding technology status are discussed in Reference 1.

The basic reactor and gallery arrangement is shown in Figure III-2. The primary-loop expansion compensators, the four system pumps with power supplies, and the TE converters are located in the gallery region between the primary and secondary shields. The components are arranged symmetrically about the system centerline. In the configuration shown, the reactor is shielded on all sides to provide shielding for vehicle rendezvous maneuvers. The reactor control-drum actuators are located outside the reactor shield. In the lunar base adaptation the equipment arrangement is very similar. In this case, however, it is advantageous to invert the whole assembly to place the control-drum drives below and the gallery components above the reactor.

An unshielded system weight breakdown is shown in Table III-1. The 1400 ft² fixed-finned-tube radiator is included for illustration. Shielded system weights are given in Section V for specific mission adaptations.

TABLE III-1
UNSHIELDED SYSTEM WEIGHT BREAKDOWN

System Component	Weight (lb)
Reactor	1422
Primary-loop piping	100
Pumps	440
Expansion compensators	208
Thermoelectric converters	1135
Gallery structure	120
Instrumentation, control, and regulation	340
Subtotal	3765
Radiator	
Piping	661
Radiator and structure	2580
Subtotal	3241
System Total	7006

B. SYSTEM PERFORMANCE

The steady-state performance of a reactor - TE system is extremely stable. Because of the relatively high radiator temperature, variations in the sink temperature due to night and day variations are insignificant.

1. Reference Operating Conditions

Table III-2 gives the performance characteristics of this system when operating at the reference conditions. The regulated power of 24.7 kwe is 2% less than the gross power output due to losses in the voltage regulation equipment. The lifetime objective for the plant is 20,000 hr; however, the system has no characteristics that definitely limit its lifetime. Operation well beyond 20,000 hr could be accomplished at only a slightly lower reliability level.

TABLE III-2
REFERENCE PERFORMANCE CHARACTERISTICS

Electric power, kwe:			
Gross			25.2
Regulated			24.7
Voltage, volts:			
System			56.0
Thermoelectric tubular module			14.0
Lifetime, hr			20,000
Thermal-power balance, kwt:			
Reactor	582.4		
Primary-loop losses	<u>-5.0</u>		
	577.4		
Converters		539.0	
Pump converters		<u>38.4</u>	
		577.4	
Radiator			551.0
Gross electrical power			25.2
Hydraulic power (adds to loop losses)			<u>1.2</u>
			577.4
Temperatures, °F			
	<u>Inlet</u>	<u>Average</u>	<u>Outlet</u>
Reactor NaK	1044	1145	1246
Converter, hot-clad	1225	1125	1025
Converter, cold-clad	470	570	670
Radiator NaK	663	563	463
Efficiencies, %			
System			4.24
Converter			4.67
Converter Carnot			35.0
Hydraulics			
	<u>Total Flowrate,</u>	<u>Pressure Drop,</u>	
	<u>lb/sec</u>	<u>psi</u>	
Primary loops	13.0	3.35	
Heat-rejection loops	12.4	1.50

Figure III-3. System Performance vs Load Voltage, Reactor-Outlet Temperature = 1246°F

Figure III-3 shows how system performance varies with changes in load voltage, for a constant reactor-outlet temperature of 1246°F. As the load voltage increases the current decreases, and because the effective thermal conductance of the converter varies with the current, the hot-to-cold-junction ΔT increases. The hot-junction temperature increases and the cold junction's decreases, with the latter resulting in reduced reactor power.

These specific performance curves resulted because the system was designed to produce power at nominally 56 vdc. For particular applications the TE modules could be wired for any nominal load voltage that is a multiple of 14 vdc.

2. Off-Design Performance

It may be desirable to operate the powerplant at off-design conditions for two reasons. First, degradation in the TE converter could be offset by raising the operating temperature, or second, the plant could be operated at less than its full power capability if electrical power requirements are projected at a lower level for an extended period. Lowering the power level would tend to increase the plant lifetime and reliability because of the reduced temperatures of all components, and would reduce the load required to be dumped by the voltage regulator. It is expected that changes in electrical output of the plant would be made only when the requirements were projected differently for a matter of weeks.

Figure III-4 shows the electrical power output of the system as a function of load voltage for different reactor-outlet temperatures. At the reference design voltage of 56 volts this information can be cross-plotted to establish the relationship between electrical power and outlet temperature, as done in Figure III-5. It should be noted that the thermal power, also plotted on this figure, does not vary proportionally to electrical power. A 40% reduction in electrical power only reduces the thermal power by 24%, from 582 to 440 kwt. An extrapolation of this curve would show that the thermal power required to obtain any electrical power at 56 volts is on the order of 300 kwt.

An important observation from Figure III-5 is that 27.2 kwe can be obtained at a reactor-outlet temperature of 1300°F compared to the 24.7 kwt at 1246°F.

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Figure III-4. System Electrical Characteristics vs Reactor-Outlet Temperature

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Figure III-5. Effect of Reactor-Outlet Temperature on System Power, Voltage = 56 Volts

TABLE III-3
PARTIAL-POWER PERFORMANCE CHARACTERISTICS
(Three Loops Operating)

Regulated power, kwe				19.8
Voltage, volts:				
System				56.0
Thermoelectric tubular module				14.0
Thermal-power balance, kwt:				
Reactor	470.0			
Primary-loop losses	<u>-5.0</u>			
	465.0			
Converters		435.0		
Pump converters		<u>30.0</u>		
		465.0		
Radiator				444.0
Gross electrical power				20.2
Hydraulic power (adds to loop losses)				<u>0.8</u>
				465.0
Temperatures, °F	<u>Inlet</u>	<u>Average</u>	<u>Outlet</u>	
Reactor NaK	1104	1184	1264	
Converter, hot-clad	1084	1164	1244	
Converter, cold-clad	508	588	668	
Radiator NaK	500	580	660	
Efficiencies, %				
System				4.21
Converter				4.57
Converter Carnot				35.5
Hydraulics		<u>Total Flowrate,</u> <u>lb/sec</u>		
Operating primary loops (3)		12.9		
Nonoperating primary loop (1)		-2.3		
Heat-rejection loops (3)		9.5		

This means that the system can accommodate as much as 10% degradation without the reactor-outlet temperature exceeding 1300°F. Operation at this temperature level is believed to be acceptable for all components, but the reference operating conditions are lower primarily to achieve temperature margin to compensate for possible system degradation.

3. Partial-Power Performance

The electrical power capability of the system is 19.8 kwe after loss of one of the four HRL's. This assumes that all TE converters in the three operating loops are generating power and that the reactor core-outlet temperature is raised to 1300°F.

Since the pump on the nonoperating leg of the primary loop has no power, this leg of the loop acts as a reactor bypass. Approximately 18% of the original total flowrate goes through this loop while the flowrate in the other loops increases to 33% of the original total flowrate. This increase is due both to the added bypass line and to the reduction in pressure drop through the reactor core. The bypass flow enters the reactor-outlet plenum at the inlet temperature so the temperature exiting the plenum is only 1264°F when the core outlet is 1300°F. Table III-3 summarizes the performance characteristics when operating with only three quadrants.

C. SYSTEM OPERATION

Operation of the reactor — TE powerplant is inherently simple because of the passive nature of TE power conversion. Both the electrical power output and the hydraulic power available from the pumps automatically increase as the reactor temperature and power are increased. The only parts required to move, for control of the powerplant, are the reactor control drums. The control drums are rotated slowly in discrete steps of approximately 1° to change the radial leakage of neutrons from the core and thus the neutron balance. Rotation of the drums in the direction to increase the neutron level within the core causes the reactor power and temperature to increase until the inherent negative temperature coefficient of the reactor stabilizes the operation at a new power and temperature level. A single drum step will change the operating temperature approximately 5 to 15°F. The corresponding electrical power change when operating near the design point would be from 1/4 to 3/4 kwe.

1. Startup

Several options are available for startup that trade off total time and standby power for startup against complexity of the electronic control circuits. The simplest circuit would involve rotating the reactor control drums at a constant rate until the desired electrical power is reached. The time for startup in this case would be on the order of 12 hr. By introducing stepping-rate changes into the startup sequence, the startup time could be reduced to 2 to 3 hr. Features must be added to the control system for this; however, even in this case the control system logic is relatively simple.

The system startup has four distinct phases. The details of a typical startup are described for the Saturn-IVB OWS power system in Section V-A-4b. Since these details are mission-dependent, the following paragraphs will describe only the general nature of each phase and the possible options.

a. Phase 1: Shutdown Margin Removal

For safe handling on the ground the reactor is designed to be approximately \$4.75 subcritical at room temperature. The first step in the startup, then, is to remove this shutdown margin. Normally a fast stepping-rate would be used during this phase and it would be completed in about 30 min. If the single stepping-rate, dictated by Phase 2 limitations, were used throughout the startup, this phase would require approximately 10 hr.

The slowdown in stepping-rate at the end of Phase 1 would be signaled by a control-drum position indicator or step counter. The selected drum position would correspond to a 25 to 50¢ subcritical condition in the reactor. Since the drum position at which the reactor is critical varies slowly throughout the life of the reactor, it is anticipated that the selected drum position could be changed. This could be coordinated routinely from the ground control center, since any single adjustment would be usable for startups during a period of at least one month.

At least 5% flow will be required during this phase to assure that no local NaK freezing occurs in the system and that an acceptable transient results when thermal power is initiated. Though several ways of providing NaK flow are

possible, each would require some standby electrical power. One way is to pass 50 amp through small startup pumps attached to each loop. This current would pass through each pump in series, for a total voltage drop of about 2 volts. Thus the total power requirement would be about 100 watts. It is anticipated that this is a relatively low requirement compared to other power requirements during spacecraft dormant periods or during nonoperating manned periods.

b. Phase 2: Critical to Sensible Heat

During this phase of the startup the stepping rate must be reduced to the minimum rate. Once the reactor goes critical the neutron flux or power level begins to increase from some low source level, but no reactivity feedback due to the negative temperature coefficient of the reactor is introduced until the power level reaches a level of about 1 kwt. This normally occurs on the order of 20 min after criticality, so the reactor is supercritical by the amount of reactivity inserted during this 20-minute period. The degree of supercriticality determines the rate of increase of power, the magnitude of the power spike, and the resulting temperature transient that occurs before the inherent reactor temperature characteristics stabilize the operating conditions.

The drum stepping-rate is limited so that the temperature transient is acceptable. When the time to remove the last 25 to 50% of the shutdown margin is included, this phase of startup takes about 40 to 60 min. The end of Phase 2 is signaled by a temperature sensor on the reactor outlet line set at approximately 300°F.

An estimate of the startup transient is shown in Section V-A-4b. The power spike and temperature transient with this reactor are greater than with previous SNAP reactors because of the reduction in fuel-temperature coefficient caused by the addition of Gd prepoison. The magnitude of the transient will be reduced as the reactor is operated, for two reasons. First, the Gd burns out resulting in an increase in fuel coefficient; and second, the source power level which affects the time between critical and sensible heat is greatly increased after operation. In fact if the reactor is to be restarted within an hour after shutdown, the stepping-rate for this phase could be easily doubled.

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Figure III-6. SNAP 10A Startup in Orbit

c. Phase 3: Heat Shield Removal

Once the temperature sensor indicates that the reactor is generating power, the heat shields which envelope the radiator during nonoperating periods to protect against NaK freezing can be removed. This phase of the startup is most affected by the design of the powerplant and the mission integration constraints. The time for this phase can vary from zero, where the heat shields are ejected or removed quickly and no hesitation in the startup is required, to about 30 min, where the removal must be accomplished more slowly. In the latter case, which may involve the deployment of folded radiators, the reactor-outlet temperature would probably be limited until heat shield removal is completed.

d. Phase 4: Ramp to Power

This phase of the startup is restricted only by the transient temperature limitation on the system. The ramp could be at a rate of temperature increase of about 20°F/min and completed in about 40 min. It is important to re-emphasize that no controls are required for the powerplant other than for the control drums. As the reactor temperature increases, the temperature difference across the TE modules increases and the NaK flow and electrical power automatically increase. Once the open-circuit voltage of the TE converter exceeds 56 volts, useful electrical power at the regulated 56-vdc level becomes available.

Phase 4 of the startup is terminated when electrical current reaches a predetermined setting. A reactor-outlet temperature signal would be used to stop drum insertion, should an anomaly prevent reaching full electrical power without excessive temperature. This cutoff would normally be set at about 1325°F. After the end of this phase of the startup, which completes the startup, the system would be controlled within a deadband on electrical current output.

Although the voltage regulation system is designed to handle electrical load fluctuations, the electrical current control point could be adjustable to take advantage of long periods (weeks) when reduced power requirements are planned. This could increase life or reliability by allowing extended operation at reduced temperatures and reduced load on the voltage regulator.

A brief review of the startup of the SNAP 10A power system in orbit, shown in Figure III-6, is helpful in understanding the sequence. This startup successfully accomplished all four phases as described above. Phase 1, shutdown margin

Figure III-7. System Shutdown Transients,
NaK Temperatures $-24^{\circ}\text{C}/\text{min}$

Figure III-8. System Shutdown Transients, Power and Rate
of Temperature Change $-24^{\circ}\text{C}/\text{min}$

removal, was accelerated by the immediate insertion of two of the four control drums immediately upon receipt of the startup command. These were spring-loaded. Phase 1 continued, however, for approximately 6 hr as the remaining two drums were inserted at the single stepping-rate. Phase 2, the time from critical to sensible heat, took approximately 25 min and culminated in the power spike and temperature transient shown. This important part of the startup established that the effective source power level in the SNAP 10A orbit was about as predicted, 10^{-9} kw. Phase 3 was accomplished instantaneously by ejection of the heat shields when the reactor outlet-temperature reached 325°F. The ramp to power, Phase 4, took about 2 hr. The control in this case was on reactor-outlet temperature.

2. Shutdown

The system is shut down simply by rotating the control drums to their least reactive position. Again, electrical generation and NaK flow follow automatically as the reactor temperature drops. Normally the shutdown would be accomplished using the same control-drum stepping-rate as used during Phase 1 of the startup. Figures III-7 and -8 show the system performance using a reactivity-removal rate of -24¢/min, typical of the rate resulting from a Phase 1 stepping-rate with the drum in the normal operation zone. The rate of cooldown of the system is controlled by its heat capacity, and the time for cooldown therefore is essentially independent of the reactivity-removal rate in the range of interest. For the rate shown, the fission power is reduced to 1% in about 3.5 min. This would probably be fast enough to meet operational requirements; however, the reactivity-removal rate could be increased to reduce the power to this level in less than 1 min. The temperature transient would not be appreciably different for this latter case.

After approximately 1 hr, replacement of the heat shields around the radiator would have to be made to protect against NaK freezing.

D. RELIABILITY

The reliability of the system has been calculated based on reasonable estimates of that for the components. These estimates represent state-of-the-art reliability for similar classes of equipment where possible, and in other areas

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Figure III-9. System Reliability, 10,000-hr Duration

they are based on demonstrable objectives. The calculated results are not to be taken as precise values of the system reliability, but as good indicators of the order of magnitude of that expected, the trend of reliability with partial power levels, and a reasonable apportionment of it to the system components.

1. System Reliability

Figures III-9 and -10 show a summary of system reliability estimates for various power levels. The calculated figures show that the system has very high reliability for delivering a large percentage of the design power. The gross system power capability is 25.2 kwe and the reliability for producing this power for 20,000 hr is 64%. The reliability figures increase significantly from this level to 95% at 23 kwe and over 99% at about 18 kwe for the same period. At 10,000 hr, the trend is the same; however, the full-power reliability is increased to 80%, the 23-kwe value is over 97.5%, and the 18-kwe value is over 99.7%. It should be noted that these partial-power reliabilities do not imply that the system must be operated at reduced power in order to achieve them. The system can be operated continuously at its maximum capability with little or no effect on the partial-power reliabilities.

The major subsystem values are also shown in Figures III-9 and -10. It can be seen that the first step-increases in reliability occur when the electrical output of individual converter 4-packs can be lost due to open or short circuits. Below 75% power a large incremental change in reliability is gained by allowing an entire HRL to fail. The reliability of the reactor and primary heat-transfer loop is the final limiting value. With the exception of insignificant gain which might be realized by lower stress on the fuel and more allowable combinations of control-drum failures, the probability of successful operation for this portion of the system remains essentially constant regardless of the power level for the system.

2. Bases for Estimates

The various component reliability values used to calculate subsystem and system reliability are best estimates of expected reliability for developed equipment. The reliability analysis of the system is thus based on values judged to be reasonably attainable. The following paragraphs contain the bases for the reliability estimates of major component classifications. A summary of these estimates is shown in Table III-4 for the entire system.

Figure III-10. System Reliability, 20,000-hr Duration

TABLE III-4
RELIABILITY ESTIMATES

Component	Estimated Reliability, R	
	10,000 hr	20,000 hr
Primary system	0.9979	0.9953
Reactor	0.99900	0.9978
Vessel	0.999	0.998
Fuel	0.999999	0.9999
Control drums and actuator	0.999999	0.99987
Piping	0.9997	0.9994
Pumps and converter piping	0.99968	0.99936
Pump and converter electrical	0.99986	0.99962
Expansion compensator unit (4)	0.99992	0.9996
Main converter piping	0.99968	0.99935
Heat-rejection loop (4 per system)	0.9949	0.990
Piping	0.99984	0.99968
Pump and converter piping	0.99985	0.99969
Pump and converter electrical	0.99994	0.99988
Expansion compensator unit	0.99998	0.9999
Main converter piping	0.9986	0.9971
Radiator		
Function	0.998	0.996
Meteoroid	0.9987	0.9975
Converter electrical		
24 of 24 (4-packs)	0.820	0.673
23 of 24 (4-packs)	0.983	0.941
22 of 24 (4-packs)	0.9989	0.9927
Full-power system reliability	0.802	0.643

a. Welds

Based on surveys of fluid-loop experience, a weld failure-rate of less than one failure in 10^{-9} hr/tube-weld has been estimated. This is supported by data obtained 3 years ago from ORNL concerning reactor fuel-element weld integrity and more recent surveys of large reactor heat-transfer loops and heat exchangers conducted by AI.

As of October 1965, Westinghouse water reactor fuel elements had accumulated in excess of 10^9 weld-operating hours without a failure. More recent experience with heat exchangers in pressurized-water-reactor (PWR) plants has demonstrated 1.5×10^9 tube-hours with 11 failures, none of which were identified as weld failures.

A survey of tube-weld performance in sodium service also supports the weld failure-rate estimate. Examination of some of the sodium systems which have accumulated an impressive amount of operating experience gives the values in Table III-5. Considering the steam-generator experience alone gives a best estimate failure rate of 1.3×10^{-8} failures per weld-hour. If the heat exchanger and Dounreay primary-loop experience is added to the steam-generator experience, the failure-rate drops a factor of five to 2.6×10^{-9} failures per weld-hour.

TABLE III-5
TUBE-WELD HISTORIES

Facility	Assembly	Tubes	Tube Welds	Hours	Failures
Hallam Nuclear Power Facility (HNPF)	Steam generator	3,720	7,440	7,194	0
	Heat exchanger	8,400	16,800	7,194	0
Sodium Reactor Experiment (SRE)	Steam generator	200	400	37,000	0
	Heat exchanger	316	632	37,000	0
Dounreay	Primary loop	-	8,000	60,000	0
Experimental Breeder Reactor II (EBR II)	Steam generator	730	1,460	4,360	1
	Heat exchanger	3,026	6,052	4,360	0
Rapsodie	Heat exchanger	888	1,776	17,400	0
MSAR (Model Steam Generator)	Steam generator No. 1	59	118	3,615	0
	Steam generator No. 2	38	76	4,926	0
	Heat exchanger	273	546	8,541	1

Considering the above data and all of the additional test-loop experience and facilities, the weld failure-rate of 1×10^{-9} failures per weld-hour appears to be a reasonable estimate. This failure-rate has been applied to all NaK-loop tube joints in the system. Where large weldments are involved, an estimate of the equivalent number of welds has been used.

b. Reactor Vessel

The reactor vessel failure-rate of 10^{-7} failures per hour represents an estimate that the vessel is equivalent to 100 tube welds in complexity.

c. Reactor Fuel

The reactor fuel reliability is determined analytically by margin correlations. These correlations for fuel growth and phase change were a major result of the SNAP 8 Experimental Reactor (S8ER) test analysis and SNAP 8 Developmental Reactor (S8DR) design program. The fuel elements are designed to provide a mean life of 36,000 hr to phase change with a deviation of 4115 hr. They also have a calculated mean life of 156,000 hr to cladding rupture with a deviation of 31,250 hr. These distributions result in a probability of failure for an element of 1.3×10^{-6} in 10,000 hr or 5.5×10^{-5} in 20,000. Combining these probabilities in a Poisson expansion for the 295 elements in the core results in a 0.99984 probability of no more than one failure in 10,000 hr and 0.99997 probability of no more than two failures in 20,000. A reliability of 0.9999 is used as the estimated value under the assumption that loss of one or two elements late in the system life would be of no consequence. This is extremely conservative since S8ER operated successfully with 80% of its fuel elements cracked. By the same reasoning the core reliability for 10,000 hr is estimated to be >0.99999 or essentially 1.0.

d. Control Drums and Actuators

Each control drum and actuator is estimated to have a failure rate of 1×10^{-6} failures per hour. This is broken down to 0.6×10^{-6} for the actuator and 0.4×10^{-6} for the bearings. These estimates are from the tabulation of "Failure Rates" published by AVCO for equipment judged to be similar in design and application. In these tables, stepper motors are estimated to have a generic failure-rate between 0.22×10^{-6} and 0.71×10^{-6} and bearings range from 0.02×10^{-6} to 5.5×10^{-6} . Because of the redundant nature of the bearing it appears reasonable

to assign a value of 0.4×10^{-6} to the two sets of bearings for each drum. The drums themselves are not considered to have a failure-rate which would be a significant addition to a 1×10^{-6} failure-rate for the drive component.

A failure-mode and effects study of the ten control drums can be summarized as follows:

- 1) Two drums can remain in the shutdown position at the beginning-of-life (BOL) with the result being a life limit of approximately 42 mo for reactor operation.
- 2) Three drums can remain seized in any operating position after hot BOL and not affect the 20,000-hr operation.
- 3) Three drums seized in the cold critical position before hot BOL will limit reactor operation to about 54 mo.
- 4) Three drums seized in the hot-BOL position will make the reactor shutdown limited in approximately 20 mo.
- 5) Control is assumed to be either simultaneous on all ten drums or sequential in such a manner that under normal operating conditions all drums will be in relatively the same position at any given time.

The reliability of the reactivity control-drum system is calculated by a binomial expansion allowing three out of ten drums to fail at any time. This appears to be a reasonable approximation to the conditions; the only critical combination of events which is ignored is the simultaneous failure of three drums at hot BOL. The probability of this occurrence is insignificant. The resulting estimated reliability for the control drums is 0.999999 for 10,000 hr and 0.99987 for 20,000 hr.

e. Primary Piping

This portion of the system includes all interconnecting piping of the primary NaK-loop with the exception of the converter manifolds and pump manifolds. A failure-rate of 3×10^{-8} failures per hour is assigned on the basis of an estimated 30 tube-welds.

f. Pumps

Each of the four pump assemblies contains three throats; two are in series for the primary system and one is for the respective HRL. Coupled to the pump are three TE modules. The modules are electrically paralleled to the pump bus bars. The pump throats are electrically in series. The primary piping to the pump converter is considered to be double-contained.

Portions of the pump and converter piping considered for the primary loop include eight pump welds per pump and 23 converter-piping welds double-contained per pump. Using the tube-weld failure-rate of 10^{-9} failures per hour results in a reliability of 0.99968 for 10,000 hr, or 0.99936 for 20,000 hr considering all four pump assemblies.

The reliability for the pump converter electrical performance considers all twelve converter modules. A short-circuit condition in the modules is of no consequence since the bus bars to the pump provide a much better short to ground than any other credible postulated short from a failure condition. An open-circuit in one module out of the twelve modules would reduce the total system electrical power capability about 1% or 250 watts. A failure-rate of 1×10^{-7} failures per hour per module is assigned for this mode. This is one-half of the failure-rate assigned to the main converter modules for both shorting and open-circuit modes. The basis for this failure-rate is described in the paragraphs covering the main converter reliability estimates. It is assumed that one pump converter out of the twelve can fail with no significant effect on the system. Using a binomial expansion for this criterion results in a pump converter electrical reliability of 0.99986 for 10,000 hr or 0.99962 for 20,000 hr. This reliability is charged to the primary system. Various combinations of pump-module failures could result in further loss of system power without complete power loss, but this possibility has been ignored for the present analysis.

Portions of the pump and converter piping considered for each HRL include four each of pump and tube-welds, and 7.5 equivalent tube-welds for the containment jacket surrounding the modules, for a total of 15.5. Using the tube-weld failure-rate of 10^{-9} failures per hour results in a reliability of 0.99985 for 10,000 hr or 0.99969 for 20,000. A failure in this category will fail only the HRL involved.

The pump and converter electrical reliability which influences each HRL is determined by the electrical-bus bond areas. Each pump has the equivalent of 6 bond areas in series. A failure of any bond will result in the loss equivalent of the respective HRL. The failure-rate for an electrical bond is assumed to be 10^{-9} failures per hour, on the assumption that an electrical bond is about the same as a tube-weld for failure-rate considerations. The resulting reliability is 0.99994 for 10,000 hr or 0.99988 for 20,000 hr for each pump.

g. Expansion Compensator Unit (ECU)

Because the primary failure mode considered for the ECU is leakage through the bellows assembly, each unit has redundant bellows. A primary containment bellows functions normally containing the NaK throughout the expansion cycle, and a secondary is provided to contain the NaK and allow uninterrupted function of the unit in event of a leak through the primary. Previous analysis of the bellows for the SNAP 10A compensator indicated a stress-margin reliability of essentially unity. A weld-flaw frequency analysis of the SNAP 10A bellows experience indicated reliability for freedom from flaws of approximately 0.997 per assembly. In addition it is conservatively estimated that each assembly will have a time-dependent failure-rate equivalent to 180 tube-welds. These values result in redundant bellows providing a reliability of 0.99998 for 10,000 hr or 0.9999 for 20,000 hr for one compensator unit. Four compensators are required for the primary system and one compensator is required for each HRL.

h. Main Converter Piping

The converter consists of 24 4-pack assemblies. The manifolding of the primary HRL into and out of the 4-packs will be double-contained, although this feature was not incorporated into the design in this study, feasible methods of double-containment were reviewed and one will be incorporated as the converter design evolves in the next phase of the program. The HRL manifolding on the cold side of the converters is manifolded into the four isolated loops. Each loop provides the heat rejection for six 4-pack assemblies. The reliability estimates are based on weld joints as follows

Primary Manifolding

32 headers, each with 17 double-contained welds as follows

7 module pipe welds,

- 1 cap weld;
- 9 seam weld on header (4 in./weld equivalent); and
- 1 pipe-to-header weld (not double-contained).

HRL Manifolding:

- 6 4-packs per loop with 24 welds per 4-pack as follows:
 - 8 module;
 - 6 pack-to-header; and
 - 10 seam-weld equivalent, making a total of 144 welds per loop.

Assigned a weld failure-rate of 10^{-9} per weld and accounting for the redundancy of the double-contained piping gives a reliability for the primary manifolding of 0.99968 for 10,000 hr or 0.99935 for 20,000 hr.

For the HRL's the reliability of the manifolding for each loop is calculated to be 0.9986 for 10,000 hr or 0.9971 for 20,000 hr.

i. HRL Piping

This portion of the system includes all of the interconnecting piping of the HRL's which connect the converter 4-packs, pumps, radiators, and ECU's into four isolated loops. An estimated tube-weld complexity equivalent to 16 welds per loop gives an assigned failure-rate of 1.6×10^{-8} failures per hour per HRL. Any leak in the piping fails only the HRL involved.

j. Radiator

The radiator is segmented into four parts with each segment being an isolated portion of the respective HRL. The functional failure-rate for each segment is estimated on the basis of approximately 200 tube-welds to be 2×10^{-7} failures per hour. In addition to this failure-rate is the meteoroid-puncture hazard which is set at 1.25×10^{-7} punctures per hour for the present design. This rate is established by the meteoroid-influx criteria and the armor thickness selected.

k. Converter Electrical

Two failure modes are considered in the evaluation of the converter. An open circuit in any converter module could cause reduction in total power

Figure III-11. Thermoelectric Converter Full- and Partial-Power Reliability (Electrical)

capability. A short-circuit to ground within any converter module could cause almost total loss of power capability without some means of isolating the fault. To protect against the short-circuit condition, each 4-pack assembly is diode-protected so that a short to ground will only cause the loss of the respective 4-pack. The addition of diodes causes a slight increase in open-circuit hazard due to the possibility of a diode failure. In manned systems the diodes would be readily accessible for replacement, but the possibility has not been considered in this analysis.

In a paper presented at WESCON in August 1962 by D. R. Earles and M. F. Eddins titled "Failure Therblig Failure Rates" it is estimated that power diodes have the mode failure-rates shown in Table III-6.

TABLE III-6
POWER DIODE "THERBLIG" FAILURE-RATES

Mode	Failure-Rate $\times 10^{-6}/\text{hr}$	
Open	0.026	
Drift	0.02	} assumed loss of short-circuit protection
Leak	0.005	
Short	0.021	
Unstable	0.068	
	0.140	

The failure-rate of a diode which results in an open circuit is assumed to be 2.6×10^{-8} failures per hour, and the failure-rate which results in loss of short-circuit protection is assumed to be 1.14×10^{-7} failures per hour.

Assumption of failure-rates for the converter elements is critical to the power rating versus reliability for the system; for this reason the converter reliability has been studied parametrically. For study purposes it was assumed that the converter module failure-rates for both shorting to ground and open-circuit are equal; a total failure-rate for a module of 2×10^{-7} failures per hour indicates failure-rates of 1×10^{-7} for shorting and 1×10^{-7} for open-circuit. These failure-rates were varied over a range of several orders of magnitude for calculating converter system reliability. The results are shown in Figure III-11.

The present demonstration level of module failure-rates is in the range of 5×10^{-5} failures per hour. This results from limited test experience and by no means represents an expected lower limit. It appears reasonable to assume that component testing of modules could demonstrate a module failure-rate to be, at most, 10^{-6} failures per hour through accelerated or margin tests as well as performance endurance tests. It is assumed that system development and qualification tests could further reduce this limit estimate to about 2×10^{-7} failures per hour. The resulting converter reliabilities shown in Figure III-11 for a module failure-rate of 2×10^{-7} are the full- and partial-power values used for calculating system reliability.

E. SYSTEM TRADE-OFFS

The reference system described above has been studied in detail for a specific operating point, but the same design concept could be used over a wide range of power requirements. The results of a parametric analysis are presented in this section for the anticipated power range of interest for the 1970's. In this study the key components (the reactor and the TE tubular modules) are unchanged over the entire range, and the other components, e.g. pumps, expansion compensators, and radiator, are similar in design but resized for the appropriate performance.

To facilitate the system parametric analyses, a reactor - TE system computer code was developed. The code input requirements are converter clad temperatures, electrical power level, converter tubular module characteristics, and general system geometric constraints. The calculated results are the thermal-power distribution, system operating temperatures, radiator area, efficiencies, flowrates, pressure drops, and weights. This code was used to determine system weight and area characteristics for power levels of 15, 25, and 35 kwe at reactor outlet-temperatures of 1200, 1250, and 1300°F; reactor coolant ΔT 's of 200, 250, and 300°F; Carnot efficiencies of 25, 30, 35, 40, and 45%; and two radiator designs.

The two radiator designs were selected as a result of detailed radiator analyses. These analyses, described further in Section IV-D-1, determined the radiator weight vs area trade-off for the thermal conditions of the reference

25-kwe system. The reference design radiator was picked at the minimum weight point, which was found to occur at about 1400 ft². This radiator has a fin effectiveness of 0.80 at the reference temperatures and a weight, including structure, of 1.84 lb/ft². The other point on the curve selected corresponded to the area, 1287 ft², available for the Saturn-IVB Workshop radiator and represented a heavier design that could be beneficial where an area limitation was involved. This radiator had a fin effectiveness of 0.87 at the reference temperatures and a weight of 2.19 lb/ft². By analyzing systems with both radiator designs, a true area-weight trade-off at a given power level can be obtained. Figure III-12 shows how the fin effectiveness of the two designs varies with cold-clad temperatures at the TE modules.

Figures III-13, -14, and -15 show the results of the computer calculations for 15, 25, and 35 kwe with the heavier radiator. At each Carnot efficiency point, system characteristics were determined for reactor coolant ΔT 's of 200, 250, and 300°F. The ΔT that resulted in minimum weight was selected and is shown on the figures. In all cases the reference converter tubular module design was held fixed with the number of tubular modules and operating temperatures varying. As Carnot efficiency decreases, the radiator temperature increases and radiator fin effectiveness decreases. This effect, coupled with an associated decrease in converter device efficiency, results in minimum radiator area occurring at Carnot efficiencies above the usual 20%.

As Carnot efficiency increases, the coolant ΔT associated with minimum weight decreases because the reactor thermal-power decreases; this results in lower flowrates and pressure drop, and reduced pumping-system weight.

Similar curves were generated for the lighter-weight radiator design. The two sets of curves were combined, as illustrated in Figure III-16, and the envelope of minimum weight established. Figures III-17, -18, and -19 show these minimum-weight envelopes at power levels of 15, 25, and 35 kwe.

Figures III-20, -21, and -22 show how system weight, area, and thermal power vary with electrical power for minimum-weight systems. These curves were established by selecting the minimum-weight point for each reactor outlet-temperature on Figures III-17, -18, and -19 and tabulating the associated radiator

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Figure III-12. Radiator Fin Effectiveness

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Figure III-13. 15-kwe System Weight and Area

Figure III-14. 25-kwe System Weight and Area

Figure III-15. 35-kwe System Weight and Area

Figure III-16. 25-kwe System, 1250°F Reactor Outlet-Temperature

Figure III-17. 15-kwe System Weight and Area (Unshielded)

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Figure III-18. 25-kwe System Weight and Area (Unshielded)

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Figure III-19. 35-kwe System Weight and Area (Unshielded)

Figure III-20. System Minimum Weight

Figure III-21. System Radiator Area,
Minimum-Weight Systems

Figure III-22. Reactor Thermal Power,
Minimum-Weight Systems

area and reactor thermal power. Thermal power in Figure III-22 is shown as a band because of the scatter in the calculated points and the small variation with temperature. It should be noted that slight differences in the minimum-weight values shown on the parametric curves and the weight estimates for the reference system are due to closer definition and refinement of the latter.

The inherent modularity of the reactor - TE system and its adaptability to any power level over a wide range of interest is clearly shown by the results of this analysis.

TABLE IV-1
SNAP REACTOR OPERATING EXPERIENCE

Reactor	Date Critical/ Shutdown	Thermal Power (kwt)	Temper- ature (°F)	Thermal Energy (kwt-hr)	Time at Power and Temperature
SNAP Experimental Reactor (SER)	September 1959/ December 1960	50	1200	225,000	1800 hr at 1200°F 3500 hr above 900°F
SNAP Developmental Reactor (SDR)	April 1961/ December 1962	65	1200	273,000	2800 hr at 1200°F 7700 hr above 900°F
SNAP 8 Experi- mental Reactor (S8ER)	May 1963/ April 1965	600	1300	5,100,000	1 yr at 1300°F and 400 to 600 kwt
SNAP 10A Flight System No. 3 (S10A-FS-3)	January 1965/ March 1966	38	1000	382,944	10,005 hr
SNAP 10A Flight System No. 4 (S10A-FS-4)	April 1965/ May 1965	43	1000	41,000	43 days

IV. SUBSYSTEMS

A. REACTOR/SHIELD ASSEMBLY

1. Technology Status

The reactor design used for this system study is based largely on the technology developed over the past 10 years in the SNAP Reactor Program. During this time 15 reactors have been built for development, qualification, and flight tests; five have been operated in sustained nuclear power tests, and the other ten were used for non-nuclear development and qualification tests. In addition, many hundreds of thousands of test hours have been accumulated on reactor components. Table IV-1 summarizes the nuclear test operation experience, which totals about 35,000 hr to date. The one year of operation of the SNAP 8 Experimental Reactor (S8ER) at power levels between 400 and 600 kw at 1300°F NaK outlet temperature and the continuous 10,000-hour operation of the SNAP 10A reactor as a part of a complete reactor - TE system test are considered to be of particular significance.

The sixth reactor test is currently being started on the SNAP 8 Developmental Reactor (S8DR) shown with one-half the reflector removed in Figure IV-1. The test objectives include 10,000 hr of high-power operation, 500 hr of which is at 1000 kw, 1100°F, and the remaining 9500 hr at 600 kw, 1300°F. In addition, several shutdown and restart tests are scheduled.

As a result of the development and test experience gained from the SNAP programs, the technology status of the zirconium hydride type reactor is considered to be sufficiently advanced to assure its availability for space missions in the early to mid-1970's.

2. Reactor Subsystem Description and Performance

Preliminary design and development work continues on the reference zirconium hydride reactor. Its design has been used for all of the reactor - TE systems studied and presented in this report.

The reference zirconium hydride reactor design, illustrated in Figure IV-2, is similar to the S8DR, except for modifications incorporated to manrate the system and permit operation within an enclosed shield. For example, the number of fuel-moderator elements has been increased from 211 to 295 and the

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Figure IV-1. SNAP 8 Development Reactor Ground Test Assembly

number of control drums has been increased from 6 to 10 to provide higher de-design margins and a wider range of power and lifetime capabilities. In addition, the reflector/control-drum design has been changed to permit cooling by the liquid-metal coolant entering the reactor, since the reflector cannot be cooled by direct radiation to space as has been the case with previous SNAP reactors.

The minimum performance objective for the reactor is to provide 600 kw of thermal power at a coolant outlet-temperature of 1300°F for 20,000 hr. The calculated performance envelope is shown in Figure IV-3.

The reactor configuration is shown in Figure IV-4. This reactor, like all preceding zirconium hydride reactors, uses the sodium-potassium eutectic NaK-78 as the coolant. The NaK enters the base of the reactor vessel at 1100°F and flows around drywells which contain the reflector control drums. The

Figure IV-2. Zirconium Hydride Reactor, Reference Design

Figure IV-3. Performance Envelope,
Reference ZrH Reactor

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Figure IV-4. ZrH Reactor Reference Design

coolant flow is turned 180°, passes over the fuel elements, and leaves the reactor vessel at 1300°F. The fuel elements in the core are spaced in a nonuniform hexagonal array to provide each element with a coolant flow approximately proportional to the power generated in the element. The nozzle-to-nozzle pressure-drop of the reactor is 0.65 psi at the normal flowrate of 13.0 lb/sec. Type 316 stainless steel is used as a structural material for the reactor vessel and internals.

The reactor fuel material is a zirconium-uranium alloy which has been hydrided to a hydrogen content of 6.3×10^{22} atoms/cm³ (the H₂ content in cold water is about 6.6×10^{22}). This fuel material is quite stable in the expected temperature and radiation environment and its performance has been well characterized as a result of the operation of five SNAP reactors plus many in-pile irradiation experiments. The fuel is contained in a Hastelloy-N cladding tube which is coated on the inside with a ceramic material to inhibit the loss of H₂ moderator from the fuel rod.

The major change from previous ZrH reactors lies in the design of the reflector control system. The SNAP 10A and SNAP 8 reactors were designed to operate in a shadow-shielded configuration. The control drums were semicylinders of beryllium surrounding the core which could be rotated to increase or decrease the neutron leakage from the system. The reference control system for this reactor is designed to operate inside a shield which completely surrounds the reactor. Ten cylindrical reflector poison control drums are mounted in drywells cooled by the inlet NaK. Neutron-leakage control is accomplished in this case by rotating the drum from positions where neutron-reflector material is adjacent to the core to positions where neutron-absorption material (poison) is adjacent.

The control drums will operate at relatively high temperatures (1500 to 1800°F) because the internal nuclear heat generated must be transferred by radiation to the walls of the drywell, which are cooled by 1100°F NaK. Beryllium oxide is used as the reflector material in this high-temperature environment. The selected poison material is europium-oxide dispersed in nickel and high-strength niobium alloys are planned for structural use.

The control drum rotates on a set of ball-and-socket bearings. Like the S8DR, an aluminum-oxide-coated shaft rotates in a carbon-graphite ball mounted in a socket coated with aluminum oxide. The maximum bearing temperature is expected to be below 1350°F. Testing of this type of bearing has been conducted at temperatures up to 1500°F. The control drum will be rotated by an S8DR actuator which has been modified slightly for this application. The actuator operating temperature will be less than that expected on the S8DR, due to its location outside the shield.

For control and monitoring purposes a drum position indicator will be incorporated into the system. This will be located in a cool part of the spacecraft and will obtain its reading by counting pulses to the actuators. A single limit switch on each drum, actuated when the drum is in the least reactive position, will provide a secondary check on the position indicator and will satisfy the probable launch pad requirement of having a positive indication that the reactor is in a safe condition.

The shield configuration will be dependent upon the particular mission for which the reactor is to be used. In general, the reactor vessel will be surrounded by a gamma shield of either tungsten or molten lead encapsulated in steel. A thick layer of insulation will separate the high-temperature Pb from a region of LiH neutron shielding. This type of two-region shield is adequate for applications where the allowable doserates are high or the separation distance from the personnel is large (e.g. manned lunar base). In the case of a shaped 4π shield for a manned space station, the shielding will be much thicker in the direction of the station. Normally the first two regions will be followed by a gallery containing the power-conversion system (PCS). Aft of the gallery will be a second gamma shield of depleted U and a second LiH neutron shield.

The LiH shields are cast in stainless-steel containers strengthened by internal shells and stringers. The shield assembly is normally the heaviest unit in the reactor system and provides primary structure for the entire system. The weight of the reactor, PCS, and shield is carried through the shield to a load ring which is mated to the vehicle. Typical shields are described in Section V for specific mission adaptations of the system.

Some of the more significant design parameters for the reactor subsystems are given in Table IV-2. In general the design involves very few deviations from the state-of-the-art as exemplified by the S8DR. In areas where conditions are more severe than S8DR, development programs are underway to establish the required capabilities.

B. THERMOELECTRIC CONVERTER

1. TE Module Technology Status

The objective of the Compact TE Converter Program begun by the AEC in mid-1965 is to develop a high-performance reliable long-life converter module for application to space systems. The basic element in the program being conducted for the AEC by Westinghouse is the tubular TE module shown schematically in Figure IV-5. It has a TE circuit encapsulated between its inner and outer clads in a completely compact void-free design that is structurally rugged. Because of the unique design of the tubular module, radial heat flows from the inner to the outer surface without the requirement of bonded joints. The TE circuit is completed through a series of washers and rings. The alternate P- and N-type washers are separated by thin washers of natural mica for electrical insulation. Hot- and cold-conductor rings span adjacent PbTe washers to form a serpentine current flowpath. The circuit is electrically isolated from the structural claddings by thin sleeves of boron nitride that provide good thermal contact between the rings and the clads.

Table IV-3 summarizes the test experience accumulated through mid-1968 with the tubular modules. Since the program began in mid-1965 approximately eighty tubular modules have been fabricated, and fifty have been life-tested. The remainder were subjected to special destructive examination, short-term performance tests, and special ones such as cyclic temperature and vibration tests. To maximize the benefits from each module life-tested an average hot-clad temperature of 1000°F was chosen at the beginning of the program as the basic test condition. There are axial temperature gradients in the inner clad, however, because of end effects. In a typical test setup an electrical heater is inserted into the bore of the module and heat is transferred to the inner clad through NaK fluid which fills the cavity between the heater and module. Because

TABLE IV-2
REFERENCE ZrH REACTOR DESIGN PARAMETERS

<u>1. General Performance</u>		<u>3. Reactor Vessel</u>	
Design thermal power	600 kw	Outside diameter	22.0 in.
Design outlet-temperature	1300°F	Vessel wall thickness	3/16 in.
Temperature rise	200°F	Inside diameter of dry-wells	4.62 in.
Design lifetime	26,000 hr	Drywell wall thickness	0.065 in.
Coolant flowrate	49,000 lb/hr	Number of inlet and outlet nozzles	4 ea
Pressure drop	0.65 psi		
Operating pressure capability	35 psia		
<u>2. Fuel and Core Internals</u>		<u>4. Reflector Control System</u>	
Number of fuel elements	295	Control-drum type	Reflector-poison
ZrH hydrogen content	6.3×10^{22} atoms/cm ³	Number of control drums	10
Uranium content	10.5 wt %	Reflector material	BeO
Hydrogen-barrier material	SCB-1	Poison material	60% Eu ₂ O ₃ in Ni
Cladding material	Hastelloy-N	Structure material	Nb-10 W
Cladding thickness	0.015 in.	Cladding material	Nb-1 Zr
Burnable poison material	Gd-155	Drum diameter	4.5 in.
Active fuel length	16.8 in.	Drum length	19.0 in.
Overall (flat-to-flat) element length	17.5 in.	Structural strongback thickness	0.25 in.
Outside diameter of fuel element	0.570 in.	Cladding thickness	0.030 in.
Fuel-element spacing (variable for flow control)	0.025 to 0.045 in.	Drum bearing shaft material	Ta-10 W
Internal reflector material	BeO	Control-drum actuator	Modified S8DR
Internal reflector cladding	316 SS	Control-drum bearings	Modified S8DR
Gridplate material	316 SS		
Core shell, inside diameter	11.4 in.	<u>5. Shield</u>	
Core shell thickness	0.030 in.	High-temperature gamma shield	Molten Lead
Core shell material	316 SS	Lead container material	Croloy 2-1/4
Reactor coolant material	NaK-78	Low-temperature gamma shield	Uranium
		Neutron-shield material	LiH
		LiH container material	316 SS

DESIGN FEATURES

- FULLY ENCAPSULATED
- FULLY COMPACTED-VOID FREE
- STRUCTURALLY RUGGED
- NO BONDED JOINTS
- USES PbTe AT HIGH TEMPERATURE
- MECHANICALLY AND ELECTRICALLY ADAPTABLE
- LONGEVITY- SHELF AND OPERATING

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Figure IV-5. Tubular Thermoelectric Module

TABLE IV-3
TUBULAR MODULE TEST EXPERIENCE

Temperature, Hot (°F)	Temperature, Maximum (°F)	Number of Modules	Total Time (hr)	Maximum Time (hr)
1000	1050	58	217,100	24,600
1100	1150	9	25,800	9,500
1125	1175	4	5,500	2,000
1150	1200	2	6,000	4,000
1200	1270	12	10,300	1,700
1250	1340	1	1,200	1,200
1300	1350	2	5,900	4,200
			271,200	

of end losses, peak temperatures are about 50°F higher than average temperatures.

2. Tubular Module

The reference tubular TE module selected for the reactor — TE system is shown in Figure IV-6. A summary of its performance and design characteristics is given in Table IV-4. The module has an ID of 0.75 in., an OD of 1.50 in., and an active TE circuit length of 15.07 in. Its overall length including inner-clad extensions is 19.0 in.

The reference module was chosen after a detailed parametric system study. Before analyzing the system trade-offs, several module design criteria were fixed based on the present state-of-the-art and realistic projections of the technology which could be made with a high degree of confidence. This was necessary because the existing development program for tubular modules has been a broadly based technology effort not specifically oriented toward modules tailored for reactor system applications. A summary of the criteria as stated for the study follows:

- 1) TE Materials. Single-piece 2P and two-piece 2N-3N washers will be the basis for module performance calculations.
- 2) Cladding Materials. High-strength Inconel or its mechanical equivalent (consistent with minimum-weight modules) will be considered for module inner and outer cladding. For parametric calculations the cladding will be sized properly to ensure sufficient contact pressures under operating conditions.
- 3) End Closures. The reference module will be based on an end-closure design that yields nominal heat losses of 100 watts per end.
- 4) Module Active Length and Voltage. For parametric calculations of module performance and weights, a fixed active length of 15.0 in. and corresponding 14.0 volts at matched-load will be used. The ratio of these two values is representative of near-maximum volts per unit axial length that can be attained within the current state-of-the-art.

Figure IV-6. Converter Layout
(Drawing No. 914E163)

TABLE IV-4
CHARACTERISTICS OF REFERENCE TUBULAR MODULE

Power output, watts electric	262	
Efficiency, %	4.67	
Voltage to matched-load, vdc	14.0	
Internal resistance, Ω	0.748	
Current, amp	18.7	
Heat input, kwt	5.61	
Mean hot-clad temperature, °F	1125	
Mean cold-clad temperature, °F	570	
Dry weight, lb	5.75	
<u>Envelope Dimensions (in.)</u>		
Inner diameter	0.75	
Outer diameter	1.50	
Total length	19.0	
Active length	15.07	
<u>Radial Thickness (in.)</u>		
	<u>Inner</u>	<u>Outer</u>
Cladding	0.090	0.020
Insulator	0.040	0.037
Conductor	0.025	0.020
Thermoelectric material	0.143	

- 5) Module Diameters. ID's from 3/8 to 3/4 in. will be considered during parametric studies. The corresponding range for OD's will be from 1.2 to 2.5 in.
- 6) Module Degradation. It was assumed that by the early 1970's high-temperature (1200 to 1250°F) modules with little or no degradation will be demonstrated for lifetimes in excess of 10,000 hr. Therefore no specific values of module degradation were used in the study. Instead, normal system operating temperatures were established so that some degradation can be recovered by raising the temperatures without exceeding component limits.

Although the converter hot-clad average temperature objective is 1200°F, an average temperature of 1125°F was selected to allow some design margin and to allow for degradation recovery.

One conclusion of the study was that a minimum OD for a given ID, or minimum practical TE element thickness, was desirable. This resulted in minimum system weight and radiator area, primarily because of the higher heat-rejection temperature, and fewer modules because of greater electrical output per module. Efficiency was minimum for this condition, but since the reactor is not thermal-power-limited this was not critical.

System weight, radiator area, and efficiency did not vary significantly with changes in ID when the element thickness was maintained, but the power output per module increased with increasing ID. To minimize the number of modules, then, the largest ID allowable within the study criteria, 0.75 in., was chosen. Minimizing the number of modules increases reliability by reducing the number of welds and the system complexity, but it can have an adverse effect on partial-power reliability by increasing the power loss with one module failure. For the range of module sizes studied this was not yet judged to be a problem; however, review of the partial-power reliability curves in Section III-D shows that further significant reduction in the number of modules may not be desirable.

With the ID established, the minimum practical OD of 1.5 in. and the average cold-clad temperature of 570°F were fixed.

3. Converter Module

a. Description and Performance

The reference TE converter module consists of an assembly of 24 tubular modules arranged into six subassemblies of four tubular modules each. Each 4-pack is enclosed in a single metal jacket that provides containment for all cold NaK flowing around the four modules. This arrangement simplifies manifolding and header requirements for delivery and removal of cold NaK to the individual tubular modules. Cross-coupling of the hot- and cold-NaK manifolding provides for the differential thermal expansion that occurs during startup and other thermal transients, and minimizes thermal stresses on the piping assembly.

A cutaway of the converter module is shown in Figure IV-7 (isometric); for this orientation the tubular modules are standing on end with vertical centerlines. The tubular modules provide the converter module structure in the vertical direction, the hot manifolds provide the longitudinal structure, and the cold manifolds provide the transverse structure. For specific applications the orientation of the converter module and the layout of the inlet and outlet manifolds can be modified to satisfy any unique requirements. Discussion of the present design, however, is predicated on the nominal orientation defined above.

The hot-loop NaK enters one end of each longitudinal manifold at the top and flows to the other end. A portion of the flow exits downward from the manifold through each tubular module to the lower longitudinal manifold where it is collected and returned to the reactor. The cold-loop NaK enters the bottom of the divided outer can which clusters each transverse group of modules into a 4-pack. Cold NaK then flows into annuli that surround each tubular module, removes the waste heat from the modules, and is then collected in an exit manifold and pumped to the radiator.

Each of the 24 tubular modules in the converter module contains a 0.5-in.-diam rod that channels the hot NaK into an annular flowpath. A spiral-wound wire centers the rod in the tubular module and provides a flowpath that ensures circumferential distribution of the flow. Use of the 0.5-in. rod and spiral wire serves two purposes. First, it provides sufficient hydraulic impedance within the tubular module to ensure good flow distribution among the tubular modules.

Figure IV-7. Converter Module Cutaway

TABLE IV-5
CONVERTER MODULE CHARACTERISTICS

Power output, kwe	6.3	
Efficiency, %	4.6	
Matched-load voltage, volts	56.0	
Number of tubular modules	24	
Number of modules electrically in series	4	
Current per 4-pack, amp	18.7	
Wet weight, lb	284	
Volume, ft ³	3.4	
Envelope dimensions, in.	12.5 x 19.5 x 24.0	
<u>Temperatures (°F)</u>		
	<u>Hot Loop</u>	<u>Cold Loop</u>
Inlet clad	1225	470
Outlet clad	1025	670
Mean clad	1125	570
NaK flowrate, lb/sec	3.03	2.88
Pressure drop, psi	0.28	0.26
<u>Energy Balance</u>		
Heat into converter module, kwt	136.1	
Primary-heat losses, kwt	1.3	
Heat delivered to tubular modules, kwt	134.8	
Electrical power, kwe	6.3	
Heat removed from converter module, kwt	128.5	

Second, it improves the convective heat transfer between the NaK and the module cladding. The calculated ΔT between bulk NaK and clad is 20°F with the rod insert. Without the rod insert the ΔT would be ~50°F and would impose a significant temperature penalty on the system.

A summary of the converter module design and performance characteristics is given in Table IV-5. For the selected system operating temperatures each converter module produces 6.3 kwe at a matched-load voltage of 56 volts. Four

tubular modules are arranged electrically in series to yield 56 volts, and the six 4-packs are connected electrically in parallel. The electrical network that connects the four converter modules and the associated voltage regulation equipment is described in Section IV-B-4.

The overall efficiency of the converter module operating at 1125 and 570°F mean hot- and cold-clad temperatures, respectively, is 4.6%. This includes heat losses of 1.3 kw in the primary-loop manifolding based on thermal interchange between the manifolds and the box that surrounds the converter module. The heat balance of the module is given in Table IV-5.

b. Mechanical Design

An engineering drawing of the reference converter module is shown in Figure IV-8. A fundamental mechanical design requirement is to provide for differential thermal expansion because the NaK loops operate at temperature levels that differ by more than 500°F. The components must be carefully arranged to allow for the resulting differential expansions.

The hot clads of the tubular modules are welded directly to the hot manifolds which are free to expand in the longitudinal direction and space the 4-packs as required. The hot clads separate the upper and lower hot manifolds and are free to move these manifolds as required by their thermal expansions. The 4-pack cans operate at cold-loop temperature and are attached directly to the cold clads of the tubular modules. The transverse spacing is thus freely adjusted by the thermal expansion of these cans. Suitable flexible connections are provided to join the four hot-inlet manifolds to the common inlet header and the four hot-exit manifolds to the exit header. Likewise, flexibility is provided in the connections to the cold-loop inlet and exit headers.

Perhaps the most critical design requirement of the system is absolute containment of NaK in the loops. All loop connections are welded and emphasis is placed on minimizing the number of welds and maximizing the quality of the required welds. Some weight sacrifices were made to reduce the number of welds such as using the complete can around each 4-pack rather than individual tubes with transverse headers at top and bottom. The weld quality was maximized by providing for pre-assembled components as much as possible before generator insertion. Thus stress relief, aging, inspection, and pressure testing are possible and practical in most of the welds.

Figure IV-8. Converter Module
Layout
(Drawing No. 939J385)

The oval-shaped can which surrounds the 4-pack is the basic building unit. It is rolled and welded Inconel 718 with a nominal thickness of 0.100 in. This high-strength material is required to prevent bulging of the large flat sides. The top and bottom dividers and the baffle tubes are inserted in these cans first. Then the perforated cover-plates are seal-welded in place. These units can then be stress-relieved, aged, inspected, etc. without fear of damaging generators which have not yet been assembled into the pack.

At this point in the assembly sequence the tubular modules can be inserted and the tips of the cold clads welded to the can cover-plates to form a complete 4-pack. A possible alternative would be to assemble the entire cold loop without generators. This would include the manifolds and the longitudinally flexible shear members between cans. The assembled cold loop (without tubular modules) could again be stress-relieved, etc. without fear of generator damage, thereby maximizing weld quality in the cold loop.

For either assembly method the entire cold-loop and generator assembly will be built before the hot manifolds are welded on. The hot clads of the tubular modules will be long enough to reach the hot manifolds without any intermediate welds being required. The hot manifolds will be channel-shaped with one open side so that the clads can be welded to the inside of the manifold. This is the only way that satisfactory clad-weld accessibility can be obtained. Finally the hot manifold cover-plates will be seal-welded to the open manifold sides. The assembly, as shown in Figure IV-8, has 202 critical welds. Many of these welds, however, can essentially be eliminated as potential problem areas by the use of manufacturing and inspection procedures which will guarantee their quality to be nearly the same as the parent material.

Three mounting lugs are shown in the reference design. These lugs are rigidly attached to the 4-pack cans. They will penetrate the cover at each end and must move thermally relative to the cover. One lug can be seal-welded to the cover, but a sliding seal (or bellows) will be used at the other penetrations. A suitable support linkage will be required to properly mount the unit to the spacecraft and allow for thermal movement of the support lugs. This method of support is preliminary and will likely be changed as the constraints of specific system adaptations and the results of further studies become available.

The stiffened shell which covers the entire converter module provides containment of NaK in the event of a leak, thus avoiding subsequent electrical shorting of other converter modules. The cover cannot withstand significant internal or external pressure; therefore, a vent has been provided for pressure equalization during launch and to allow NaK vapor, in the event of a leak, to vent overboard or to a safe area.

Because a two-loop reactor system was selected for the reference configuration, an additional provision for containing the hot NaK in the converter module was briefly investigated. Redundancy in containing the hot NaK is needed because all four converter modules in the system will share a common hydraulic loop with the reactor. Therefore a single hydraulic leak anywhere in the primary loop will cause failure of the complete system. Over 80% of the primary-loop containment welds are associated with these hot headers. A conceptual sketch shown in Figure IV-9 shows provisions for providing double containment of the hot-loop headers. The bellows shown is to allow differential expansion between the primary and secondary containment. A conclusion of the brief investigation is that double containment of these headers is feasible, and can be incorporated into the converter design.

Figure IV-9. Double Containment
of Converter Module Header

c. Off-Design Performance

If the reference converter module is operated at temperatures other than those selected for the system design points, the power output, efficiency, and voltage will vary.

Figure IV-10 shows the calculated variations in power output for mean hot-clad temperatures ranging from 1000 to 1225°F and for mean cold-clad temperatures from 400 to 700°F. Similarly, for the same ranges of temperatures, off-design values for efficiency and voltage are shown in Figures IV-11 and IV-12, respectively.

Although the final selection of axial-NaK ΔT in the converter module was 200°F, the design analysis was made, based on a tentative selection of 150°F. By increasing the ΔT in each loop from 150 to 200°F, the electrical performance characteristics change by a negligible amount. Hydraulic parameters, however, are significantly affected. Figure IV-13 shows the off-design variations in hot- and cold-NaK flowrates for the final selection of 200°F, while Figure IV-14 indicates the values for the earlier 150°F ΔT . The pressure-drop variations are shown in Figure IV-15 as functions of flowrate with the 200°F ΔT design point indicated.

4. Electrical Network and Voltage-Regulation Equipment

The electrical network for the reference power system provides shunt-voltage regulation of the nominal 56.0 vdc output of the TE converter. A schematic diagram of the network is shown in Figure IV-16. The 24 TE 4-packs are connected to a common negative bus. The positive lead of each 4-pack is routed individually to the power-conditioning equipment, all of which is located in a low-temperature environment. Each of the 24 4-packs has an open-circuit voltage of 112 vdc at the reference operating conditions. Based on the test experience of the compact converter development program, this no-load voltage will be nearly constant throughout the mission lifetime.

Shunt-voltage regulation was selected since the TE converter attains its maximum reliability and minimum degradation when it is operated at constant temperature conditions, i. e. without thermal transients. This operation is attained when the electrical load is held constant. Constant thermal-load operation also simplifies the reactor controls, thereby improving overall system reliability and reducing weight.

Figure IV-10. Converter Module Off-Design Power

Figure IV-11. Converter Module Off-Design Efficiency

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Figure IV-12. Converter Module Off-Design Voltage

Figure IV-13. Converter Module Off-Design Flowrates,
Axial ΔT 's Assumed Constant at 200° F

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Figure IV-14. Converter Module Off-Design Flowrates,
Axial ΔT 's Assumed Constant at 150°F

Figure IV-15. Converter Module Hot- and Cold-Side Pressure Drops

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Figure IV-16. Converter-Assembly and Power-Conditioning Circuit Diagram

Figure IV-17. Voltage-Current Profile

It is an inherent characteristic of each independent 4-pack that a direct short-circuit may be placed across its terminals indefinitely without damage. This means that any value of load resistance from zero to infinity may be applied. When the load resistance is infinity, i. e. the 4-pack is operating as an open-circuit, the terminal voltage is a maximum. When the load resistance is zero, i. e. a short-circuit exists, the output voltage is zero. When the load resistance equals the internal resistance, the terminal voltage is one-half the open-circuit voltage, as illustrated in Figure IV-17. Thus, the terminal voltage can be adjusted by controlling the resistance of the load.

Power is delivered to the power conditioner on 24 independent positive leads and one common negative lead. Because the load may consist of a large number of power-consuming devices that will be switched on and off in a random fashion, the total power consumption may vary over a wide range. To design the system with wide flexibility it was assumed that the load could go all the way to zero.

The total load is further assumed to be made up of two subloads; a single dc load of approximately 56 volts requiring a regulation of $\pm 2\%$, and an inverter load which requires approximately 56 volts input. It was also assumed that these loads will be applied as step functions and that they will draw high-frequency currents which must be supplied without the introduction of high-

frequency output-voltage variations. The power-conditioning components shown in Figure IV-16 provide a regulation voltage of 56.0 vdc $\pm 1\%$. These components are described in the following paragraphs.

a. Protection Diodes

A blocking diode is placed in series with each of the 4-pack leads to decouple the subassembly from the output bus if the 4-pack or its lead should become faulted to ground. As long as the output terminal voltage of a 4-pack is greater than 56 volts, the diode will conduct and supply current to the output bus. If the terminal voltage drops below 56 volts, as it would if shorted to ground, a reverse voltage would appear across the diode and no current would flow. Without the diode a fault on any 4-pack or lead would take current from the output bus and thereby reduce the current available for the load. If the fault current exceeded the rated load current, the output voltage of 56 volts could not be maintained. The blocking diodes thus protect the converter assembly against internal faults.

b. Shunt Voltage Regulator

Under a no-load condition, i. e. no power being used by the spacecraft, the power-dissipation resistors of a shorted regulator must be able to carry the entire rated current of the power system, or 446 amp. Since no transistors with this current rating are available, a large number of low-current transistors must be used. This is not a disadvantage, however, since it permits the circuit to be designed with higher reliability and with a reduction in the power that must be dissipated at low temperature.

In the circuit of Figure IV-16, 22 of the transistors are operated as switches, in which case the maximum transistor dissipation is 660 watts. This occurs only in the rare case when the entire load current is being dumped. With this circuit practically all of the excess power is dissipated in the radiating shunt resistors, which can operate at very high temperatures and dump large amounts of power with very little space and weight.

Each of the 22 switching transistors of Figure IV-16 carries a maximum of 20 amp. Since the internal resistance of the 24 4-pack subassemblies in parallel is approximately 0.125 ohms, the voltage on the output bus will drop 2.5 volts each time a transistor is switched-on. The transistors could be switched-on

when the bus voltage reaches 56 plus 1.25 volts so that the voltage would drop to 56 minus 1.25 volts. The output voltage would thus be held within $\pm 2.2\%$ by the rough current control. In the circuit of Figure IV-16 these step-voltage changes are eliminated and the regulation improved by using one transistor operating linearly so that it carries the current which is intermediate to the 20-amp steps. The maximum dissipation of this single linearly operated transistor will be only 250 watts, a value which can be accepted by the low-temperature environment.

The operation of the switching transistors is controlled by a logic circuit which senses the load current. The number of transistor switches open is proportional to the load current. The current drawn by the linear transistor is controlled by sensing the output bus voltage. A filter capacitor provides low internal impedance of the power sources to high-frequency load currents. Since the voltage-regulating circuits are very fast this capacitor is not very large.

c. Characteristics of the Power-Conditioning Circuit

(1) Efficiency

The efficiency of the power-conditioning equipment at rated load is important since the power-conditioning losses will subtract from the maximum power which is available from a fixed-converter assembly. The efficiency of the power-conditioning equipment at partial load is not important since it does not affect the maximum available power.

The efficiency of the proposed circuit at full load is 98%, including the loss due to the 1-volt drop across the blocking diodes. The losses in the voltage-regulation components are negligible at rated load because all of the transistor switches would be open and no current would be flowing in the linear transistor. The power required to operate the control circuitry is also negligible.

(2) Cooling Requirements

The estimated power-conditioning equipment power losses which must be picked up by the environmental control system at a temperature not over 100°C are as in Table IV-6.

TABLE IV-6
POWER LOSSES

Source of Loss	Loss at Zero- Load Conditions (watts)	Loss at Rated- Load Conditions (watts)
Blocking diodes	447	447
Switching transistors	660	0
Linear transistor	250	0
Control circuits	10	10
Wiring losses	<u>20</u>	<u>20</u>
Total:	1387	477

(3) Performance

The regulating capability of the circuit is limited only by the electrical time constant of the converter assembly and the power-conditioning components. It is very probable that the voltage can be regulated to $\pm 1\%$ or better so that additional dc regulators for critical dc loads will not be required.

The reference power system has no overload capacity, since the load is matched to the internal resistance of the converter assembly. Any attempt to draw more than rated current will cause the output voltage to drop instantly and the total power will go down. This is an advantage when designing protection for the power-distribution system since the short-circuit current cannot be more than twice the rated current.

(4) Size

The construction of the power-conditioning package will follow practices similar to those used in the Apollo inverter. The cooling of the diodes and transistors will be by conduction to the power conditioner base-plate or by internal circulation of cooling liquid or gas.

The minimum volume requirements for the power-conditioning chassis (not including the radiating resistors) will be approximately as follows:

24 diodes at 6 in. ³ /diode	144 in. ³
23 transistors at 16 in. ³ /transistor	368
2 printed circuit boards at 50 in. ³	100
1 capacitor at 27 in. ³	27
Terminals	68
Enclosure structure	<u>250</u>
Total Volume	957 in. ³

Detail design will be required to establish precise dimensions for this component.

(5) Weight

The weight of the power-conditioning equipment (not including the radiating resistors) will be almost exclusively the weight of the structure since the rectifiers weigh only 0.65 oz each and the transistors only 1 oz each.

Assuming that the packaging density would be the same as attained for the Apollo inverter at 0.0288 lb/in.³, the weight will be approximately 28 pounds.

C. NaK-LOOP COMPONENTS

1. Pump System

The pumps selected for this system are of the dc conduction EM type powered by special low-voltage TE modules. As with the electrical generation in this system, the pump packages have no moving parts and their hydraulic power output increases automatically as the reactor operating temperature increases. The advantages of this type pump are simplicity of operation and high reliability. The one disadvantage is that the pressure-drop within the loops must be kept low. However, in the design of a TE system this is not particularly restrictive.

a. Technology Status

Due to the compatibility of TE power sources with dc pumps, most of the pump development has been devoted to integral source dc pumps. In this type the TE generator is intimately attached to the throat of the pump and the need for high-current buses is virtually eliminated.

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Figure IV-18. Mercury-Rankine Program Integral Source Pump

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7561-5471

Figure IV-19. SNAP 10A Integral Source Pump

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The SNAP 2 Mercury-Rankine Program (MRP) developed a dc conduction pump which used chromel-constantan for the TE power generator. The pump throat consisted of a Type 316 stainless-steel tube having a wall thickness of 0.020 in. The active throat length was 10 in. The MRP pump is shown in Figure IV-18. This pump was designed to operate in a vacuum environment at 1200°F. Over 20,000 hr of test experience were accumulated on this pump.

The SNAP 10A pump, shown in Figure IV-19, was a dc conduction pump powered by a lead-telluride TE generator. The pump operated at 1000°F in a space environment and met all shock and vibration requirements for launch into an Earth orbit. More than 150,000 hr of test operation were logged by this pump including over 20,000 hr by a single pump. Moreover, the pump was successfully operated in space during the SNAP 10A space flight.

In addition to these integral source pump designs which in general impose the most severe restrictions on pump design, over 50 dc conduction pumps have been fabricated at AI for use in ground test facilities. These pumps have been powered by remote power supplies and have been used for various component tests. They have operated without a single failure for over 200,000 hr. The design concepts and fabrication methods used in them are those specified for the pump to be used in the ZrH reactor - TE system.

A triple-pass pump similar to the reference design pump has been fabricated and was performance-tested. The measured performance was within 5% of that predicted.

All fabrication steps of the selected pump are state-of-the-art and no new processes are involved.

b. Pump Power Source

To maximize the use of existing tubular TE module experience and to minimize the different types of hardware development required for the program, a separate pump power source, consisting of modules similar to the power-generation modules, was chosen for the reference design.

The basic design problem that had to be overcome was to obtain a high current at a low enough voltage to match the impedance in the pump throats. Preliminary studies showed that a practical multipass pump, one in which the electrical current flows through more than one throat in series, could be designed

Figure IV-20. Pump Converter
(Drawing No. 939J386)

if a tubular module could be developed to provide 500 amp at a nominal voltage of 0.22 volts. The design of such a special purpose module was evaluated and found to be feasible.

The TE-pump module has an active length of 7 in., consisting of four thermocouples in series that produce an open-circuit voltage of 0.54 volt at the nominal mean hot- and cold-clad temperatures, 1125 and 570°F, respectively. A layout of the reference module is shown in Figure IV-20 and a summary of its characteristics is given in Table IV-7.

TABLE IV-7
PUMP MODULE SUMMARY

<u>Nominal Load Requirements</u>	
Power, watts electrical	110
Current, amp	500
Voltage, volts	0.22
Resistance, milliohms	0.44
<u>Module Characteristics</u>	
Mean hot-clad temperature, °F	1125
Mean cold-clad temperature, °F	570
Efficiency, %	3.46
Internal resistance, milliohms	0.54
Electrical pin resistance, milliohms	0.10
Inner diameter, in.	0.75
Outer diameter, in.	2.24
Open-circuit voltage, volts	0.54
Active length, in.	7
Number of couples	4
Weight, lb	7.4
Heat required, kwt	3.2

Figure IV-21. Primary and Heat-Rejection Loop Electromagnetic-Pump Assembly

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Because the high current and low-voltage output requires the pump module to have a low internal resistance, its electrical conductors are relatively thick. The radial and axial thicknesses of the conductors and the TE washers were sized so that the module internal resistance would equal the effective load resistance, 0.54 milliohm. Design trade-offs were also made to satisfy the load requirements without imposing significant thermal-power or weight penalties on the system.

Although the pump module design differs from that of the tubular modules in the main converter, stress calculations and consideration of the manufacturing process indicate that fabrication of this design concept is feasible.

c. Pump System Description

Several alternate pump designs were considered before an attractive package was designed based on the characteristics of the tubular TE modules described above. The best design using these modules was found to result when the pumping requirements for both the primary loop and HRL's were combined at one location so that three modules could be operated in parallel to provide high current at the location without a penalty due to inefficient use of thermal power. In this way 1500 amp was available to the pumps at 0.22 volts.

The characteristics of the system dictated that the optimum configuration would be as shown in Figure IV-21, where the electrical current is passed through two throats on the primary loop and one on the HRL. With this configuration the hydraulic power available to the primary would be approximately twice that available to the HRL. Also it was determined that the primary-loop throats should be in the cooler portion of the loop (1044°F) and the heat-rejection throat should be in the hotter portion of its loop (663°F). This would minimize the thermal shunting between loops.

A system optimization was performed, trading off NaK-system weight against pump weight with pressure drop as the variable. On the basis of the optimization, pressure drops of 3.35 psi in the primary loop and 1.5 psi in the HRL's were selected.

Figure IV-22 shows the reference design pump package. The three-module power source is designed similar to the 4-packs in the main TE converter. One

Figure IV-22. Pump Assembly,
Separate Source,
Three-Throat

of these pump packages is used in each quadrant of the system. The power supply weighs 30 lb, the pump also 30, and the electrical bus 50 for a total of 110 lb.

Figure IV-23 shows the predicted performance of the pump as designed. Note that at the reference flowrates the primary-loop pressure-drop is 3.45 psi and that at the HRL is 1.65. These values are greater than those in the system design, to provide a design margin for meeting the pumping requirement. Further margin also exists since the calculated pressure-drops for both loops are well below the limit. The total thermal power required to run the four-pump system is 38.4 kwt or 6.6% of the reactor power.

Thermal and stress analyses were conducted to evaluate the pump, and no serious problems were determined for either steady-state or transient operation. The differential expansion between the hot and cold throats is basically alleviated by slits in the connecting bus bar which allows it to bend more freely. The maximum magnet temperature, even when operating at 1150°F in the primary loop and 650 in the HRL is 790°F. This is well within the allowable temperature range for the magnet material.

2. Expansion Compensator

The primary loop and HRL are designed to be void-free at all times. Expansion compensators are used in the loops to accommodate the expansion of the NaK from the cold shutdown condition to the hot operating condition, and to maintain the system at the operating pressure.

a. Technology Status

More than 50 expansion compensators of the type shown in Figure IV-24 were built under the SNAP 10A development program for development, qualification, and system tests. This unit is a spring-loaded bellows with a latch mechanism to prevent deformation due to hydraulic loads experienced during launch. A position indicator was also included to provide a measurement of the NaK-loop status during operation. More than 100,000 hr of testing were accomplished on the SNAP 10A expansion compensator; the longest single test was 10,000 hr as a part of a complete nuclear system test.

Figure IV-23. Reference Pump Performance

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Figure IV-24. SNAP 10A Expansion Compensator

b. Design Description

The size and weight of the compensators are a function of loop NaK volumes, the operating temperatures, and operating pressures. Table IV-8 presents the NaK volumes for the reference system. At the reference operating temperature the expansion volume of the primary loop is 0.161 ft^3 per ft^3 of NaK volume, and 0.061 ft^3 per ft^3 of NaK volume for the HRL's. Using the volumes in Table IV-8 the total primary-loop expansion requirement is 0.59 ft^3 and that for the HRL is 0.44 ft^3 .

Four expansion compensators are required for the HRL, one for each quadrant. It is also convenient to have four compensators in the primary loop. Thus, the primary loop would require four 0.15-ft^3 compensators and the HRL four 0.11-ft^3 compensators. To provide commonality of design, a single compensator size was selected (0.15 ft^3), which results in a slight overdesign in the HRL. A double-sealed gas-backed compensator affording secondary NaK containment was selected to meet these expansion requirements. The characteristics

TABLE IV-8
NaK VOLUMES

<u>Primary Loop</u>	
Reactor	1.75 ft ³
Converter	1.07
Piping	<u>0.82</u>
Total:	3.64 ft ³
<u>Heat-Rejection Loop</u>	
Converter	1.59 ft ³
Gallery piping	0.63
Radiator	<u>4.95</u>
Total:	7.17 ft ³

TABLE IV-9
EXPANSION COMPENSATOR
CHARACTERISTICS

Type	Double-bellows series
Expansion volume	0.15 ft ³
Pressurization	Inert gas
Size:	
Diameter	11 in.
Height	9.65 in.
Weight	26 lb
Number required	8

of such a compensator are summarized in Table IV-9 and a conceptual drawing of it is shown in Figure IV-25.

The principle of operation of the compensator involves two bellows assembled in series as shown in Figure IV-25. Two sets of series-stacked bellows are mutually opposed. The inner surface of the primary bellows and the bellows-top cups of the compensator provide containment for the NaK. The

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Figure IV-25. Expansion Compensator, 25-kwe Nuclear Thermoelectric Power Supply

space between the bellows outer surface and the cylindrical sections inner surface is evacuated and constitutes the secondary containment in event of a NaK leak through the primary bellows. The volume of the inner surface of the secondary bellows is closed with a dome to facilitate gas fill for system pressurization. The opposed bellow design provides partial system pressurization in the event of the loss of pressure from one gas chamber. The null point of the bellows (heat-treat position) is at about 2/3 of the maximum stroke, to allow the bellows to operate at a low stress at the operational and launch volumes.

With increase of system temperature, the NaK volume change is displaced by the primary bellows and the initial pressure within the secondary bellows is increased proportional to the PVT (pressure/volume/temperature) relationship. This gas pressure, in addition to the stiffness of the bellows, establishes the system operating pressure. Figure IV-26 shows this pressure as a function of average NaK temperature for the two loops. The normal operating pressure for both loops is 20 psia while pressure within the loops at launch, when non-operating, is approximately 6 psia. The curves in Figure IV-26 also show that

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Figure IV-26. Expansion-Compensator Pressure Characteristics

even with one chamber vented to space, both loops would maintain adequate pressure during a shutdown.

At operating temperature both bellows are at minimum extension-stress and maximum pressure-stress levels. The temperature limitation on the bellows is approximately 725°F. At this temperature the bellows maintain their spring-rate, assist in maintaining system pressure, and are safely below the normal heat-treat temperature of 800°F. The temperature of the bellows will be maintained at this level by design of the gallery. However, no NaK-containment failure of the bellows would be expected until a temperature of at least 900 to 1000°F is exceeded.

The expansion compensators will be located near the high point of their loop during launch. The actual attach point for the compensator supply line will be at the high point so that as the launch acceleration increases, the line will drain down into the compensator eliminating large static head forces.

D. RADIATOR

1. Concept Selection

The radiator for the HRL is one of the most mission-dependent subsystems in the powerplant. Integration constraints associated with launch package size, operational cycle, and reliability, all affect the choice of a radiator type.

Several radiator design variations were considered during this study, including heat-pipe designs and relatively standard fin-and-tube radiators with either fixed or folding NaK joints. Although final selection of a radiator design concept would depend strongly on mission and integration constraints, a fixed, cylindrical tube-and-fin type radiator was tentatively selected for the reference power system design in order to more completely define its design and performance characteristics. Several radiator material combinations were analyzed, including aluminum-beryllium alloy (Lockalloy) and pyrolytic graphite for the radiator fin and meteoroid armor; however, aluminum fins diffusion-bonded to stainless-steel tubes were selected, due to the relative simplicity and technology available for this combination. A semimonocoque titanium support structure similar to that used in the SNAP 10A system was also selected for the same reasons.

TABLE IV-10
TUBE-AND-FIN RADIATOR DESIGN CRITERIA

Thermal power	551 kwt
Inlet temperature	663°F
Outlet temperature	463°F
NaK flow (total)	12.4 lb/sec
Thermal-control coating:	
Emissivity	0.90
Solar absorptivity	0.30
Meteoroid nonpuncture probability*	0.990
Tube diameter	3/8 in.

CONFIGURATION

11.5 ft-diam CYLINDER
RADIATING FROM ONE SIDE
STRUCTURE WEIGHT= 0.75 lb/ft²

*Reference for meteoroid armor calculations:
H. D. Haller and S. Lieblein, NASA LERC,
Analytical Comparison of Rankine Cycle Space
Radiators Constructed of Central Double and Block-
Vapor-Chamber Fin-Tube Geometries, " NASA
TN D-4411, February 1968

Several feasible designs for folding NaK joints which would make possible the use of deployable radiator panels were evolved. Although such a design is not specifically incorporated in the reference system, the concept may be of sufficient interest for applications requiring compact powerplant packaging to justify further investigation and development. The heat-pipe radiator concept was not selected due to the lack of a desirable working fluid for the 500 to 600°F temperature range of interest for this system.

2. Radiator Design

The assumptions, configurations, and criteria used for the radiator design are shown in Table IV-10. The thermal power and temperatures listed are those which were determined to be near-optimum for the reference system on the basis of overall system weight.

Figure IV-27 shows the total radiator-plus-structure weight as a function of radiator area for different numbers of tubes. The minimum-weight envelope is also plotted. The weight includes the tube, fin, armor, structure, and NaK holdup. A structure weight of 0.75 lb/ft^2 , determined by a separate design study, was used. This plot shows that as the area is increased from 1250 to 1400 ft^2 , the optimum number of tubes for minimum weight decreases. The minimum radiator-weight point exists at about 1450 ft^2 with approximately 100 tubes; however, it is clear that an area/weight trade-off can be made for the reference system over a radiator area range from 1200 to 1450 ft^2 .

Another consideration in the radiator design is the NaK pressure-drop in the tubes. Preliminary analysis showed that the tube size should be small to minimize radiator weight and area, but the minimum size was restricted to 3/8-in. diam based on potential NaK-plugging considerations. Calculations indicated that even for this tube size the pressure-drop was excessive for radiator areas of interest when the NaK was allowed to flow the complete length of the tube. This excessive pressure-drop was alleviated by breaking the flow into two to three parallel paths. This also provides some advantage in system assembly; however, such an arrangement requires additional headers feeding the individual NaK tubes.

Thermal performance for the radiator was calculated for the worst case where the projected area is normal to the sunlight. Performance of the radiator

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Figure IV-27. Cylindrical-Radiator Weight Characteristics

in the full shade or with sun reflection and direct radiation from the earth will be increased by a maximum of about 2.5%.

Table IV-11 presents the characteristics of the 1400 ft² cylindrical radiator selected for the reference system. An area of 1450 ft² would result in a slight weight reduction but not enough to warrant the larger area. Areas below 1400 ft² result in rapidly increasing weight characteristics. A drawing showing the cross-sectional design of a typical radiator is shown in Figure V-9.

TABLE IV-11
REFERENCE RADIATOR CHARACTERISTICS

Radiator area, ft ²	1400
Geometry	Cylindrical
Number of tubes	94
Armor thickness, in.	0.19
Fin thickness, in.	0.035
Fin and armor material	6061 Aluminum
Tube outside diameter, in.	3/8
Tube thickness, in.	0.020
Tube material	347 Stainless steel
Structure	Titanium alloy
Total weight, lb*	2580

*Includes tube, NaK fin, armor, and structure

V. MISSION ADAPTATIONS

The reference 25-kwe reactor - TE system described in the preceding sections of this report provides a general design basis from which powerplants can be configured for specific space applications. Mission and integration considerations are particularly important when concerned with the radiation shield and heat-rejection radiator design, which in turn affects the design and performance characteristics of the power system. To illustrate several typical integration concepts and corresponding powerplant characteristics, designs for three missions for which reactor - TE systems have been and are being considered are presented in this section. The first design is tailored to the Saturn-V OWS mission currently under study by NASA as a part of the Apollo Applications Program (AAP). The second is an update of a powerplant concept evolved in a recent NASA/AEC study of reactor power systems for manned lunar bases. The third updates an earlier design developed in a joint NASA/AEC study of reactor power systems for the MORL. In the latter two cases the basic integration concepts and constraints established in previous studies were maintained, whereas the OWS powerplant design and integration concept were evolved in this study.

A. SATURN-V OWS POWERPLANT

1. Mission Requirements and Integration Considerations

The Saturn-V OWS concept being studied by NASA is a direct, generic evolution from the Saturn-I Workshop which is currently under development as part of the AAP. As currently conceived, the Saturn-V OWS would consist of a dry Saturn-IVB stage structure fitted with docking ports, airlocks, power and life-support equipment, experiments, and other subsystems required to function as a manned OWS. The Saturn-V OWS would be launched (fully equipped) using the first two stages of the Saturn-V launch vehicle. The planned launch date is currently estimated to be in the 1973 to 1975 time period. The nominal orbit altitude and inclination are 270 n. mi (nautical miles), 50°.

One of several possible Saturn-V OWS configurations is shown on the frontispiece of this report with a nuclear power system attached to the forward docking port. This concept would provide accommodations for a six-man crew with

growth capability to nine. The design goal for the operational lifetime of the OWS is 2 yr, although the crew would be rotated several times per year, using a modified version of the Apollo Command and Service Module (CSM).

The orbital average conditioned power requirements for the Saturn-V OWS are currently estimated to be from 12 to 16 kwe.⁽²⁾ Considering power conditioning losses, the gross dc power requirements would thus be in the range of 14 to 18 kwe. A power growth margin is also desired and the minimum range of interest for the nuclear power system has therefore been assumed to be from 15 to 20 kwe. Unconditioned voltage requirements are 28 vdc or higher.

No specific reliability requirements for the power system have been established, but it is known that a mission-success probability for the entire OWS of 0.95 or better would be desired. Thus the reliability of the power system producing 15 to 20 kwe for the 2-yr duration would probably have to be ~ 0.99 , assuming that this level of power is required for mission success. Survival reliability requirements in excess of 0.99 for the entire OWS are also desired but difficult to project, much less demonstrate. Previous studies of reactor power systems for the MORL have concluded that a backup power system capable of producing sufficient power for minimum station and orbit-keeping for a period of about 42 days would be necessary to provide such assurance.

In addition to the general power system requirements discussed above, a number of important integration factors must be considered. Among these are:

- 1) Power system configuration and location.
- 2) Radiation-shield weight and dose profile.
- 3) Launch and deployment modes.
- 4) EOL disposal provisions.

All of the above considerations are interrelated, particularly the first two. For example, it is desirable that the power system integration impose minimal modifications to the OWS configuration or compromises in its operation. The location of the telescope with its radiation-sensitive film and other experimental sensors in the aft end of the OWS make the integration of the nuclear system in that region difficult and undesirable. Similarly, attachment of the powerplant to

the sides of the workshop would require the use of long deployment booms to obtain acceptable radiation-shield weights, due to the length of the OWS, which is about 120 ft (including a docked CSM in the forward docking port). Thus by a process of elimination it appears that the most favorable location for the nuclear power system for the OWS as now conceived would be attached to the forward docking port, as shown on the frontispiece. The side docking ports would then be used for docking the CSM's.

The basic radiation shielding requirements are that the total radiation dose received by the crew during normal operation, rendezvous, and extravehicular activities (EVA) should not exceed predetermined allowable levels. An allowable whole-body dose of 100 rem/yr has been proposed for this mission.⁽³⁾ The expected annual whole-body dose due to natural radiation (electrons and protons) for the specified orbit is approximately 56 rem. Thus an allowable annual whole-body dose of 44 rem or less from the nuclear power system would appear to be an acceptable and reasonable requirement. For the present study a shield doserate requirement in the range of 20 to 30 rem/yr within the Workshop and a rendezvous dose of less than 5 rem were assumed.

Launch and deployment considerations require that the power system configuration, size, and weight be compatible with available launch vehicles appropriate for the mission. An objective for this study has been to evolve a power-plant design which, with minor modifications, could be compatible with any of the following launch options:

- 1) Integral launch with the OWS on the two-stage Saturn-V.
- 2) Separate launch on a Saturn-IB.
- 3) Separate launch on a Titan-3.

The latter two cases would require an unmanned rendezvous with the OWS, using the Apollo service module, or Titan Transtage. Additional details on payload capabilities and proposed launch configurations are discussed in Section V-A-3.

The EOL-disposal requirement is based on nuclear safety considerations. Previous studies made under the AEC Aerospace Nuclear Safety (ANS) Program

have shown that it will be desirable to provide reliable means for disposing of the reactor after sustained operation in the orbit altitude range of interest for the OWS. Two general approaches toward satisfying this requirement considered to be acceptable are to:

- 1) Boost the reactor up to a higher orbit (~ 450 miles), or
- 2) Deboost the reactor into deep ocean areas.

In the first approach the fission-produce activity will decay to safe levels before eventual random re-entry. Recovery is not required in the second approach.

Table V-1 summarizes the mission and power-system requirements which have been specified, derived, or assumed for this study.

2. System Description

In adapting the reference reactor - TE system to the Saturn-V OWS there are no changes in performance, and all of the foregoing mission requirements are met. At full power the system produces 24.7 kwe at 56 volts dc $\pm 1\%$. The reliability requirement of 0.99 is exceeded at a partial-power level of about 18 kwe. All performance parameters and reliability estimates are as described in Section III. The only difference from the reference system described in that section is that the radiator area is reduced from 1400 to 1287 ft² at a weight penalty of 320 lb.

The radiation environment imposed by the operating reactor will be presented later in Subsection a. with the discussion of the two shield options.

A layout of the complete plant as adapted for the Saturn-V OWS is shown in Figure V-1. It is designed to mount in line with the Workshop on the Multiple Docking Adapter (MDA) as depicted in Figure V-2.

During launch the power system is housed within the heat shield shroud (or power-supply adapter), which acts as an aerodynamic fairing and structure. This shroud is coated to provide a relatively high solar absorptivity and low emissivity so that the equilibrium temperature within it, when the powerplant is not operating in space, is about 100°F. This technique, proven during the SNAP 10A flight test, assures that NaK freezing does not occur. When inside the shroud the overall plant length is 47.3 ft and the shroud diameter is 12.8 ft.

TABLE V-1
SATURN-V ORBITAL WORKSHOP MISSION REQUIREMENTS
FOR NUCLEAR POWER SYSTEM

Unconditioned power level:	15 to 20 kwe
Unregulated voltage:	≥ 28 vdc
Design lifetime:	≥ 2 yr
Reliability:	≥ 0.99
Radiation dose (wholebody):	
Total, including natural radiation	100 rem/yr
Reactor (normal operation)	20 to 30 rem/yr
Reactor (rendezvous)	~ 5 rem
Special nuclear safety provisions:	End-of-life disposal (Orbit boost to ~ 450 mi or deboost into ocean)
Launch options:	Integral with two-stage Saturn-V Separate with Saturn-IB/Com- mand and Service Module or Titan-III/Transtage
Probable launch date:	1973 to 1975
General integration constraint:	Minimal modification to Orbital Workshop or launch vehicles
Preferred power system location:	Docked to forward port of Multiple Docking Adapter

Figure V-1. 25-kwe Nuclear
 Thermoelectric Power
 Supply
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Figure V-2. Saturn-V Orbital Workshop with 25-kwe Nuclear Thermoelectric Power Supply

During operation the system is extended out from within the shroud to expose the radiator. This provides the added advantage of increasing the separation distance to over 100 ft between the reactor and the primary areas of the Workshop where persons are located. The method of extending and retracting the powerplant was studied only enough to establish feasibility. With the method evolved, the plant is guided by rails incorporated into the radiator moving on rollers attached to the shroud, and is moved by a screwjack arrangement. A conceptual design of the deployment mechanism is shown in Figure V-3. The motive force is provided by a drive motor operating through a gear train on a ball screw-and-nut combination. A magnetic brake is employed for positive locking. The design is sized to extend the system in about 15 min.

The reactor control equipment, TE converter protective diodes, and the voltage-regulation equipment would be located in the space station, accessible for equipment replacement or repair during operation.

Table V-2 gives a weight breakdown for the power system excluding the heat-shield shroud. Included are the weights for the two-shield options discussed in the following subsection.

The components for the system are described in Section IV. In the following paragraphs the specific component arrangements are described for this adaptation of the plant.

a. Radiation Shield Design

The radiation shield requirements and concepts have an important effect on the overall characteristics of reactor powerplants for the Saturn-V OWS mission. The most important shield considerations are the dose criteria, the geometry of both the reactor and the spacecraft, and the shield materials. The assumptions and general approach taken towards evolving a conceptual shield design for this mission are discussed in this section along with the results obtained.

The shielding analysis required to evolve an optimum minimum-weight shield design for this type of manned space mission is quite complex and the results in the present study, therefore, must be considered as preliminary estimates. Refinements in estimates of the radiation-source terms and the possible shield gallery dimensions which have been made since the shielding analysis task was completed, however, indicate that the results presented should be conservative.

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Figure V-3. Actuator, Nuclear
Thermoelectric Power
Supply, Saturn-IVB
Orbital Workshop
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TABLE V-2
SATURN-V ORBITAL WORKSHOP POWER SYSTEM
WEIGHT BREAKDOWN

Component	Weight (lb)	
Reactor	1,422	
Thermoelectric converters	1,135	
Pumps	440	
Expansion compensators	208	
Piping	761	
Gallery structure	120	
Instrumentation and controls	340	
Radiator and structure	2,900	
Power cable	214	
Deployment mechanism	410	
Total Unshielded Weight	7,950	
	<u>Shadow</u>	<u>4π</u>
Radiation Shield Weight	14,330	16,500
Total Shielded Weight	22,280	24,450

(1) Dose Criteria

The radiation dose criteria assumed for this mission were derived from data presented in a recent study of Early Orbital Space Stations (EOSS) by McDonnell-Douglas Corporation.⁽⁴⁾ Table V-3 shows the maximum-allowable dose proposed for this type mission, the expected dose due to natural space radiation, and (by subtraction) the maximum dose allowed from the reactor. Different values are shown for the allowable and expected dose to the whole body and blood-forming organs, the lens of the eye and skin. The expected space radiation dose is based on the same orbit altitude and inclination as the OWS and allows for structure and body self-shielding.

TABLE V-3
RADIATION DOSE CRITERIA

Duration (days)	Maximum Allowable Dose (rem)				Space Radiation (rem)				Maximum Allowable Dose from Reactor (rem)			
	60	90	180	360	60	90	180	360	60	90	180	360
Whole body and blood-forming organs	50	60	80	100	9	14	28	56	41	46	52	44
Lens of eye	200	225	240	270	40	59	118	238	160	166	122	32
Skin of whole body	275	300	350	400	40	59	118	238	235	241	232	162
Skin of extremities	600	650	750	900	40	59	118	238	560	591	632	662

The last column in Table V-3 shows that the allowable reactor dose to the lens of the eye is the smallest and therefore controls the shield design. For missions up to one year the reactor dose rate should therefore not exceed approximately 32 rem/yr. In the shielding calculations performed for this study a maximum-allowable operating dose from the reactor was established in the range of 20 to 30 rem/yr.

(2) Geometry and Operational Mode

Figure V-4 shows the proposed integration arrangement for the nuclear power system and the OWS. The shaded zones superimposed on this arrangement identify general regions with different radiation dose criteria. The primary shielded zone corresponds to a cone with a 10° half-angle which includes the basic Workshop structure where approximately 99% of the crew's time will be spent, the pressurized experiment canister which would contain radiation-sensitive film, and approximately a 10-ft radial clearance around the Workshop for possible EVA or other externally mounted experiments. The design dose point shown is located at the control station for the Workshop, which is the closest point to the reactor which would be occupied routinely. Dose rates closer to the reactor and further back into the Workshop would vary approximately as the inverse square of the distance from the reactor.

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Figure V-4. Radiation Shield Design Criteria

Figure V-5. 4π Shield Outline, Reference Design

The shaded conical region extending from the primary shielded zone out to a half angle of 24° is the scatter shield zone. The major considerations in this region are scattering of neutrons and gammas from parked CSM's and from the small portion of the radiator which extends outside the primary shielded zone. In general the doserates in the scatter shield zone can be one or two decades higher than in the primary zone before scattered radiation into the workshop becomes important.

The third zone of interest covers the path that might be taken by a manned CSM approaching the workshop for rendezvous and docking. Allowable dose-rates in this region determine the amount of shielding which must be placed on the side of the reactor if it is operating during the rendezvous maneuver. If such shielding is provided, the shield is classified as a 4π shield even though the shielding is not spherically symmetrical. Without side shielding the shield is referred to as a shadow shield. With a shadow shield the reactor would have to be shut down shortly before the rendezvous maneuver is performed. Both 4π and shadow-shield designs were evolved in this study.

If the primary shielded-zone angle were extended to include the parked CSM's with the same dose criteria as are used within the orbital workshop, excessive shield weights would result. Thus the proposed multizone dose model represents a refinement which more accurately represents the expected operating conditions and results in reduced shield weights while preserving a feasible integration configuration and operational environment.

(3) Reactor PCS Geometry

The reactor design shown in Section IV-A can be used with either a 4π or shadow-shield configuration. In either case the geometry of the shield is also affected by the layout of the power-conversion equipment in the shield gallery. Figure V-5 shows the 4π -shield geometry for the proposed integration arrangement, reactor design, and minimum gallery dimensions. The 10° cone half-angle combined with the gallery dimensions determine the diameter of the lower gamma and neutron shields. The geometry of the upper neutron shield surrounding the reactor is designed to limit the scattered radiation from the parked CSM's to tolerable values. Neutrons scattered from the CSM's are primarily those that emerge from the surface of the 4π shield at grazing angles between 10 and 24° .

Figure V-6. Shadow Shield Outline, Reference Design

Figure V-6 shows the configuration of the shadow shield. The lower shield diameter is the same as that of the 4π shield, since both designs have the same gallery arrangement. The upper shield in this case is designed to protect the service modules from reactor direct radiation.

(4) Materials

Shielding materials selected for both the shadow and 4π shield designs are Pb, U, and LiH. Pb is used for the first gamma shield immediately adjacent to the reactor because of its low secondary gamma production rates and its relatively high density. Depleted U is used for the second gamma shield located at the bottom of the gallery where the neutron flux has been decreased several orders of magnitude. LiH is used for both neutron shields due to its high neutron-shielding effectiveness, good physical and mechanical properties, and advanced technological status. Table V-4 shows the effective densities of the shield materials used. In the case of LiH the density has been increased 30% to account for canning and internal structure.

TABLE V-4
DENSITY OF SHIELD MATERIALS

Material	Density (lb/in. ³)
Lead	0.410
Uranium	0.676
Lithium hydride	0.035*

*An additional 30% is included to account for canning.

(5) Results

Using the basic dose criteria, geometry, and materials discussed above, a number of iterations were made between shield thicknesses and doserate estimates. The basic tool used for this analysis was the Duplex-2 shield optimization code which determines a near-optimum distribution of thicknesses for the various shield laminations. In addition, the DOT and ANISN codes were used

to determine neutron leakage flux from the unshielded reactor. The sources of radiation included in the axial (shadow) direction were core neutrons, core gamma rays, gamma rays from radioactive sodium-24 in the primary loop, and secondary gamma rays from both gamma shields. In the radial direction only, three sources were considered, namely, core neutrons, gamma rays, and secondary gamma rays from the lead shield. Sodium-24 gamma rays were not included in the radial direction since their dose contribution is small compared to the radial-dose criteria.

The shield design iterations narrowed down to the 4π and shadow-shield designs shown on Figures V-5 and -6, respectively. The total weight of the shadow shield (including structure) is estimated to be 14,330 lb. The weight of the 4π shield is estimated to be 16,500 lb. Thus for the specific criteria and constraints used the 4π shield is only 15% heavier than the shadow shield.

For the 4π shield the integrated dose to the astronauts during rendezvous has been calculated to be less than 5 rem with the reactor at full power, assuming they approach the Workshop from one mile out at 1 mi/hr in a direction normal to the OWS center line.

The estimated radiation doserates at the command and control station within the OWS are shown on Table V-5, for both shield types. The direct dose is the

TABLE V-5
ESTIMATED RADIATION DOSERATES AT SATURN-V ORBITAL
WORKSHOP COMMAND AND CONTROL STATION

Number of Parked CSM's	4π Shield		Shadow Shield	
	1	2	1	2
Direct Dose, mrem/hr	1.56	1.56	1.56	1.56
Command and Service Module Scattered Dose, mrem/hr	0.53	1.06	0.88	1.76
Radiator Scattered Dose, mrem/hr	<u>0.08</u>	<u>0.08</u>	<u>0.08</u>	<u>0.08</u>
Total, mrem/hr	<u>2.17</u>	<u>2.70</u>	<u>2.52</u>	<u>3.40</u>
Annual Dose, rem	19.0	23.7	22.1	29.8

same in both cases but the scattered dose from the parked CSM's is slightly higher for the shadow-shield design and depends on how many CSM's are parked. Thus the total annual doserate estimate from all sources ranges from 19 to slightly less than 30 rem per year, which is within the dose criteria assumed for the study. It should be mentioned that the amount of time spent by any single crew member in the command and control station has been estimated to be approximately 17%.⁽⁴⁾ The doserates in the aft portions of the OWS where the crew will be spending a larger fraction of their total time will be lower than the values shown. Thus the doserates and shield-weight estimates are believed to be conservative. Additional more-detailed shield design and analysis beyond the scope of the present study are required, however, to obtain more accurate dose or weight estimates.

b. PCS Installation

The TE PCS along with the pumps, primary-loop expansion compensators, and interconnecting piping are located in a gallery between the two shield sections as shown in Figure V-7. The components were arranged to minimize the diameter and height of the gallery since both of these have a relatively strong effect on the shield weight. The gallery height is 20 in. and all components fit within the 10° shield cone having a diameter of 68 in. at the bottom of the gallery. An isometric view of the reactor and gallery arrangement that provides a clearer understanding of the pipe routing is shown in Figure III-2.

For this design the main TE converter assembly is rearranged as shown in Figure V-8. The basic structure of the assembly is the same as described in Section IV-B-3; however, the attachments to the main manifolds are changed. Also the unit is placed in the gallery with the 4-packs in the horizontal plane. This orientation presents no particular problem, however, since the lateral design load factors are approximately two-thirds of the longitudinal load factors and the unit must be designed with about the same strength in all directions.

In the assembly sequence the gallery components are mounted on top of the secondary shield before mating to the top shield. Such an arrangement allows for clear access to all piping runs and components during assembly. After installation and checkout of the PCS components, the bottom shield and the gallery

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Figure V-7. 25-kwe Nuclear Thermoelectric Power Supply, Two-Loop System

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Figure V-8. Thermoelectric Power Package with Modified Port Locations

assembly are mated to the top shield and reactor. The reactor coolant pipes are then connected providing a completely sealed primary loop. The radiator is next mated to the lower portion of the secondary shield and the heat-rejection piping connected.

The converter assembly and pump yoke assembly are mounted to the lower shield. Pipe anchors will be incorporated at each point where lines penetrate the main converter box and near the pump mounts. Calculations of the piping loads for the worst case, in which the NaK system has heated to operating temperature but the shields are still at about 100°F, showed that the maximum stress occurred at the point where the lines bend downward after coming out radially from the reactor. Even these stresses were below the allowable of 24,000 psi; however, they could be reduced with a more generous elbow so that all stresses would be below about 16,000 psi.

The expansion compensators for the primary loop are attached to the nearest primary-loop line by a 3/8-in.-diam fill line. This line would run to the high point of the loop during launch, a different location depending on the system orientation during launch, and would be inside the main line or wrapped with it to prevent NaK freezing.

c. Radiator

The fixed finned-tube radiator has 1287 ft² of usable radiating area. A cross-section of a typical radiator panel is shown in Figure V-9. In it are 96 individual NaK tubes of 3/8-in.-diam 347 stainless steel with a 0.020-in. wall thickness. Extrusions of 6016 aluminum, which provide both the fin and meteoroid armor, are diffusion-bonded to these tubes. The individual tube-fin pieces are assembled into panels by welding the NaK tubes to headers at either end. Each quadrant contains six individual panels. The three longitudinal panels are required to minimize the NaK pressure-drop as well as for ease of fabrication. The two circumferential panels on each quadrant are for ease of assembly. The NaK supply and return lines are routed to allow for differential expansion.

The panels are attached to a titanium semimonocoque structure by clips that allow differential expansion between the tubes and the structure. The structure is designed to support the radiator during launch and accommodate docking and maneuvering loads when the plant is extended in orbit. The radiator structure

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Figure V-9. Preassembled Radiator Assembly Integration Details

is not required to support the reactor shield weight during launch. The 0.010-in.-thick corrugated stiffeners and structural skin and the frames are all made of titanium since the maximum operating temperature of the structure will be between 650 and 700°F.

d. Structure

The primary loadpaths for the system are shown in Figure V-10. The LiH upper shield is relatively light and will be supported by its own shell. It will

Figure V-10. Power System Loadpath Schematic

DRY S-V WORKSHOP WITH NUCLEAR POWER SYSTEM

STANDARD APOLLO SATURN V

Figure V-11. Integral Saturn-V Launch Configuration,
Nuclear Thermoelectric Power System

be removable with a bolt ring on its lower outer periphery. Its loadpath will follow down the outer shell of the intermediate LiH shield. The reactor and the 4π gamma shield will be supported on a common conical shell within the intermediate LiH shield and which intersects the outer shell at the lower outer periphery.

To provide maximum volume and access to the gallery during system fabrication, the structure adjacent to the gallery is at the outer limit of the shield area. A series of permanent posts will form the basis of this structure. These will be given torsional rigidity by structural panels that can be removed for access to the gallery on the ground.

The structure of the lower shield will be the outer shell with attachment rings at both the lower and upper outer edge. The selection of the attachment ring will depend on the launch mode, as the power system is designed to be launched in either direction. The radiator structure is tied into the lower attachment ring and is required to support only the radiator.

The primary reactor and shield structure is 316 stainless steel. Selection of this material is dictated by compatibility with LiH and shield-casting-temperature considerations.

3. Operational Mode

a. Launch Options

Several options are available for launching the nuclear powerplant into orbit and mating it to the Saturn-V OWS. If the OWS is launched unmanned (which is being considered) the powerplant could be mounted on top of the stack attached to the forward end of the MDA, as shown in Figure V-11. In this case the powerplant would be already located in its operational position, ready for subsequent startup, extension, and operation after the OWS is manned.

The overall height of the Saturn-V OWS stack with the nuclear power system mounted as shown on Figure V-11 is about 9 ft less than that of the standard Apollo/Saturn-V including the launch escape system. The nuclear power system shroud, including the standard Marshall Space Flight Center (MSFC) nose fairing, is about 20 ft longer than the Apollo CSM, however, and the center of

Figure V-12. Separate Launch Configuration, Saturn-IB Service Module

gravity of the power system is near the top. Therefore, this configuration would require further analysis to determine whether the aerodynamic and structural characteristics are acceptable.

Figure V-12 shows the launch configuration for a separate unmanned launch of the nuclear power system using the Saturn-IB/Service Module (SIB/SM). The SIB/SM combination has been studied and proposed as an unmanned launch vehicle combination by North American Rockwell, Space Systems Division. For the present application, the service module would serve both as a multiple-restart third stage to reach the parking orbit and final orbit, and as a maneuverable rendezvous vehicle. The power system would be supported from the service module with the reactor/shield assembly at the lower end and a docking adaptor at the upper end. After rendezvous with the manned OWS and docking have been achieved, the service module would be disconnected from the power system and discarded. Figure V-13 shows a similar launch configuration for a separate unmanned launch using the Titan-III Transtage. In this case the Transtage serves the same function as the service module in the SIB/SM vehicle. In either case some modifications would be required for the unmanned rendezvous maneuver. These modifications have been studied by the vehicle contractors and found to be reasonable and feasible.

The available payloads and margins for the designated orbit, launch vehicles, and modes discussed above are summarized in Table V-6. The payload information was obtained from personnel at the Martin Marietta Corporation, Denver, Colorado, North American Rockwell's Space Systems Division, Downey, California, and NASA-MSFC, Huntsville, Alabama.

The gross payload for an unmanned launch of the OWS on a two-stage Saturn-V is 186,000 lb. A direct ascent to the 270 n.mi, 50° orbit is necessary in this case, since multiple burn of the S-2 stage is not feasible with the present engines due to the short burn time that would be required for a Hohmann transfer from a parking orbit. This payload capability is about 65,000 lb less than that achievable with the manned launch, where the CSM propulsion system can be used to transfer the OWS to the desired orbit.

The current Saturn-V OWS weight estimate is in the range of 156,000 lb for a three-man version to 188,000 lb for a six-man design, including supplies,

Figure V-13. Separate Launch Configuration, Titan-III Transtage

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TABLE V-6
LAUNCH VEHICLE PAYLOAD ESTIMATES*

Launch Mode	Integral Unmanned Direct Ascent	Separate Unmanned, with Hohmann Transfer and Rendezvous		
		Titan-IIIC (Transtage)	Titan-IIIF (Transtage)	Saturn-IB/SM
Launch vehicle	Two-stage Saturn-V			
Gross payload, lb	186,000	23,000	34,000	28,800
Orbital Workshop weight, three-man/six-man, lb	156,000/188,000	-	-	-
Net payload available for nuclear power system, lb	30,000/(-2,000)	22,700	33,700	28,500
Nuclear power system weight, † lb:				
with 4π shield	27,000	27,000	27,000	27,000
with shadow shield	24,800	24,800	24,800	24,800
Payload margin, lb:				
with 4π shield	+3,000/(-29,000)	(-4,300)	+6,700	+1,500
with shadow shield	+5,200/(-26,800)	(-2,100)	+8,900	+3,700

*Orbit altitude = 270 n.mi

Orbit inclination = 50°

†Includes 2,500-lb shroud/adaptor

experimental equipment, and a 12.5-kwe solar-panel battery power system. Thus the payload available for the nuclear power system ranges from about +30,000 to -2,000 lb for the three- and six-man OWS concepts, respectively.

The weights shown for the nuclear power system include either 4 π or shadow shielding, as noted, and a 2,500-lb allowance for the shroud and docking adaptor. (These numbers have been rounded upwards to the nearest 100 lb.) Comparison of the payload weights with data available shows that the integral launch would be feasible only with the three-man OWS, in which case the margin would be from 3,000 to 5,200 lb depending on whether a 4 π or shadow shield is used. If the power level of the solar-cell battery system were cut in half the payload margin could be increased by approximately 11,000 lb. Nonetheless, with the integral launch mode it is apparent that the payloads available for the nuclear power system would be inadequate for the six-man OWS, which is the one that could most profitably use the additional power.

The payloads available for the separate launch cases are all based on an initial launch angle of approximately 44.5 or 135.5° to achieve a 100-mi parking orbit in the correct inclination for the final orbit. Two burns of the Titan Transtage or the service module are used for the Hohmann transfer. Fuel weight required for the rendezvous with the OWS is estimated to be approximately 300 lb, which reduces the net payload available for the nuclear power system to the values shown. It can be seen that a separate launch with the Titan-IIIC does not appear to be feasible, but either the Titan-IIIF or the Saturn-IB/SM vehicles could be used for this mission. (The Titan-IIIF is the designation given to the launch vehicle being developed for the Manned Orbital Laboratory (MOL) program, but with the Transtage replacing the MOL and Gemini capsule.) The estimated payload margins available with these vehicles in the separate launch mode ranges from about 5 to 36%, depending on which vehicle and shielding option is ultimately selected.

From this preliminary evaluation of launch options, it is concluded that the separate unmanned launch and rendezvous with a manned OWS using either the Saturn-IB/SM or the Titan-IIIF vehicle appears to be the most promising approach. Additional more-detailed studies beyond the scope of the present study will be required, however, before a final selection can be made.

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Figure V-14. Saturn-IVB Power System Control Logic

b. System Operation

In Section III-C the general requirements for system control were discussed along with the characteristics of the four phases of a startup. The details of a control system have been further defined for the specific case of the Saturn-IVB OWS power system. Figure V-14 shows the logic diagram for this control system and V-15 summarizes the features of the startup including the results of preliminary calculations of the startup transient. In the logic diagram the standard definition is used where both signals to an "AND" box are required to pass a signal, while only one of the signals to an "OR" box is required.

In the following paragraphs each phase of the startup will be described.

(1) Phase 1, Shutdown Margin Removal

All drums are moved simultaneously at a rate of one step/15 sec until the drum position indicator shows they are at 105°. At this time, the drums have each moved 75° and the elapsed time is 31 min. The degree of subcriticality at this point is dependent upon NaK temperature but would vary from 25¢ at 75°F to 35¢ at 150°F.

As the gadolinium in the reactor core is burned out, the drum position where this phase is terminated would move outward, and later in life, when hydrogen leakage overcomes the burnout effect, it would move inward. The position setting in the control system would be adjustable and could always be set for a period of at least one month with a change.

(2) Phase 2, Critical to Sensible Heat

As seen in Figure V-14, when the control drums are rotated past the 105° position the stepping period increases to 30 sec and only one drum is moved at a time. Assuming the reactor is at 100°F, it would go critical 24 min into this phase, and the sensible-heat transient would occur in another 17 min. A power spike of approximately 180 kwT will occur at this time resulting in a maximum rate of change of temperature of 120°F/min. The reactor would automatically stabilize at approximately 270°F without further reactivity insertion; however, the control system will cause the drums to rotate further until the reactor is at 310°F.

STARTUP PHASE	I SHUTDOWN MARGIN REMOVAL	II CRITICAL TO SENSIBLE HEAT	III POWERPLANT EXTENSION	IV RAMP TO POWER	STEADY-STATE OPERATION					
STEPPING RATE	10 DRUMS AT 1 STEP/15 sec	1 DRUM AT 1 STEP/30 sec	1 DRUM AT 1 STEP/30 sec AS NECESSARY	1 DRUM AT 1 STEP/15 sec	(AS NECESSARY)					
PRIMARY CONTROL	a) DRUM POSITION ON STEP COUNTER	a) REACTOR OUTLET TEMPERATURE CUTOFF (310°F)	a) REACTOR OUTLET- TEMPERATURE CUTOFF (310°F) b) "POWERPLANT- EXTENDED" SWITCH	a) SYSTEM ELECTRICAL OUTPUT b) REACTOR OUTLET- TEMPERATURE CUTOFF (1325°F)						
	0	20	40	60	80	100	120	140	160	180

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Figure V-15. Saturn-IVB Orbital Workshop Power-System Startup

(3) Phase 3, Powerplant Extension

The extension of the powerplant from within the shroud would be accomplished at a rate of about 1 to 2 ft/min. In this discussion it is assumed that full extension requires 30 min.

As the powerplant is extended the average reactor temperature tends to remain constant and the thermal power starts to increase as the radiator is gradually exposed. As this occurs, pump power increases and the supplemental pumping used during the shutdown period can be terminated. As the ΔT in the primary loop increases and the average reactor temperature remains constant, the reactor outlet-temperature drifts upward, so no further reactivity is added during this phase.

The minimum radiator temperature occurs when the upper conical section is first exposed since the flow is still quite low. The 310°F temperature limit was selected so that this minimum temperature would be about 150°F.

(4) Phase 4, Ramp to Power

When the "plant-extended" switch shows the system is fully extended, the reactor outlet-temperature limit is raised to 1325°F and the stepping period is returned to 15 sec. Reactivity is then inserted at a rate that results in a primary-loop heating rate of about 20°F/min. As this heating occurs, all plant functions automatically increase toward their operating point, and in approximately 43 min the normal operating conditions are reached. After about 14 min of the ramp the open-circuit voltage of the converter exceeds 56 volts and useful power becomes available.

The parameter used to control the plant and to terminate the ramp to power is electrical current from the TE converter. This current is used to operate the electric power control switch which adds or subtracts reactivity as necessary to maintain the electric power within a deadband about the selected power level. As previously stated, this setting could be adjusted if operation for a period of weeks were projected with power requirements significantly different than 25 kwe.

If for some reason the power output is not adequate when the reactor outlet-temperature reaches 1325°F, the insertion of reactivity is stopped, as noted in

the control system logic diagram. This temperature level is still well within the range where serious damage or rapid degradation of the system would not result.

The above startup sequence would take approximately 2 hr and 25 min from beginning to full-power.

To shut down, the startup-shutdown switch is moved from the "operate" to the "shutdown" position. As seen in Figure V-14, this causes all drums to step out together and, since the plant would be extended, it would be at a 15-sec stepping rate. With the drums in the normal operating position, this results in a reactivity removal rate of about 24¢/min. The resulting shutdown transient was shown in Figures III-7 and III-8 of Section III-C. The radiation flux from fissioning would be reduced to about 1% in 3.5 min.

In about 1 hr the heat-rejection NaK temperatures would be near 150°F and retraction of the system into the shroud would have to be started to prevent NaK freezing. The retraction rate would be slow enough that sufficient radiator would be exposed to reject the reactor decay heat without excessive temperatures, but fast enough to maintain the minimum radiator temperature above about 100°F.

A restart of the system would be accomplished exactly as the initial start. However, because of an increased radiation source level within the reactor and an increased fuel-temperature coefficient after a long period of operation, the sensible heat transient would be significantly reduced. In fact, if the restart is undertaken before retraction of the system into the shroud, the critical-to-sensible-heat phase of the startup would be accomplished with a 15-sec stepping rate, since the source level would still be near the sensible heat power level.

4. Final Reactor Shutdown and Disposal

At the end of the nuclear power system operational lifetime the reactor would be shut down, using the normal control system, and disposed of in a manner which will minimize the possibility of radiological hazards.

Numerous studies and experiments performed in the AEC's ANS program and the experience in the SNAP 10A flight test program have provided a practical basis for establishing preliminary nuclear safety guidelines for SNAP reactors. The safety devices and procedures for the factory-through-launch and orbital

startup phases of the mission would be similar to and perform the same functions as those used for SNAP 10A flight. The 10A flight was completely reviewed and approved by all government agencies affected. The fact that the reactor is not radioactive until after it has been operated at power greatly simplifies the nuclear safety requirements for this part of the mission.

The orbit altitude range of interest for the OWS mission is from 200 to 300 n.mi, for which estimates of the orbital lifetime of an abandoned space station range from approximately 1 to 10 yr. If the reactor power system randomly re-entered 1 to 10 yr after shutdown, survived re-entry without burn-up (which is quite probable with a 4π shield), and impacted on land, a small but finite possibility of serious radiation exposure to anyone coming in close contact with the debris exists. To further reduce the risk of this situation occurring, alternate means for safe disposal of the reactor have been proposed and analyzed in detail.⁽⁷⁾ The two most promising disposal techniques are: (a) boost the reactor to a higher orbit or, (b) deboost the reactor into deep ocean areas.

If the first option is used, an altitude of about 450 n.mi would provide orbital storage for several hundred years, after which time the fission-product activity would have decayed to safe levels. If the reactor is deboosted into deep ocean areas, radiation from the fission products would not pose a significant hazard.

References 7 and 8 present the relative hazards, reliability estimates, attitude control and propulsion requirements, etc. for the above disposal options. If a separate communication, control, and propulsion package is used to automatically boost or deboost the reactor system, the weight penalty would be approximately 12 to 22%, depending on the altitude and other variables. The reliability of this equipment after extended storage in space was estimated to be from 0.85 to 0.95, and the risk of radiation injuries could thus be reduced by about one order of magnitude relative to that which would exist from random re-entry. In the SNAP 10A Safeguards Report⁽⁹⁾ it was shown that the individual risk probability due to random re-entry of a reactor after sustained operation would be less than 10^{-7} for radiation injury and less than 10^{-8} for lethal radiation exposure. These hazards are at least 6 orders of magnitude lower than the already existing injury or death potential from all other accidental causes.

For the Saturn-V OWS mission it is proposed that the CSM used for routine crew rotation be used to provide the control and propulsion capability needed for reactor disposal. The reliability of the manned CSM for this purpose should be greater than 0.99, the service module's control and propulsion systems should be more than adequate for this task, and an extra launch would not be required. Basically the proposed disposal technique would be to decouple the CSM and the reactor power system from their respective docking ports, couple them together, and then use the CSM to push the power system up to a higher orbit or to deboost it into the ocean. If required, a separate, automated disposal system (controlled from the ground or the OWS) could be incorporated in the powerplant package as a backup, in which case the total reliability for safe disposal should exceed 0.999. The individual radiation injury or death probability could thus be reduced to less than 10^{-10} and 10^{-11} respectively, which is believed to be technically and politically acceptable.

Although the foregoing discussion is of necessity an oversimplified summary of a complex problem, the suggested approach towards assuring adequate nuclear safety margins for this mission is thought to be reasonable. Additional more-detailed studies of the proposed disposal techniques and hazard analyses similar to those made before obtaining approval for the SNAP 10A flight test will be required.

B. LUNAR BASE POWERPLANT

1. Mission Requirements

Reactor power systems for manned lunar bases were studied recently in a joint NASA-AEC study^(3,5) to determine the design and development requirements and the performance characteristics of this type powerplant for such a mission. The basic requirements and results regarding integration, deployment, and operating mode obtained from that study are thought to be still valid and have been retained, therefore, in the present study for the purpose of updating the reactor - TE system design and performance characteristics.

The key power system requirements for a lunar base powerplant designed to support extended manned lunar exploration are summarized on Table V-7.

This mission is envisioned as a logical outgrowth of the Apollo and Advanced Apollo programs, wherein the level of exploration, crew size, and stay times would gradually increase in a stepwise fashion. One or two personnel shelters capable of supporting up to six men each for six months without resupply would constitute the lunar base.

TABLE V-7
KEY POWER SYSTEM REQUIREMENTS
FOR LUNAR BASE

Power level range of interest, kwe	10 to 30
Number of men	6 to 12
Minimum lifetime, yr	1
Pre-operational storage on moon, mo	≤6
Availability	1975-1980
Allowable dose to astronaut from reactor, rem	70
Allowable separation distance, mi	≤1
Available radiator area, ft ²	1500 to 2500
Allowable powerplant weight, lb	29,475
Shield concepts	a) Integral 4π b) Lunar soil

The basic housekeeping power requirements have been estimated to be ~1 kwe per man, so the minimum lunar base powerplant capacity, therefore, would be in the range of 6 to 12 kwe, depending on the actual base size. Additional power would be required for experiments, recharging mobile vehicles, and similar functions. The maximum power level of interest would thus depend on the scope and nature of the exploration program, and would probably correspond to the maximum capability that could be provided within the payload limits of the designated launch and landing vehicles. Up to two weeks emergency power would also be supplied by fuel cells.

The Saturn-V booster combined with a Lunar Landing Vehicle (LLV) having a net payload capacity of slightly less than 30,000 lb (landed on the lunar surface) was selected by NASA as the standard logistics system for this mission. The

area available for fixed radiators within the standard shroud was about 1500 ft². This can be increased to approximately 2500 ft² using a larger shroud of the size designed for the Voyager mission, or by using folding radiator panels.

The nuclear powerplant would be landed as a separate unmanned payload in the vicinity of the lunar base, mounted on the LLV. As long as 6 mo of pre-operational storage in the moon might be required before base manning and full-power operation.

Three possible deployment modes and associated plant concepts were considered in the referenced study:

- 1) An off-loaded arrangement wherein the reactor assembly would be buried in a hold in the lunar soil and the plant would then be assembled, checked out, and started up on the lunar surface,
- 2) An integral powerplant using 4π shielding and fixed radiators, all of which would be assembled and checked out on Earth before launch, and
- 3) An integral, 4π shielded concept similar to 2) with deployable radiators which would be assembled on the moon.

The integral (pre-assembled) powerplant concept with a 4π shield was selected, to reduce astronaut labor and avoid technical problems associated with the other concepts. Consequently in the present study, consideration was limited to the integral design approach using a 4π shield to reduce the annual dose to the astronauts to the previously specified value, 70 rem. The allowable separation distance between the powerplant and the lunar shelters was also determined to be up to 1 mile, based on power transmission and operational considerations.

Another important general criterion was that assembly, startup, and operation of the plant should require a minimum of astronaut labor or attention, since the primary mission objectives are not to work on powerplants but to explore the moon. Thus a premium would be placed on powerplant simplicity and reliability.

2. System Description and Performance

The updated baseline lunar powerplant design consists of the reference 25-kwe system presented in Section III of this report, packaged in a configuration suitable for this mission. Figure V-16 shows the powerplant arrangement, which is designed to be mounted on the top of the LLV. The reactor, shield, and PCS assembly is mounted along the centerline, inside the radiator at the base of the powerplant to maintain a low center of gravity. The reactor/shield assembly is supported by struts attached to a mounting ring. The converters, pumps, and primary-loop expansion compensators are located atop the shield. Each of the four radiator sections consists of cylindrical and conical quadrants connected in parallel hydraulically. The expansion compensators for the HRL's are mounted within and near the top of the radiator.

The electronic package used for remote startup, control, and monitoring of the system from Earth during low-power operation on the moon is located at the top of the system. The electronic package is thermally insulated from the rest of the system and is exposed to space for proper thermal control.

A thermal shroud covers the radiator to reduce heat losses during storage and periods when the reactor is shut down. When the system is at full power, the shroud is deployed, as shown in Figure V-17.

The reactor control-drum drive-motors and electrical connectors are located at the base of the system where they are accessible to the astronauts during reactor shutdown for possible maintenance.

Table V-8 summarizes baseline lunar power system characteristics. The gross electrical power is 27.0 kwe; losses in transmission and power conditioning reduce the power available at the lunar shelter to 22.9 kwe. The converter power output is inverted to ac, transformed to 4160 volts, and transmitted via cable to the lunar shelter.

The converter modules are identical with those of the reference system design and the Saturn-IVB Workshop design. The higher power output is due to the larger available radiator area and consequent lower converter cold-clad temperature.

Figure V-16. 25-kwe Nuclear Thermoelectric Power Supply Lunar Base Application

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Figure V-17. Lunar Base Power Supply Design Alternates

TABLE V-8
 BASELINE LUNAR POWERPLANT CHARACTERISTICS
 (Sheet 1 of 2)

Gross power output, kwe	27.0		
Loss in conversion and transmission, kwe	4.1		
Net power to shelter, kwe	22.9		
Thermal power, kwt:			
Reactor	613.4		
Converter	570.0		
Pump converter	38.4		
(Primary loop	25.6)		
(Heat-rejection loop)	12.8)		
Radiator	581.4		
Primary-loop losses	5.0		
Temperature, °F:	<u>Inlet</u>	<u>Outlet</u>	<u>Average</u>
Reactor	1045	1247	1146
Converter, hot-clad	1225	1025	1125
Converter, cold-clad	456	656	556
Radiator	648	448	548
Efficiencies, %:			
System	3.74		
Converter	4.74		
Converter Carnot	35.9		
Voltages, volts			
Shelter high-voltage bus	4160.0		
Converter:			
Tubular module	14.4		
Converter module	57.6		

TABLE V-8
 BASELINE LUNAR POWERPLANT CHARACTERISTICS
 (Sheet 2 of 2)

Flowrates, lb/sec:		
Primary loop		13.7
Heat-rejection loop		13.1
Pressure-drop, psi:		
Primary loop		3.0
Heat-rejection loop		1.4
Radiator area, ft ²		1500
Weights, lb:		
Reactor		1,422
Converter		1,135
Radiator/structure		2,760
Pumps		440
Expansion compensators		210
Piping		518
Instrumentation and control equipment		240
Power conditioning		<u>800</u>
	Subtotal	7,525
Nuclear shield		14,000
Reactor and power-conversion system support structure		525
Thermal shield		500
Direct current transmission cable		300
Alternating current transmission cable		<u>250</u>
	Subtotal	<u>1,575</u>
Total system weight		23,100
Allowable payload		29,475
Design margin		6,375

8-J14-099-59

Figure V-18. Reactor Shielding and Structure, Lunar Base Conceptual

The total estimated system weight is 23,100 lb (including the 14,000-lb shield, power-conditioning equipment, and transmission cables) which is 6,375 lb less than the 29,475-lb payload limit for the designated launch vehicle system. This margin provides the possibility for increasing the design power output by adding TE converters and radiator area.

The necessary increase in radiator area can be obtained by using radiators which can be deployed with the thermal shroud, as shown in Figure V-17, using flexible NaK joints at the hinge points. An alternate approach is to use fixed radiators and a larger shroud. The Voyager shroud design, for example, is the same diameter and same general configuration as the standard shroud, except that its cylindrical section is long enough to accommodate an additional 1000 ft² of radiator. These two alternate configurations are shown on Figure V-17, along with the baseline system.

As shown in Table V-9, with 2500 ft² of radiator available the electric power output increased to 42.9 kwe gross and 35.5 kwe net. The reactor power and outlet-temperatures are 962.4 kwt and 1251°F still within the reference ZrH reactor performance capability. The shield weight was held constant at 14,000 lb and the minimum separation distance would thus be increased to approximately 3250 ft for the same dose rate at the higher reactor power level. A coolant ΔT of 300°F is used to minimize pumping-power requirements. The total system weight is 27,675 lb; the allowable weight limit is 28,775 lb (700 less than the 29,475 because of the use of the heavier Voyager shroud), which still leaves a design margin of 1100 lb. This margin, while probably adequate, could be increased by approximately 3200 lb by transporting the power-conditioning equipment and transmission cables to the moon in the lunar shelter or other logistics vehicles.

Thus reactor - TE lunar powerplants with net capacities up to 35 kwe appear feasible within the constraints and guidelines established for this mission.

3. Subsystem Description and Performance

a. Reactor/Shield Assembly

The heat source consists of the reference ZrH reactor surrounded by a 47 shield. A drawing of the reactor and shield is shown in Figure V-18. The reactor

TABLE V-9
HIGH-POWER LUNAR POWERPLANT CHARACTERISTICS
(Sheet 1 of 2)

Gross power output, kwe			42.9
Loss to conversion and transmission, kwe			7.4
Net power to shelter, kwe			35.5
Thermal power, kwt:			
Reactor			962.4
Converter			919
Pump converter			38.4
(Primary loop			25.6)
(Heat-rejection loop			12.8)
Radiator			914.4
Primary-loop loss			5.0
Temperature, °F:	<u>Inlet</u>	<u>Outlet</u>	<u>Average</u>
Reactor	949	1251	1100
Converter, hot-clad	1230	930	1080
Converter, cold-clad	390	690	540
Radiator	384	684	534
Efficiencies, %			
System			3.78
Converter			4.67
Converter Carnot			35.0
Voltages, volts:			
Shelter high-voltage bus			4160
Converter:			
Tubular module			14.0
Converter module			56.0

TABLE V-9
HIGH-POWER LUNAR POWERPLANT CHARACTERISTICS
(Sheet 2 of 2)

<hr/>		
Flowrate, lb/sec:		
Primary loop		14.4
Heat-rejection loop		13.7
Pressure-drop, psi		
Primary loop		3.3
Heat-rejection loop		1.5
Weights, lb		
Reactor		1,422
Converter		1,928
Radiator/structure		4,600
Pumps		530
Expansion compensators		310
Piping		900
Instrumentation and control equipment		300
Power conditioning		1,600
Radiation shield		14,000
Reactor and power-conversion system support structure		630
Thermal shield		835
Direct current transmission cable		300
Alternating current transmission cable		320
		<hr/>
Total system weight		27,675
Allowable payload		28,775
Design margin		1,100
<hr/>		

is the same as that described in Section IV-A with the exception that it is operated in an inverted position. The control-drum drive-shafts pass downward through the lower end of the shield into a right-angle gear and then to the drive-motors. The latter are located near the lower periphery of the radiator to provide access for possible maintenance when the reactor is shut down.

The reactor shield is composed of an inner Pb gamma shield surrounded by a canned LiH neutron shield. A layer of insulation separates the two shields to avoid overheating the LiH. The neutron shield is cooled by radiation to the inner surface of the power system radiator. The shield envelope is 68 in. in diam by 68.5 in. high, and the total shield weight is approximately 14,000 lb. The shield thicknesses shown on Figure V-18 are sized to limit the annual radiation dose to 70 rem/year (8 mrem/hr) at the lunar shelter, which is located at a distance of approximately 1/2 mi. In addition, the integrated dose to the pre-operational control equipment located above the reactor was limited to 5×10^{12} nvt in 6 mo of operation at 10% power. No shield is placed around the power-conversion equipment, and the doserate from the activated NaK in the exposed part of the primary loop is included as a source in the calculation of expected doserates. Table V-10 presents the doserate contributions from neutrons and gammas at a separation distance of 0.5 mi.

TABLE V-10
DOSERATE AT 0.5 mi FROM
LUNAR BASE REACTOR

	Doserate (mrem/hr)
Neutrons	1.57
Gamma rays (primary and secondary)	3.66
Na ²⁴ in power-conversion system	2.32
Total	7.55

b. PCS Arrangement

The TE PCS including the converters, pumps, and primary-loop expansion compensators are located above the reactor/shield as shown in Figures V-16 and -18. The arrangement is essentially the same as that in the gallery of the Saturn-V OWS (see Figure V-7). Pump power requirements, converter size, and expansion compensator size are the same for both plants. Detailed descriptions of each of the PCS components are given in other sections of this report.

For the 35.5-kwe plant the reactor ΔT has been increased, resulting in nearly the same pump power requirements. The converter packages will be larger, however, requiring a somewhat expanded arrangement of the power-conversion equipment shown previously.

c. Radiator/Structure

The radiator/structure is similar to that on the Saturn-V OWS plant (see Figure V-9). The radiator consists of a 6061 aluminum fin and armor which is diffusion-bonded to a stainless-steel NaK tube. The individual tube-fin pieces are assembled into panels by welding the NaK tubes to headers at either end. The panels are then assembled to the structure through supports to provide differential thermal expansion between the structure and the tube-fin panels. The NaK headers are connected to the supply and return lines.

The radiator structure is of the semimonocoque type, consisting of corrugated stiffeners, skin, and frames. Titanium is used as the structural material because during power-system operation, the maximum temperature is between 650 and 700°F.

The radiator structure is attached to a load ring located at the base of the radiator. The reactor/shield is supported off this same load ring through spar beams attached to the outside of the shield structure.

4. Operational Mode

The methods and procedures proposed for deployment of the powerplant on the lunar surface, pre-operational storage, startup, and operation, are the same as those identified in the previous study of reactor power systems for this mission.^(3,5) Briefly, the planned operational mode is as follows:

- 1) The power system will be launched using the Saturn-V/LLV booster and landing vehicle, and landed on the lunar surface at a predetermined position located approximately 1/2 to 1 mi from the position of the lunar shelters.
- 2) The reactor will be started up by a command signal from Earth, and the reactor power level raised to approximately 5 to 10% of its design full-power operating point. The thermal shields will then be opened to expose approximately 10% of the radiator area (again by control from Earth). Under these conditions several hundred watts of electrical power will be generated, sufficient to power the communications and control equipment at the top of the powerplant. Its operability can thus be confirmed on Earth before the astronauts are committed to the lunar base. In addition the powerplant can be kept warm through the lunar thermal cycles thus avoiding freezing of the liquid-metal loops.
- 3) The astronauts will land sometime during the two-week lunar day at which time the reactor powerplant will be shut down by remote command. The astronauts then will deploy the power-transmission cables between the lunar shelter and the powerplant, and set up the operational control and power-conditioning equipment, on the lunar surface within about 100 ft of the powerplant.
- 4) After the astronauts have returned to the lunar shelters, the heat shields will be lowered and the system started up and brought to the desired operating power level. (The operational control system will be of the type discussed under the reference power system in this report.)
- 5) In the event of system shutdown (planned or unplanned), the heat shields will be raised back into position to avoid eventual freezing of the liquid-metal loops. Maintenance and repair will be possible on the control-drum actuator motors, located at the outer surface of the powerplant, and on the electrical control and power-conditioning equipment located on the lunar surface.

- 6) At the end of the mission the powerplant will be shut down using the normal control system and abandoned in position. If desired, the power level can be reduced to 5 to 10% of its design-power level and left on the moon in this condition, ready for subsequent restart and operation.

Nuclear safety requirements for this mission can be met quite easily since the power system would not be started up until it has been safely landed on the moon.

5. Comparison With Previous Design

The current lunar base powerplant design represents a considerable improvement over that reported in Reference 3. Table V-11 is a comparison of the more significant features of the current and previous designs. The new

TABLE V-11
DESIGN COMPARISON

	Current	Previous
Electrical power delivered to shelter, kwe	22.9	20.4
Degradation allowance, %	10	14.0
Reactor power, kwt	613.4	541
Reactor outlet-temperature, °F	1247	1229
Converter clad average temperature, °F: hot	1125	1100
cold	556	500
System efficiency, %	3.74	3.77
Radiator area, ft ²	1500	1500
Number of tubular modules	96	256
Total number of loops	5	17
Weight, lb:		
Power-conversion system and reactor	7,525	11,195
Nuclear shield	14,000	13,900
Support structure	525	525
Thermal shield	500	500
Transmission cable	550	500
Total	23,100	26,620
Allowable payload	29,475	29,475
Design margin	6,375	2,855

system has a higher net power primarily because of improvements in the TE converter and system design. The reactor thermal power is higher for the new system because of the higher electrical power output. The system efficiencies are nearly the same.

The previous design used 256 converter tubular modules which were smaller than the current reference tubular module design. This change in converter design not only drastically reduced the number of tubular modules required, but also reduced converter weight by over 2400 lb. This accounts for most of the weight differences between the current and previous designs. Another 1000-lb reduction was achieved by using improved radiator design, using fewer parallel loops, and eliminating the intermediate loops entirely. This greatly simplifies the system design and should increase the reliability. The current design has twice the weight design margin as the previous design.

C. MORL POWERPLANT

1. Mission Requirements

The MORL is a preliminary design for an advanced space station that has been studied extensively over the past several years by the McDonnell-Douglas Corp. for NASA. A joint NASA/AEC study to determine the design requirements and characteristics of several types of reactor power systems for the MORL was conducted in 1966.^(2,6) One of the power systems studied was a 22.5-kwe reactor — TE system based on the PbTe tubular compact converter. Although the MORL design has now been superseded by the OWS series, updating of the reactor — TE power system design for the same integration constraints used previously is of interest.

The major power system requirements and integration constraints established for the MORL mission are shown in Table V-12.

2. System Description and Comparison with Previous Design

The general configuration and performance characteristics of the updated MORL reactor — TE system are the same as those of the reference 25-kwe system described in Section III of this report. The powerplant layout and dimensions

TABLE V-12
KEY MANNED ORBITING RESEARCH LABORATORY MISSION
AND REACTOR POWER SYSTEM REQUIREMENTS

Electrical power range, kwe	10 to 30
Lifetime objective, yr	5
Allowable radiation dose rate from reactor, rem/yr	20
Reactor — Manned Orbiting Research Laboratory separation distance, ft	125
Doseplane diameter, ft	80
Shield type	Shadow
Available payload for power system, lb	
Initial launch	41,000
Replacement	18,110

shown on Figure V-19 are set primarily by the 17° shield half-angle which results from the doseplane diameter and separation distance requirements. A shadow shield is used, consistent with the previous requirements for this application. This power-conversion equipment is located in the shield gallery.

Table V-13 is a brief summary of the current MORL system characteristics and a comparison with the previously published system design.⁽²⁾ That had an electrical power output of 22.5 kwe and the current design power level is 21.9 kwe. These are net conditioned powers based on a conditioning efficiency of 0.87.

The reactor thermal powers and efficiencies are approximately the same for the two systems. As was the case with the lunar base system, the current design uses the improved converter module design which reduces the number of modules required by 70%. The current design does not use an intermediate loop, thereby eliminating heat exchangers, intermediate loop pumps, compensators, and piping.

The previous design used 12 active and 2 standby redundant loops with NaK valves. The current design has four active HRL's and no standby redundant loops. Any system degradation which might occur is compensated for by adjusting reactor outlet-temperature, which has been reduced 54°F in the current design.

	Current	Previous
Regulated electrical power, kwe	21.9	22.5
Reactor thermal power, kw	582	622
Reactor outlet-temperature, °F	1,246	1,300
Converter clad average temperature, °F: hot	1,125	1,150
cold	570	550
System efficiency, %	3.77	3.62
Radiator area, ft ²	1,400	1,891
Number of tubular modules	96	336
Number of loops in series	2	3
Number of heat-rejection loops in parallel	4	14
Total number of hydraulic loops	5	22
Weights, lb:		
Reactor	1,422	755
Primary loop	515	503
Heat exchangers	-	147
Converters	1,135	5,082
Expansion compensators	285	693
Pumps	440	280
Piping	100	200
Support structure	113	-
Radiator/structure/piping	<u>2,990</u>	<u>3,573</u>
Subtotal	7,000	11,233
Radiation shield	<u>12,300</u>	<u>9,315</u>
Total	19 300	20,548

The current system has a total of five hydraulic loops, i. e. one primary and four HRL's, whereas the previous design had 22 hydraulic loops, i. e. one primary, seven intermediate, and 14 HRL's

The radiator area has been reduced by 491 ft^2 , which reduces the overall package height approximately 7 ft.

The weights shown in Table V-13 are arranged to provide a consistent comparison and do not include integration penalties in either case.

The current design uses the 4π -shieldable 295-element reactor, and the previous design used a 349-element reactor concept with a Be reflector designed for use with a shadow-shield. The converter weight is reduced nearly 4000 lb by use of the current module design. Other weight differences except for the nuclear shield are a result of the different hydraulic arrangements.

The current shield design is significantly heavier at 12,300 lb than the previous weight of 9,315 lb. This difference is caused by the use of a larger gallery to accommodate the pumps, converters, and expansion compensators. The previous design used compact heat exchangers to reduce gallery size and shield weight. However, the current study has shown that it is necessary to use larger heat exchangers with fewer tubes to improve reliability. Heat exchangers of this type result in galleries as large as those required for the two-loop design and result in shield weights nearly as heavy as the current design. Without a significant weight advantage there is no reason to use an intermediate loop, especially since the additional components in the loop reduce overall system reliability.

Thus the major improvements in the updated powerplant for the MORL are considered to be the simplification in the system design which should enhance the reliability, a 26% reduction in radiator area, a 50°F reduction in reactor outlet-temperature, and a 5% reduction in shielded system weight.

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GLOSSARY

AAP	Apollo Applications Program
ac	alternating current
AI	Atomics International
ANS	Aerospace Nuclear Safety
BOL	Beginning-of-Life
CSM	Command and Service Module
dc	direct current
EBR	Experimental Breeder Reactor
ECU	Expansion Compensator Unit
EM	electromagnetic
EOL	End-of-Life
EOSS	Early Orbital Space Station
EVA	Extravehicular activities
HNPF	Hallam Nuclear Power Facility
HRL	Heat-rejection loop
ID	inside diameter
IHX	Intermediate heat exchanger
kwe	kilowatts electric
kwt	kilowatts thermal
LLV	Lunar Landing Vehicle
MDA	Multiple Docking Adaptor
MOL	Manned Orbital Laboratory
MORL	Manned Orbiting Research Laboratory
MRP	Mercury-Rankine Program

MSFC	Marshall Space Flight Center
n.mi	nautical miles
NPS	nuclear power system
OD	outside diameter
OWS	Orbital Workshop
PCS	power-conversion system
PVT	pressure/volume/temperature
PWR	Pressurized Water Reactor
SRE	Sodium Reactor Experiment
SIB/SM	Saturn-IB Service Module
S8DR	SNAP 8 Developmental Reactor
S8ER	SNAP 8 Experimental Reactor
TE	thermoelectric
TEM	thermoelectric module
WANL	Westinghouse Astronuclear Laboratories