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LARGE RADIOISOTOPE- COMPACT CONVERTER POWER SYSTEM STUDY (U)

FINAL REPORT

APRIL 15, 1966 THROUGH JUNE 30, 1966

PREPARED FOR:

U.S. ATOMIC ENERGY COMMISSION

NEW YORK OPERATION OFFICE

376 HUDSON STREET

NEW YORK, NEW YORK 10014

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1. INTRODUCTION

This report presents the results obtained during the "Large Radioisotope Compact Converter Power System Study" which was conducted by the Advanced Nuclear Systems Engineering Component of the General Electric Company under AEC Contract No. AT (30-1)-3526. The program performance period was April 15, 1966 to June 30, 1966.

The objective of the study is to combine the results of continuing AEC contract efforts on large radioisotope heat sources and on compact thermoelectric converters to evaluate the mutual compatibility of these components in a power system and to thereby provide information to the AEC for use in its direction of the heat source and thermoelectric converter development programs. In particular, the results reported under the following contract efforts were utilized to investigate radioisotope/thermoelectric power systems parametrically over a range of 1 to 5 KWe.

- Compact Thermoelectric Converter, PbTe, Westinghouse Astronuclear Laboratory, AEC Contract Number AT (30-1)-3584
- Compact Thermoelectric Converter, SiGe, Radio Corporation of America, AEC Contract Number AT(30-1)3582
- Preliminary Design and Safety Studies of Large Radioisotope Heat Sources for Space Power, General Electric Company, AEC Contract Number AT(30-1)-3526

In addition, specific power system designs considering the factors of vehicle integration were prepared for 2 KWe systems suitable for use in the Apollo Applications Program (AAP).

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In the parametric evaluations, consideration is given to:

- Selection of optimum thermoelectric (T/E) element parameters (pressure drop, voltage, T/E element length, or diameter).
- The system effect of varying the thermoelectric module inlet temperature over the range of 1300 to 1600°F for SiGe and over 1100 to 1300°F for PbTe.
- The difference between minimum system weight and minimum system cost selections.
- The effect of off-design performance of the T/E converter modules and of the isotope heat source.
- The effect of varying the reliability goal from .95 to .99 and the requirements for overdesign and redundancy.
- The importance of shielding requirements and of isotope selection on optimum T/E converter parameters.
- The effect of radioisotope operating temperature on system parameters.

In the 2 KWe power systems for AAP, conceptual designs were prepared employing Po-210 and Pu-238 fuels with both the SiGe and PbTe converters for a total of four systems. The T/E converters operated at inlet temperatures of 1500 and 1300°F, respectively. In these evaluations, consideration was given to;

- Definition of the mission profile and pertinent parameters
- Pre-operation heat rejection
- Emergency heat rejection
- Alternate locations for the radioisotope heat source
- Alternate locations for the power system radiators
- Variations in electrical output from "night-to-day"
- Degradation of T/E converter performance

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2. SUMMARY AND CONCLUSIONS

The parametric evaluations over the range of 1 to 5 KWe and the design point evaluations at 2KWe result in the same general conclusions for the four power systems examined (Po-210 with SiGe and PbTe and Pu-238 with SiGe and PbTe). Those cases in which the general conclusion is affected by the factors of integration peculiar to the vehicle, the mission profile, or the design point power level of 2 KWe are identified.

To assure credibility and realism in the parametric and design point evaluations, one of the Apollo Applications Missions (AAM) was selected for use in the vehicle integration studies and for definition of the mission parameters. The Lunar Shelter/Taxi mission selected is one of the most difficult missions in the AAP series. The mission involves two launches; the first launch will deliver a modified Lunar Excursion Module (LEM) Shelter to the surface of the moon. The shelter, which can be stored on the moon for 90 to 120 days, will contain the isotope-T/E power system, various experiments, and life support for two men for 14 days of lunar exploration. In 90 to 120 days after the first launch, a second launch will deliver the lunar exploration crew. Two men will use a modified LEM Taxi to descend to the moon's surface, where the LEM Shelter will provide the necessary life support for 14 days of exploration. The LEM-Taxi is used to return the two men to the orbiting Command and Service Module. The study guidelines derived for this mission are summarized in Table 2-1.

The cycle arrangements selected for the power systems to satisfy the reliability and operating requirements and the proposed arrangement of the system components on the LEM vehicle are shown in Figures 2-1A and B. The Pu-238 system utilizes a simple two-loop system, whereas the Po-210 system incorporates a separate third loop for power flattening. The power flattening system is controlled on heat source outlet temperature by a reduction of power to the pump in that loop. All systems include EM pumps. Two hydraulically connected heat sources are provided to minimize the weight and volume of a single source for ease of integration. On the LEM Shelter, the heat source and strongly sculptured shield

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 Table 2-1. Study Guidelines

• Mission Hardware	Apollo Applications Program	
• Mission Class	Manned Lunar Surface	
• Launch Vehicle	Saturn V Vehicles No. 519/520 and 524/525	
• Mission Lifetime for Po-210 and Pu-238	<u>Duration, days</u>	<u>Total time, days</u>
Pad wait	14	14
Transit	5	19
Lunar wait	90-120	109-139
Mission	14	123-153
Post-mission (Pu-238 only)	To failure	
• Year of Launch	1970 and 1971	
• End of Life Power Level	2 kW•	
• Power Conversion	Compact Thermoelectric Converter	
• Re-entry Mode	Intact for accident	
• LEM Power Requirements	<u>DC, W</u>	<u>AC, W</u>
Avg. Power (lunar storage)	501	
Avg. Power (mission)	636	17
Peak Power (mission)	1500	27
• Experiment Power Requirement (Moltke B Site)		
Peak Power	3500 W	
Energy	58 Kw-hr	

assembly is mounted in one of the external bays of the octagonal-shaped LEM. The compact converter thermoelectric modules, hot and cold loop EM pumps, and accumulator (pressure regulator) are mounted on the opposite side of the vehicle to minimize the effect on vehicle center of gravity. The main power system radiators (3 large panels, 180 ft² total) are mounted on three sides of the LEM descent stage. They are offset from the LEM to minimize thermal input to the LEM Structure and to provide increased area. The small power flattening radiator required in the Po-210 fueled systems is mounted above the heat source on the fourth face of the LEM. The characteristics of these systems selected for the mission nominal electrical requirement of 2 KWe are summarized in Table 2-2.

The conclusions derived from the study of the power systems parametrically and as applied for the LEM Shelter Mission are discussed herein.

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BASIC Pu-238 SYSTEM

BASIC Po-210 SYSTEM

Figure 2-1A. Basic Systems Diagrams

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POWER SYSTEM/VEHICLE ARRANGEMENT, Po-210 / GeSi

Figure 2-1B. Power System/Vehicle
Arrangement, Po-210/SiGe

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Table 2-2. Characteristics of 2 KWe Power Systems

Thermoelectric	SiGe	SiGe	PbTe	PbTe
Isotope	Pu-238	Po-210	Pu-238	Po-210
No. of Modules	18	20	16	16
Net Elec. Power (KWe)	1.96	1.99	2.01	2.04
Unshielded Specific Wt. (lb/KWe)	851	580	733	512
Shielded Specific Wt. (lb/KWe)	1360	1630	940	1200
Capsule Temp. (°F)	1700	1900	1700	1900
Shielded Specific Cost (\$/KWe)	1.64×10^7	9.5×10^6	1.08×10^7	6.16×10^6
Hot Side T/E Temps. (°F)				
Inlet Temp.	1500	1500	1300	1300
Outlet Temp.	1288	1201	1100	1100
Cold Side T/E Temps. (°F)				
Inlet Temp.	327	285	302	291
Outlet Temp.	540	584	502	491
Heat Source Power (KWT*)				
BOL	42.3	94.7	38.3	73.7
EOL	42.2	44.7	38.2	34.7
Ratio Area Limit/Opt. Area	0.84	0.83	0.83	0.79
T/E Leg Length/Module Dia. (in.)	0.8	0.8	1.96	1.99
Sys. Eff. (%)	4.63	4.45	5.24	5.87
Weight T/E Converters (lb)	138	153	246	254

*Includes Allowance for 5% Heat Loss

2.1 RCA SiGe THERMOELECTRIC CONVERTER

The evaluations indicate that the parameters of the SiGe Compact Converter Module being developed are compatible with, and near optimum, for application with either a Po-210 or Pu-238 heat source, provided that element length is in the range of 0.6 to 0.9 inch. Changes in the parameters would not be justified for the relatively small gains to be obtained.

The basic SiGe converter that is defined as a module for this study is shown in Figure 2-2. It consists of two of the RCA "submodules" which contain 2 T/E layers with 36 couples (3 by 12) in each layer. The total number of couples per module is 144, and the approximate power output is 100 watts.

2.1.1 CONVERTER WEIGHT AND PHYSICAL DIMENSIONS

Parametric and design studies indicate these factors are relatively unimportant to the system. Integration of the converters with the spacecraft presents no unique problems beyond the usual considerations of support, vibration, insulation, etc. Depending upon the shielding requirements, the fraction of total system weight attributable to the converter varies from 12 percent for completely unshielded systems down to only 5 percent for heavily shielded systems such as the 2 KWe reference designs of this study. Because of this low weight

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RCA - SiGe
REFERENCE MODULE

WESTINGHOUSE - PbTe
REFERENCE MODULE

Figure 2-2. Reference Compact Thermoelectric Converter Modules

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fraction, modifications to the converter which improve efficiency at the expense of converter weight prove beneficial to the system up to the point where a 0.1 percent increase in converter efficiency (e.g. 5.0 to 5.1 percent) causes a converter weight increase of 15 percent and 40 percent for unshielded and shielded systems, respectively.

2.1.2 THERMOELECTRIC ELEMENT LENGTH

Optimum element lengths are found to lie in the range of 0.6 to 0.9 inch, depending upon the system constraints imposed. With no radiator area restrictions and no shielding, the optimum lengths tend toward the lower end of this range. With regard to this parameter, a qualitative conclusion can be made; changes to the system which increase the weight percentages of those components on the high temperature side of the converter cause the optimum element length to increase and, conversely, decreases in the weight percentages of these components shift the optimum element length to lower values. The sensitivity of the system weight to this parameter is low, and a compromise element length of approximately 0.75 inch would not impose significant penalties.

2.1.3 CONVERTER PRESSURE DROP

Sensitivity to this factor is significant - about 150 lb/KWe per psi lost in the converter. However, the reference module configuration provides a very low pressure drop, less than 0.04 psi, and at this level, the associated penalty for even doubling the pressure drop is insignificant. A greater pressure drop would likely be required in any case to assure that a proper flow distribution could be maintained. Arrangement of the module plumbing, so that two or more are connected hydraulically in series, would provide a predictable flow network, and the resulting pressure losses would remain at an acceptable level.

2.1.4 CONVERTER VOLTAGE OUTPUT

Flexibility in the choice of electrical connections enable the module voltage output to be tailored to the demands of a particular application. This feature can be of considerable significance, since the power requirements of a low-voltage electromagnetic pump can be accommodated directly and the need for the low voltage power conditioning equipment may be eliminated.

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2.1.5 HOT-JUNCTION TEMPERATURE

The lower efficiency of silicon germanium indicates the desirability of attaining hot-junction temperatures above 1500°F. The increase in T/E element temperature will require a concurrent increase in fuel capsule temperatures to limit the size and weight of the heat source.

2.1.6 RELIABILITY

The ability to provide "laddering" between each thermoelectric couple allows the couple to be taken as the basic element in reliability considerations and gives the converter excellent reliability potential. Studies show that with successful development, the converter will be one of the most reliable system components.

2.2 WESTINGHOUSE PbTe THERMOELECTRIC CONVERTER

The evaluations indicate that the parameters of the PbTe Compact Converter module being developed are also compatible with, and near optimum, for application with either a Po-210 or Pu-238 heat source. The tubular PbTe thermoelectric element that is defined as a module for this study is shown in Figure 2-2. The module provides a power output of about 120 watts net.

2.2.1 CONVERTER WEIGHT AND PHYSICAL DIMENSIONS

As in the case of SiGe, the studies show that these factors are relatively unimportant to either system weight or in vehicle integration. Converter weight fractions are slightly greater than in the silicon germanium systems, as the lead telluride converters account for 7 to 18 percent of the total weight, for shielded and unshielded systems, respectively. Despite this higher weight fraction, improvement of the converter efficiency at the expense of converter weight yields improvements to the system up to the point where a 0.1 percent increase in converter efficiency (e. g. 6.7 to 6.8 percent) causes a converter weight increase greater than 6 percent for the unshielded systems and 15 percent for the shielded systems.

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2.2.2 CONVERTER DIAMETER

Depending on system constraints, optimum module diameters are found to be 1.5 to 2.0 inches. Radiator area limitations and heavy shielding shift the optimum diameter to the upper end of the range. Variations of the optimum converter diameter with respect to isotopes are relatively minor. Sensitivity of system specific weight to this factor is low, and use of the reference design value selected by Westinghouse, 1.75 inches, will result in negligible system penalty.

2.2.3 CONVERTER PRESSURE DROP

The sensitivity of system specific weight to this parameter is moderate - approximately 100 lb/KWe per psi. Reference design modules have pressure drops of only 0.19 psi which is largely due to the orifices that are included in the modules to prevent flow maldistributions. At this level, changes in pressure drop by a factor of two would have a negligible effect on system weight.

2.2.4 CONVERTER VOLTAGE

To meet a load requirement of 28 vdc, the reference module voltage of 7 volts is very nearly optimum, and the system is relatively insensitive to this parameter over the range of module output voltages examined (3.5 to 14 volts). The fixed voltage output requires that low-efficiency power conditioning equipment be used to operate the system electromagnetic pumps; however, the pumping power requirements over the range considered was only about 3 percent of system power, considering pump and busbar inefficiencies, and the effect on the system is minor. Thus, although the pump power conditioning requirement is a disadvantage, it is not serious in systems of this type that are necessarily optimized for low-pressure drops.

2.2.5 RELIABILITY

The tubular module geometry presently does not provide the capability of "laddering" the individual couples; hence, the module itself must be taken as the basic reliability element. To provide a system reliability on the order of .95 for a 2 KWe system, the converter module reliability must exceed .997 or redundant T/E modules must be used. The

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reliability requirements may be lowered with minimum penalty if the system is overdesigned to include one or more excess modules. The degree of fineness in which modules may be added is affected by the electrical arrangement (e. g., one module for 7 volt arrangement, two modules for 14 volt arrangement, and four modules for 28 volt arrangement). In addition, the system total weight is increased in almost direct ratio to the increase in power output selected in the overdesign. These factors combined indicate that systems which emphasize parallel electrical arrangements of modules and require power conditioning from 7 or 14 volts to 28 volts, and T/E modules of shorter length and lower electrical output, would allow greater flexibility in the selection of the amount of overdesign necessary to meet the system reliability requirements.

2.3 RADIOISOTOPE HEAT SOURCE AND SHIELD

The study of Large Radioisotope Heat Sources* was reviewed to determine the heat source configuration, from those previously considered, that would most satisfy the requirements for integration with the thermoelectric converters in a 2 KWe power system for the AAP. The "torus" configuration identified in Section 4 was selected and modeled analytically for incorporation into the power system optimization program. This program was utilized to parametrically examine the various power systems and select the 2 KWe design points with the results discussed in the following paragraphs.

2.3.1 CONTRIBUTION TO SYSTEM WEIGHT

The percentage of total system weight attributable to the shield and heat source is given in Table 2-3 to show the significant contribution to system weight. The values tabulated will vary somewhat with the particular operating conditions specified, particularly capsule and T/E module inlet temperature, (those shown are for the conditions listed in Figures 7-5, 7-6, 7-18, and 7-19); however, the general conclusions will be unaffected.

* Preliminary Design and Safety Studies of Large Radioisotope Heat Sources for Space Power , GE Document No. 65SD4508, Volumes I and II, January 24, 1966.

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Table 2-3. Weight Percentages for Heat Source and Shield, 2 KWe System

	Shielded Systems				Unshielded Systems			
	SiGe		PbTe		SiGe		PbTe	
	Po-210	Pu-238	Po-210	Pu-238	Po-210	Pu-238	Po-210	Pu-238
Fraction of System Weight due to Heat Source (%)	14	41	12	41	37	62	27	52
Fraction of System Weight due to Shield (%)	62	35	55	22	--	--	--	--

In the Pu-238 fueled shielded and unshielded systems, the heat source contribution ranges from 41 to 62 percent, respectively. The shield contribution of an additional 22 to 35 percent will increase the combined contribution to 63 to 76 percent of the total weight. With this large weight fraction, system perturbations that affect the heat source, such as capsule temperature, design radiation dose rates, T/E module inlet temperature, T/E module coolant ΔT , and T/E module efficiency, will sharply affect total system weight.

In the case of the shielded Po-210 fueled systems, the combined shield and heat contribution ranges from 67 to 76 percent, and the same conclusion is applicable as for a Pu-238 shielded system. However, the system weight sensitivity to heat source changes is materially reduced in the unshielded system, as the weight contribution is only 27 to 37 percent.

2.3.2 VEHICLE INTEGRATION

The requirements to provide access for loading the heat source into the vehicle power system immediately prior to launch and to provide access for the possible ejection of the heat source throughout the mission are important factors that should be considered early in the power system/vehicle integration. In the LEM Shelter mission examined in this study, significant modifications to the Saturn shroud would be necessary to meet these requirements.

The weight of heat sources for 2 KWe power systems range from a low of 300 lb with Po-210 to a high of 1100 lb with Pu-238. With the addition of shielding, the combined heat source and shield weights range from 1200 to 2500 lb. This factor, combined with the volume

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requirement of 15 to 40 ft³, impose limitations on the possible locations within the vehicle. In particular, the heat source and shield must be located near the vehicle primary structure to provide the necessary structural support, and in a position with the necessary free volume. In the LEM Shelter, these requirements can be met by locating the assembly within one of the octagonal bays of the LEM descent stage as illustrated in Figure 2-1B.

2.3.3 NUMBER OF HEAT SOURCES

For a 2 KWe power system, thermal outputs of about 40 KWt (end of life) are required. The physical dimensions of heat sources at these power levels are such that it appears advisable to provide two smaller heat sources for greater ease in handling and for greater flexibility in integration.

2.3.4 PRESSURE DROP IN HEAT SOURCE

Evaluations indicate that with NaK as the coolant medium, the weight of the heat source will be little affected by limitations on coolant pressure drop. Generally, the heat source may be designed for a pressure drop that is only adequate to prevent flow maldistributions (estimated at 0.1 psi) without penalty to the system.

2.3.5 SELECTION OF RADIOISOTOPE

Pu-238 and Po-210 fuels may be successfully employed with the compact T/E modules to accomplish the same short-duration missions. In particular, both fuels are satisfactory for the LEM Shelter mission considered herein, and, in fact, the Pu-238 fueled power system is lower in weight. Thus, factors other than the obvious differences in half-life should be considered in the selection of the fuel for a mission. Three such factors -- weight, cost, and safety -- are discussed below.

The weight of the systems, particularly the Po-210 systems weights which are tripled by the shield, is significantly affected by the shielding requirements. For the 2 KWe LEM Shelter mission described herein, the Pu-238 systems result in lower systems weights by 600 pounds. In contrast, if the mission required no shielding, the Po-210 system would be lower by 400 pounds than the Pu-238 system. Generally, for the short-duration missions,

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Pu-238 will result in minimum total weight when shielding requirements are high, and, conversely, Po-210 will result in minimum total weight when shielding requirements are low.

The specific energy cost of Pu-238 and Po-210 are in the ratio of about 40 to 1 (\$1,000,000/KWt to \$25,000/KWt), which would indicate a higher cost of electrical power from a Pu-238 fueled system. However, these costs are not directly comparable because of the differences in their half-lives. A simple cost model which applied "use," "interest," and "insurance-against-loss" fees to the Pu-238 in a manner similar to that developed in the use of U-238 in conventional power plants was used in this study to compare the cost of system fueled with Po-210 and Pu-238. On this basis, which recognizes that the Pu-238 fuel is a reusable resource, the ratio of costs is reduced to the range of 4:1 to 8:1, excluding the additional complexities required in ground handling equipment for Po-210.

It is expected that a Pu-238 system will be more reliable and safer because of two inherent differences between the fuels. First, the Pu-238 system does not require a power flattening system and, thus, its inherent reliability will be greater. Second, the PuO_2 fuel form is superior to GdPo and, thus, the system inherent safety will be greater.

2.3.6 DEVELOPMENT PROGRAM

A brief comparison of the relative improvements required in technology for the isotope heat source and the two compact converters indicates that the development of the heat source will likely require the greatest increase in the state of the art. A more costly program with a development cycle of about 4 years is expected.

2.4 POWER SYSTEM AND INTEGRATION FACTORS

2.4.1 PUMPS

DC conduction pumps are selected for use with the T/E power system because of the ready availability of dc power, relative ease of integration with the system, and their demonstrated simplicity and reliability. Permanent magnet pumps are used where operating temperatures

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are below 600°F, and series excited pumps are used for high-temperature applications. Pump weights account for only a very small fraction of system total weight (less than 2 percent at 2 KWe). Increases in EM pump efficiency above the nominal values used in the studies (7 to 10 percent) would not reflect in major reductions in system weight.

2.4.2 INCREASING SYSTEM RELIABILITY FROM .95 TO .99

The cycle arrangements shown in Figure 2-1A are expected to result in systems with a reliability of .95 with successful development. Analyses indicate that increased system reliability, from .95 to .99, can most economically be achieved by the addition of selected redundant components. The addition of redundant pumps in all loops and a redundant shorting regulator will provide the desired increase in reliability for a weight increase of only about 5 percent.

2.4.3 BUS BARS

Power for the EM pumps is transferred from converters, or power conditioning if used, via silver conductors. The optimum transmission efficiency for these conductors is found to be about 50 percent, and the system shows very little sensitivity to this transmission efficiency over the range of efficiencies from 30 percent to 70 percent. Bus bar weights constitute a very small fraction of the system total weight.

2.4.4 PRESSURE DROP AND PARASITIC POWER REQUIREMENTS

The optimizations indicate that minimum weight systems are attained with low pressure drop coolant loops (0.3 to 1.0 psi total per loop) and low pumping power requirements (about 1 watt hydraulic per 300 to 600 watts electrical). This result is to be expected since the T/E module is a low-efficiency device and since the system weight is dominated by the heat source and shield assembly weight which is directly proportional to the gross power output. An optimum weight is thus attained by adjusting the system to minimize the thermal power requirements.

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2.4.5 SHIELD WEIGHT

The LEM Shelter mission examined in this study places the astronauts in close proximity to the heat source for a period of 14 days. The shield weights are based on evaluations that indicate that about 82 percent of the astronauts' time could be spent evenly divided at locations 1 and 3 meters from the heat source, and upon the assumption that a dose of 20 rem will be received. At separation distances this low, shield weights can be significantly affected by changes of separation distance of only one or two feet which could result with better definition of astronaut duty stations and/or a change in the sleeping location. Accordingly, the shielded system specific weights listed herein should be used with recognition that this mission is one that would be classified as requiring heavy shielding. For other missions, the unshielded specific weights should be used and shielding added as required.

2.4.6 AUXILIARY HEAT REJECTION

In the LEM Shelter mission, the LEM spacecraft is enclosed by the shroud which is planned for ejection 2 hours after launch, but which may not be ejected until ~9.5 hours after launch. Provision for auxiliary heat rejection during this period is required, and evaporative systems result in a prohibitive weight (greater than 1380 pounds). Evaluations indicate that a heat pipe radiator system can provide the necessary heat rejection; however, significant modifications to the Saturn shroud (Saturn LEM Adapter-SLA) would be required.

In addition, modifications to the shroud would be required to provide for the loading, and for the unrestricted emergency ejection, of the heat source from the vehicle in the event of an abort. These modifications would require serious evaluation early in the program.

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2.4.7 DEGRADED MODE PERFORMANCE

The use of completely redundant power systems, each rated at a fraction of the desired power level, provides a reliable and economical means of incorporating degraded mode capability. For a nominal 2 KWe design, the optimal arrangement was found to be dual 1 KWe systems with redundant pumps and shorting regulator in each loop. This additional complexity results in a system weight increase of 12 to 20 percent, depending upon the isotope and converter used. The estimated reliabilities achieved with this arrangement are .99 for producing 2 KWe throughout the mission and .99998 for producing at least 1 KWe for the same length of time.

2.4.8 RADIATORS

An important conclusion resulting from the parametric studies is that the optimum radiator inlet temperatures fall within the limits of aluminum radiators. Optimum temperatures varied from 400°F to 585°F, depending on converter type, fuel, shielding, and radiator area limitations. The fraction of total system weight attributable to the radiators is dependent on the system configuration and constraints and is generally in the range of 15 to 35 percent.

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3. STUDY GUIDELINES AND MISSION DEFINITION

To assure credibility and realism in the parametric and design point evaluations of this study, the AEC gave initial guidance for the selection of one of the earth orbital AAP missions for use in the vehicle integration studies and for definition of mission parameters. These reference design guidelines are summarized in Table 3-1.

Table 3-1. Reference Design Guidelines

Mission Lifetime	
For Po-210	90 days in orbit, allow 14 days launch pad hold time
For Pu-238	2 years
End-of-Life Power Level	2 KWe
Mission Class	Manned Earth Orbit (Saturn V)
Mission Hardware	Apollo Applications Program
Power Conversion	Compact Thermoelectric Converter PbTe - Westinghouse SiGe - RCA
Year of Launch	1972
Re-entry Mode	Intact
Reliability Criteria	Full Power: .95 at 50% confidence
Overall Power System	25% rated power: .98 at 50% confidence

A review of the present AAP Mission Plan indicates that a mission exactly compatible with these guidelines is not planned. However, such a mission could be synthesized in the evolving AAP Mission Definition, or the guidelines could be modified slightly to allow

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selection of one of the presently defined missions. As discussed below, one of the planned AAP missions was selected with AEC approval.

3.1 AAP MISSION DESCRIPTION

The AAP missions are divided into the various categories listed in Figure 3-1. The categories are:

- Group, referring to the overall operational area
- Family, referring to major operational characteristics
- Experiment class, referring to the generic experiments aboard
- Key orbit parameters
- Manned flight duration
- Flight assignment

Figure 3-1. AAP Mission Summary

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The "near-28.5 degree inclination rendezvous" missions and polar orbit missions are performed with the Saturn IB booster. All other mission families utilize the Saturn V booster.

3.1.1 NEAR-28.5 DEGREE INCLINATION RENDEZVOUS MISSIONS

This family of missions has the primary objective of demonstrating and developing space operations and technologies. The mission durations extend from 28 to 90 days. Twenty-eight-day missions are made possible by a single rendezvous of two standard Command and Service Modules (CSM) each having a nominal lifetime of 14 days. Ninety-day missions are accomplished by rendezvousing three CSM's with uprated lifetimes of 30 to 35 days. The modifications involved in uprating the CSM are primarily increasing of reaction control system (RCS) and cryogenic tankage volumes. The experiments will be placed aboard a Lunar Excursion Module Laboratory (LEM/LAB). The LEM/ LAB is essentially the LEM pressure vessel and subsystems minus the engines and propellant tankage.

Launch operations will be conducted from Kennedy Spacecraft Center (KSC) with a nominal mission orbit that is circular at 200 nm altitude and with orbit inclinations of 28.5 degrees (± 4 degrees). The exact inclination for each mission will be planned to facilitate rendezvous operations which are sensitive to orbit inclination.

Abort operations reduce to two types: ballistic aborts and aborts from orbit. In both cases the LEM/LAB included in the configuration would be abandoned to enter the atmosphere ballistically.

The 90-day rendezvous missions establish the highest sustained power requirement for experiment operations over the longest period of any of the defined AAP missions.

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3.1.2 POLAR ORBIT MISSIONS

The objectives of this family of missions are:

- Space operation/science
- Remote surface sensing.

The nominal mission durations, which are accomplished by rendezvous in the polar orbit, are 14 to 45 days. Spacecraft modifications to increase onboard RCS and cryogenic storage volumes will uprate the CSM lifetime to the required value. The LEM/LAB will be the primary location of experiments and will provide the necessary environmental and power support.

Launch operations will be conducted from KSC with nominal mission altitudes from 120 to 200 nm. A typical launch ground track is shown in Figure 3-2. Note that the impact points in case of abort largely avoid both inhabited land areas and major shipping lanes.

The power requirements for this family of missions are typical of radar applications which include high peak loads approaching 5 KWe and relatively low average power.

3.1.3 SYNCHRONOUS ORBIT MISSIONS

The objectives of the synchronous orbit missions include:

- Space operations/technology
- Astronomy
- Space applications.

The missions range from 14 to 45 days, and the longer missions are accomplished with a single CSM/LEM-LAB modified to increase the volumes of RCS and cryogenics aboard. The LEM/LAB is the primary experiment support module.

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Figure 3-2. Ground Trace of a Typical Polar Orbit Launch Trajectory

The vehicles are launched from KSC into a nominal circular 100 nm orbit, and the Saturn-IVB is utilized to kick the spacecraft into a Hohmann transfer to the mission orbit altitude of 19,350 nm. The Service Module (SM) propulsion system provides the circularization thrust at mission altitude. For a mission orbit inclination of 0 degrees, a plane change of 28.5 degrees must be made. This propulsion requirement is divided between the Saturn-IVB and the SM to take advantage of the large ΔV capability of the Saturn-IVB. The SLA

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and Saturn-IVB are jettisoned immediately after ejection from the 100 nm orbit and the LEM/LAB is redocked.

After synchronous abort circularization, the LEM/LAB will be in a long-term stable orbit. If abort occurs prior to circularization and after 100 nm orbit ejection, the LEM will be placed in an elliptic orbit that will circularize rapidly and eventually decay to LEM/LAB re-entry.

Power requirements for this type of mission are intermediate to those previously discussed.

3.1.4 LUNAR POLAR ORBIT MISSIONS

The objectives of the lunar polar orbit missions are the remote sensing and evaluation of the total lunar surface. Mission durations are either 14 or 35 days for the missions planned, and the CSM configurations are nominal Apollo types for the 14-day missions and are modified by increasing RCS and cryogenic volumes for the 35-day missions. The LEM/LAB is the primary experiment support module; however, the ascent stage propulsion system is retained for backup propulsion capability. The operational sequence of events are identical to the basic Apollo Manned Lunar Landing (MLL) mission until after translunar injection. The outbound orbit transfer plane is twisted so that injection occurs in a 44 nm circular polar orbit instead of the normal Apollo equatorial orbit at the moon. The transfer trajectory is not a free-return type. Because of payload implications, transfer times are in the order of 100 hours; hence, for 14-day lunar survey missions, the time spent in lunar orbit is approximately six days. For the 35-day mission orbit time, the time spent in lunar orbit is about 28 days, or one lunar orbital period. A 14-day mission will survey almost half of the lunar surface, and a 35-day mission will provide redundant coverage over the total lunar surface.

An abort after translunar injection will place the LEM/LAB into a solar orbit or a high perigee earth orbit, due to the lunar perturbation, as the LEM/LAB passes behind the moon. An abort after lunar orbit injection would place the LEM/LAB in lunar orbit where it would eventually decay and impact.

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The power requirements for this mission are typical of radar applications, high peak power loads, and a low average load.

3.1.5 LUNAR SURFACE MISSIONS

The objective of this family of missions is the detailed exploration of the lunar surface which is accomplished by two types of missions: (1) a normal Apollo MLL Mission with an up-graded experiment load is flown (this type of mission allows 2 to 3 days of intensive exploration near a lunar landing site); and (2) a LEM shelter/Taxi mission can be flown for a rendezvous on the lunar surface of two modified LEM vehicles that can support a 14-day surface exploration period.

The LEM Shelter/Taxi missions consist of the following sequential operations.

- a. Launch of a CSM/LEM shelter using a Saturn-V
- b. Delivery of the LEM shelter to lunar orbit by the CSM
- c. Delivery of the unmanned LEM shelter to the lunar surface under CSM control
- d. Return of the CSM to earth with the first crew
- e. Unmanned standby of the LEM shelter for 90 to 120 days on the lunar surface
- f. Launch of a CSM/LEM taxi using a Saturn-V
- g. Injection of CSM/LEM taxi into lunar orbit
- h. Landing of LEM taxi on the lunar surface at the LEM shelter landing site
- i. Use of the LEM shelter for 14 days as an operations base by second crew
- j. LEM taxi lunar launch and rendezvous with the orbiting CSM
- k. Return of CSM to earth with the second crew
- l. LEM shelter continues to act as an unmanned lunar surface experiment station to failure.

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The trajectory of the LEM shelter/taxi mission is identical to the basic Apollo MLL mission except that non-free return trajectories will be used to increase the payload. Hence, the abort possibilities are similar to those of the lunar orbit survey mission. However, the probability of impacting the lunar surface is higher because the unmanned LEM shelter must land in an automatic mode, with no pilot available to supply control redundancy.

The LEM shelter has the most severe profile of the AAP missions. The Electrical Power System (EPS) must supply power to maintain the LEM shelter during the translunar transfer and for 90 to 120 days on the lunar surface; it must then support, for 14 days, the astronauts and the experiment performance. At the termination of the 14-day exploration period, the LEM shelter will provide electrical power support for unmanned surface emplaced experiments for a period governed by design lifetime.

3.1.6 AAP MISSION SCHEDULE

The approximate launch dates for the AAP missions are summarized in Figure 3-3. The earlier missions in 1968 and 1969 involving the Saturn IB (200 series) and the Saturn V (500 series) are not good candidates for the isotope/thermoelectric power system because it is likely that the system could not be developed and qualified in the time available. The large isotope heat source, with an expected development time of 3-1/2 to 4 years, is likely to be the limiting development item and, thus, missions compatible with this development cycle will occur in late 1970's and onward.

Of the missions in this time period, only those shown enclosed in blocks on Figures 3-1 and 3-3 have mission durations that would make an isotope/thermoelectric power system attractive compared to the present fuel cell or battery systems. The mission duration listed on Figure 3-1 for the lunar surface mission (Vehicles No. 519/520 and 524/525) is for the manned portion of the mission only and the power system must also operate during the lunar "wait" time of 90 to 120 days. Thus, operating time will range from 111 days to 141 days, exclusive of pad wait time, which is the greatest duration required in the AAP mission series.

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Figure 3-3. AAP Flight Mission Launch Schedule

An evaluation of the earth orbital missions (Vehicles No. 220-225) and the lunar surface missions (Vehicles No. 519/520 and 524/525) shows that both could utilize an isotope/thermo-electric power system and, therefore, that either could be selected as an example for the definition of the mission parameters and for use in the integration studies. The lunar surface or lunar-taxi mission was selected because it appears to impose the most restrictive set of requirements on the power system. In particular:

- The lunar taxi mission is of sufficient duration that either Pu-238 or Po-210 may be utilized and, thus, a direct comparison of the two systems may be made. In addition, the mission lifetime, which is presently limited by the fuel cell power system, may be extended with Pu-238.
- The degree of flexibility in the choice of location for the power system within the Apollo hardware components is reduced as the system must be placed within the LEM.

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- The size of the LEM is such that the isotope must be located within a few feet of the manned cabin and the shielding required is relatively high.
- The LEM is enclosed by the Apollo shroud for approximately 2 hours after launch and special provisions are required for heat rejection from the power system during this interval.
- The power system must operate in a greater number of environments, including:
 1. Earth wait
 2. Launch
 3. Earth orbit
 4. Lunar surface
- The variation of sink temperature from lunar day to night will impose power transients on the system.
- The LEM vehicle has a restricted area for radiator systems ($\sim 180 \text{ ft}^2$ maximum).

It was concluded that if these limiting conditions could be met in the integration studies, there would be reasonable assurance that the power system would be satisfactory for other missions.

3.2 DESCRIPTION OF LUNAR TAXI MISSION

The Lunar Shelter/Taxi Mission involves two spacecraft launches. The first will deliver a modified LEM shelter to the surface of the moon. The shelter, which can be stored for 90 to 120 days, will contain experiment equipment and life support for two men for 14 days of lunar exploration. Approximately 90 days later, the second launch will deliver the LEM taxi and the lunar exploration crew. The taxi is a slightly modified LEM, capable of ferrying two men from a lunar orbiting CSM to the lunar surface, and back again, to rendezvous with the CSM.

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3.2.1 CONFIGURATIONS

The launch vehicles used for both launches of this mission type will be the Saturn V. The spacecraft for the LEM-Shelter portion of the mission will be the standard CSM; a modified LEM capable of supporting the lunar surface exploration for 14 days and withstanding a 3 to 4 month lunar surface storage period following delivery and prior to activation; a Launch Escape System; and spacecraft LEM adapter.

The spacecraft for the LEM-Taxi portion of the mission will use a CSM and a LEM-Taxi essentially the same as the basic manned lunar landing LEM, but with provision for storage in a standby state for up to 14 days.

3.2.2 OPERATIONS

The LEM shelter will be delivered to lunar orbit by a standard CSM. The crew of the CSM will land the unmanned LEM shelter at the designated site automatically and establish the LEM shelter in its storage mode. After a minimum duration stay in lunar orbit, the CSM will return to earth, re-entering at the Pacific Recovery Area (PRA). This sequence of operations is illustrated in Figure 3-4.

At a later launch opportunity, the spacecraft, consisting of the LEM-Taxi and a CSM, will be placed in a lunar orbit compatible with landing at the shelter site. The LEM-Taxi, manned by two astronauts, will then land in the nominal Apollo mode. The LEM-Shelter is activated and checked out. If the shelter has withstood the storage period within design limits, the lunar surface exploration period is initiated and the LEM-Taxi is placed in standby storage. This sequence of operations is illustrated in Figure 3-5.

Exploration of the lunar surface will be conducted at the landing site (Moltke B site) during the 14-day lunar stay period. The exploration involves a fairly wide range of measurements as shown by the experiment load summary listed in Table 3-2.

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Figure 3-5. LEM Shelter Taxi Mission, Part B - Taxi Delivery

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Table 3-2. Experiment Load Summary

Experiment Site	Experiment Category/Abbreviated Title	Total Weight (lb)	Volume (ft ³) (3)
Moltke B Site Experiment Support	Topographical Survey	125 0	21
	Geological Survey, and Erosion	79 0	
	100-foot Drill	200 0	
	10-foot Drill	30 0	
	Laboratory LEM (Geology)	17 0	0 3
	Gravity	13 0	
	Magnetic	8 8	
	Seismic	239 8	41 8
	In Situ	18 1	
	Core Hole Logging	15 8	0 6
	Nuclear	34 4	
	ESS Emplaced Scientific Station	300 0	4 1 60-80
	Astronomy	112 1	
	Photo and Radiometry (Multiband)	85 8	
	Surface Mobile Vehicle	1000 0	
	LSE Life Support Equipment	310 0	
	Astronaut Hazards	6 2	
	Equipment Data Processing System	55 0	
	Power Expendables	175 0	
	Totals	2824 4	
	Spacecraft Capability	2500 0	250

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3.2.3 LEM SHELTER SPACECRAFT WEIGHT

The first LEM delivered to the moon will be modified to serve as a lunar shelter for the astronauts with the weight changes summarized in Table 3-3. The EPS weight is listed as 3461 lb. This fuel cell power system is designed to provide an average power of 517 watts to power primarily the Environmental Control System (ECS) during the lunar wait time and an average power of 663 watts during the 14-day mission.

3.2.4 LEM SHELTER POWER REQUIREMENTS

In addition to supporting the spacecraft, the power system must also supply the experiments. As shown in Table 3-4, the power levels of the individual experiments are low with the exception of the hole digging experiment. The experiments are usually limited to those of low power because of the limited energy capacity of the fuel cell system. With the greater energy capability of the isotope/thermoelectric system, the experiment mix would likely be modified.

The experiment energy requirements for each day and for the mission are summarized in Tables 3-5 and 3-6, respectively. It is apparent that the energy requirements are well within the 2 KWe power level specified for this study. Generally, an excess of power will be available.

3.2.5 LEM SPACECRAFT DESCRIPTION

The LEM consists of two stages as shown in Figure 3-6, the Ascent Stage and the Descent Stage, which are joined together by explosive bolts. The composite of the stages provides the necessary work area for the astronauts and provides continuity of systems and sub-systems. Connection between the stages is provided by interstage umbilicals. Both stages will function as a single unit during lunar orbit, descent, and landing on the lunar surface.

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Table 3-3. Weight Changes to LEM for LEM Shelter Mission

Grumman	Ascent	Descent	Total	Changes	New Net Weight
Structure	1158	1274	2432	+ 700	3132
S&C	74	14	88	- 114	280
N&G	278	28	306		
Crew Provisions	690	0	690	+ 150	840
ECS	321	361	682	- 800	
EPS	774	675	1449	+2130	3461
Instruction	270	175	445	- 170	275
Propulsion	683	1580	2263		2263
Reaction Cont. Sep.	419	0	419		419
Communication	101	14	115		115
Control and Disp.	207	0	207	- 105	102
Landing Gear		560	560	- 570	560
Propellant	4908	16465	21373	-5244	15559
Preusage Storage				+ 800	+800
Totals	9883	21146	31029	-3223	27806
Experimental Payload (Including Spacesuits - 280 lb)					
				+ Payload	2500
				(including spacesuits)	30306
Mission No. 6 (519) Summation:					
			Subsystems	3035	
			Expendables	21079	
			Structure	3692	
			Experiments	<u>2500</u>	
			Total	30306	
Reference: <u>Apollo Space Vehicles Weight Performance Prediction Memorandum</u> , Volume III, Spacecraft Book III, Block II Stages and Modules, 14 May 1965 (78). Bellcomm Changes from LEM Derivatives, 29 January 1965 (4).					

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Table 3-4. Experiment Power Requirements

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Table 3-5. Experiment Energy Requirements per Mission Day

Table 3-6. Experiment Energy Requirements for Surface Activities in Vicinity of Shelter

Experiment	Power Required (watts)	Operating Time (hr)	Energy (watts-hr)	Days Monitored
100-Foot Drill Hole	3500	16	56000	3, 4, 5, 6, 7, 8, 9
X-Ray (Phase II)	10	1	10	3, 12
Optical (Phase II)	2	2.75	5.5	5, 8, 13
Radio Astronomy (Phase II)	8	3.16	25.28	10, 13
Core Hole Logging				
Nuclear	52	0.5	26	12
Sonic Velocity	N/A	1.5	-	11
Electrical Induction	2	0.5	1	12
Seismic Refraction	12	N/A	-	6, 7, 9
Local Site Survey	75	0.5	37.5	2
LEM/LAB (Geological Analyzing)	5	N/A	-	N/A

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Figure 3-6. LEM Ascent and Descent Stages

The approximate dimensions of the assembled LEM, front, side and top views, are shown on Figure 3-7. The Ascent Stage is the manned portion of the LEM which will serve as living quarters for the astronauts during the 14-day lunar stay. The cabin consists of the Crew Compartment area and a portion of the midsection. A controlled habitable environment is provided within this pressurized area as well as a crew station, equipped to permit crew monitoring and control of all aspects of spacecraft performance.

In addition to the pressurized Crew Compartment, the Ascent Stage is comprised of an unpressurized Aft Equipment Bay and houses or mounts the following:

- The Ascent Engine and its propellant storage tanks and feed system
- The Reaction Control System and related tankage and feed system
- A portion of the Environmental Control Subsystem

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Figure 3-7. LEM Dimensions

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- d. Part of the Electrical Power Subsystem
- e. Stowage Compartments
- f. Windows and Hatches
- g. Radar and Communications Antennas
- h. The Flight Crews Instruments and Controls.

The Ascent Stage's structural makeup is divided into five structural areas; the Crew Compartment, Midsection, Aft Equipment Bay, tank and equipment mountings, and the outer skin and insulation. Aluminum alloys are used in the construction of the Ascent Stage with some titanium used for bracketry and fasteners.

The Crew Compartment Section is constructed as a pressure tight unit, approximately 92 inches in diameter. The front face assembly incorporates openings for two triangular windows and the ingress/egress hatch. A small window, located in the compartment's curved shell directly over the Commander's Crew Station, provides the necessary visibility for docking maneuvering. The forward RCS Engine Clusters are mounted to each side of the Crew Compartment by means of trusses bolted to the front face bulkhead and a longeron located at the compartment's maximum breadth. Additional external mountings are secured to the compartment structure to support the rendezvous radar and S-band antennas.

The Descent Stage of the LEM is the unmanned portion of the vehicle and contains all of the equipment necessary for lunar landing. The Descent Stage contains or mounts the following:

- a. The Descent Engine, its tankage and propellant distribution system
- b. The Landing Radar Antenna
- c. ECS Oxygen and Water Tanks
- d. The four Descent Batteries

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- e. Scientific Equipment
- f. The four Landing Gear Legs (on outriggers mounted externally to the Descent Structure).

The primary load carrying structure of the Descent Stage consists of two pairs of parallel beams arranged in a cruciform, plus upper and lower decks and end enclosure bulkheads. The beams, decks, and bulkheads are of the conventional skin and stringer construction formed from aluminum alloy.

The main beams form the center section and tank bay areas. These are centered along the Z and Y axis. The diagonal enclosures, or bays, formed between the beams are known as quadrants. Location of equipment and tanks are referenced to the various quadrants and they are so numbered for ready reference.

Quadrant I houses spare batteries.

Quadrant II area houses a water storage tank for the ECS subsystem and the scientific equipment. Scientific equipment is accessible to the crewman while on the lunar surface by means of a removable cover panel. The landing radar antenna is externally mounted on the lower bulkhead in this area.

Quadrant III area houses the cryogenic helium storage tank for the main propellant pressurization system and a gaseous oxygen storage tank to supply oxygen to the ECS subsystem.

The EPS subsystem is included within the Quadrant IV area.

At earth launch, the LEM is within the SLA which is between the CSM and the Saturn-IV booster. The SLA has an upper and lower section. The outriggers, to which the landing gear are attached, provide the attachment points for the LEM to the SLA lower section.

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Before transposition, the upper section of the SLA is explosively separated into four segments. These segments, which are hinged to the lower section, are released, separating the SLA and booster from the LEM.

3.2.6 LEM THERMAL INTERFACE REQUIREMENTS

The isotope/thermoelectric power system must conform with the thermal limits specified for the compartment in which it is located. These allowable internal compartment temperatures listed in Table 3-7 are generally low (0° to 160° F) which will require that the power system be designed for a low surface temperature to minimize thermal leakage to the compartment.

Table 3-7. LEM Operating Temperatures

	Launch	Translunar Coast	LEM Descent	Lunar Stay
Cabin (uncontrolled)	$0 - 130^{\circ}$ F	$0 - 130^{\circ}$ F	$0 - 130^{\circ}$ F	$0 - 130^{\circ}$ F
Cabin (controlled) average local spots	-	-	$70 - 80^{\circ}$ F $50 - 90^{\circ}$ F	$70 - 80^{\circ}$ F $50 - 90^{\circ}$ F
Equipment bay (ascent)	$0 - 130^{\circ}$ F	$0 - 130^{\circ}$ F	$0 - 130^{\circ}$ F	$0 - 160^{\circ}$ F
Equipment bay (descent)	$0 - 130^{\circ}$ F	$20 - 100^{\circ}$ F	$20 - 100^{\circ}$ F	$0 - 160^{\circ}$ F
Fuel and Oxidizer	$40 - 100^{\circ}$ F	$40 - 100^{\circ}$ F	$40 - 100^{\circ}$ F	$40 - 100^{\circ}$ F
LEM external	$-65 - +270^{\circ}$ F	$-300 - +270^{\circ}$ F	$-300 - +270^{\circ}$ F	$-300 - +270^{\circ}$ F

3.2.7 CREW RADIATION EXPOSURE

In addition to radiation from the isotope, the crew will normally be exposed to:

- Van Allen Radiation
- Solar Flare Radiation
- Galactic Radiation.

Galactic radiation is expected to be about 0.45 rem/week; however, the contribution of the other two sources is variable with time and must be defined probabilistically. The Van Allen

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radiation belts center at altitudes of 2000 nm and 10,000 nm and their intensity is known within a factor of about three. There are no reliable prediction techniques for solar flares, but statistical averages can be obtained based upon the previously observed events in sunspot cycles. These data can be combined to indicate the probability of attaining a given dose as shown in Table 3-8 (not including the design dose from the isotope power system). Generally, the probability of exceeding 20 rems total dose is quite low, exclusive of the isotope dose.

The allowable design dose for the isotope heat source is assumed to be 25 rem for this study. Shielding required to achieve this dose is related to the time spent by the astronauts at their various duty stations relative to the location of isotope heat source. The No. 1 Crew which delivers the unmanned LEM to the Lunar surface occupies the positions shown in Figures 3-8 and 3-9 for the times noted. The No. 2 crew, which occupies the LEM Shelter for 14 days on the moon, occupies the vehicle and extra-vehicle positions noted in Figure 3-10. Relative positions of the crews with respect to the LEM Shelter and the duration of the missions makes it clear that the dose to the second crew will be limiting. For a shield designed to result in a dose of 25 rem to crew No. 2, the No. 1 crew will receive a dose significantly lower than 25 rem.

Table 3-8. Total Mission Dose Versus Probability

Dose* (Rads)	Probability in Transit	Probability on Moon (per day)	Probability on Moon (14 days)	Total Mission Probability
260	0.00055	0.0007	0.0098	0.0104
140	0.0049	0.0013	0.0182	0.0231
60	0.0082	0.0020	0.028	0.0362
20	0.0137	0.0027	0.038	0.0517
*Does not include dose from isotope				

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Figure 3-8. Duty Position for Crew No. 1 (Lift-off to Turnaround and Docking)

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Figure 3-10. Duty Position for Crew No. 2 (LEM Shelter Area)

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3.3 MISSION GUIDELINES

With the selection of the Lunar Shelter/Taxi Mission for this study, the original design guidelines listed in Table 3-1 were slightly modified and amplified with the result indicated in Table 3-9.

Table 3-9. Study Guidelines

• Mission Hardware	Apollo Applications Program	
• Mission Class	Manned Lunar Surface	
• Launch Vehicle	Saturn V Vehicles No. 519/520 and 524/525	
• Mission Lifetime for Po-210 and Pu-238	<u>Duration, days</u>	<u>Total Time, days</u>
Pad wait	14	14
Transit	5	19
Lunar wait	90-120	109-139
Mission	14	123-153
Post-mission (Pu-238 only)	To failure	
• Year of Launch	1970 and 1971	
• End-of-Life Power Level	2 KWe	
• Power Conversion	Compact Thermoelectric Converter PbTe - Westinghouse Si Ge - RCA	
• Re-entry Mode	Intact for accident	
• Reliability Criteria for Overall Power System	Full Power: .95 at 50% confidence 25% Rated Power: .98 at 50% confidence level	
• Present Fuel Cell EPS Weight	3461 lb	
• Present EPS Energy Capability	1340 kw-hr	
• LEM Power Requirements	<u>DC, W</u>	<u>AC, W</u>
Avg. Power (lunar storage)	501	
Avg. Power (mission)	636	17
Peak Power (mission)	1500	27
• Experiment Power Requirement (Moltke B Site)		
Peak Power		3500 W
Energy		58 kw-hr

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4. SYSTEMS ANALYSES AND RELIABILITY

This section describes the alternate system arrangements and system components which were considered for the reference system and discusses the reasons for selection of those used in the study. Also included are the reliability analyses for the reference system and the various system arrangements conceived to meet the increased reliability requirements.

In addition to the mission design guidelines discussed in Section 3, which affect the power system selections, the following assumptions were utilized in the system evaluations:

- Meteoroid penetration probability is adequately described by the Whipple 1963A criterion.
- The stress levels and strengths of the materials are accurately known, and are satisfactorily represented by normal distributions.
- All faulty welded joints are detected by inspection during manufacture.
- Thermoelectric degradation occurs in a predictable way.
- Failure rates are time-invariant.
- EM pump failure will not occur because of duct rupture.

4.1 SYSTEM CONFIGURATIONS

For the basic system design, certain requirements were established to serve as guidelines. The basic requirements of the coolant system include:

- Transfer heat from Large Isotope Heat Source (LIHS) to converter
- Transfer heat from converter to radiator
- Transfer heat from LIHS to power-flattening radiator in Po-210 system
- Meet reliability requirements

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- Allow for volume changes of coolant
- Provide pressurization
- Maintain LIHS and converter temperature within allowable limits throughout life.

The two candidate systems, designated the two-loop system and the regenerative system, considered are shown in Figure 4-1. The choice between these basic configurations was made on the basis of relative efficiencies, fuel loadings, and complexity. The two-loop system was selected for detailed analysis because:

- The efficiency of the regenerative system is lower because a finite log mean ΔT must exist across the heat exchanger; hence, more heat must be rejected from the main radiator and more heat must be delivered by the heat source for a given electrical power (e.g., for a typical ΔT of 25° F across the heat exchanger, the fuel loading is increased by 12 percent).
- The fuel loading of the regenerative system will always be higher for the same thermoelectric efficiency and electrical output.
- The weight of the regenerative system is increased by the greater shield mass resulting from the higher fuel loading and larger heat source volume.

The reference system configuration for Pu-238 fueled systems is illustrated in Figure 4-2 and that of Po-210 systems, with the additional power flattening loop, in Figure 4-3.

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* TYPICAL SiGe CONVERTER TEMPERATURES SHOWN AT BEGINNING OF LIFE

Figure 4-1. System Arrangements
(2-Loop and Regenerative)

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Figure 4-2. Basic Pu-238 System

Figure 4-3. Basic Po-210 System

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4.2 SUBSYSTEM ARRANGEMENTS AND COMPONENT SELECTION

4.2.1 POWER FLATTENING METHOD

The Po-210 systems require power flattening to provide sufficient end-of-life fuel to meet the electrical output requirements. To meet the end-of-mission heat source requirements, extra heat source capacity must be built into the system at the beginning of mission life. The power flattening loop disposes of this extra heat source capacity so that the amount of heat delivered to the thermoelectrics is constant. The heat to be rejected by this loop is greatest at the start of mission life; it decreases exponentially and approaches zero at the end of mission life.

The lightest and most compact active power flattening loop is achieved when the radiator uses the highest system temperatures available. As shown in Figure 4-3, the loop receives heat from the heat source by passing the working fluid through one set of the independent coolant channels in the heat source. The fluid passes through the power flattening radiator and is pumped back to the heat source. This general layout uses the heat source outlet temperature as the radiator inlet temperature which minimizes the loop weight and heat rejection area. This arrangement also allows the power flattening loop to be independent of the primary system so that control of the loop can be maintained without affecting the primary system.

Control of the power flattening loop is accomplished by varying the power delivered to the EM pump in that loop. By sensing the heat source outlet temperature, the pump power can be controlled to maintain this temperature within a given range. By reducing the pump power, the flow rate is decreased and the effective temperature of the radiator is lowered. This reduces the heat rejected from the radiator. Increasing the pump power will raise the effective temperature of the radiator and increase the heat rejection capacity of the radiator. This method can vary the heat rejected from the maximum at the be-

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ginning of life to the minimum which would exist due to natural convection with no pumping. Control of thermal losses below this point can be accomplished by valving to prevent the natural convection. This would reduce the heat loss in the power flattening loop toward the end of mission of life to the conduction heat leak in the piping between the heat source and radiator. This heat loss would be quite small and there would be almost no penalty in initial fuel loading.

The power is provided for the power flattening loop pump in a unique manner. The heat to be rejected decreases exponentially with mission time and is essentially parallel to isotope decay relationship. Thus, the required fluid pumping power in this loop will reduce even more sharply with time, and will equal zero at some time near the end of mission. Because the requirements for pumping power have this profile, it is not necessary to provide additional power supply capacity for the pump. It is possible to utilize the excess capacity provided in the converter to allow for thermoelectric degradation.

Thermoelectric degradation is considered in this system analysis by providing excess capacity in the converter at the beginning of life to meet the design power requirements at the end-of-mission. As a result, for most of the mission lifetime, it is possible to generate more net power than the design value. Since this excess power is greatest at the beginning of mission life and approaches zero at the end of life, it is available when the power flattening loop pump requires power. It is this excess power capability that is used to provide pumping power for the loop.

The loop is designed so that its pumping power requirements at the start of life are equal to the extra power provided in the converters to compensate for the degradation effects. Due to the shape of the degradation relationship and the pumping power requirements versus time, the extra power from the converter is always greater than the pumping power required. Thus, the power flattening loop pump power is essentially "free" because it is provided from power that is normally not utilized.

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4.2.2 SELECTION OF HEAT TRANSFER FLUID

For this application, liquid metals offer more advantages than either organics or water.

The temperatures are excessive for stability of organic coolants, while the pressures which would be developed with water are excessive. For the liquid metals, NaK containing 78 percent potassium is the optimum fluid. This selection is chosen since:

- A low melting point is essential to avoid the requirement to preheat the system (78 percent NaK melts at 10°F).
- While 78 percent NaK boils at 1440°F , thereby requiring a pressurized system, its vapor pressure is not a strong function of temperature. At 1550°F , which is approximately the highest anticipated operating temperature, the vapor pressure is only 25 psia. This characteristic is advantageous in selecting the system design pressure, which is established above the pressure corresponding to the temperature at which the isotope capsules are ejected from the heat source.
- An ideal liquid metal would remain in the liquid phase without pressurization above one atmosphere and also would not require preheating. This combination cannot be obtained for the temperature range of this cycle. Some examples are listed in Table 4-1. It is considered best to use the lowest melting point NaK composition because pressurization would be required in any case.
- NaK is compatible with stainless steel and Haynes-25; therefore, no corrosion problems are expected.
- NaK has excellent heat transfer properties, allowing the use of small components. While either Na or Li is better from an overall heat transfer standpoint, the preheating requirements outweigh the possible benefits.
- NaK can be pumped by electromagnetic pumps, although the pumping power is somewhat higher than with sodium.
- NaK is stable under radiation.
- NaK does not ignite spontaneously in contact with air unless its temperature exceeds 200°F . Consequently, fire hazard during filling operations is minimized.

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Table 4-1. Liquid Metal Melting/Boiling Point Comparison

Fluid	Melting Point (°F)	Boiling Point at One Atmosphere (°F)
Na	208	1621
K	152	1396
Li	371	2446
51% NaK	50	1505
56% NaK	35	1490
78% NaK	10	1440

4.2.3 SELECTION OF EM PUMPS

Three types of EM pumps were considered: helical induction, thermoelectric, and dc conduction types. The dc conduction pump was selected as most suitable for this application.

The dc conduction pump is slightly inferior to the helical induction pump in weight and efficiency for the size range of interest. However, the induction pump requires a dc to ac converter for power, and this additional device detracts from the weight and reliability of the induction pump.

The selection between the thermoelectric pump and the dc pump was influenced by the particulars of the system configuration. The thermoelectric pumps have an advantage in that an external power supply is not required. However, this advantage is offset by several application requirements:

- Either a view of space or a liquid coolant loop at low temperature must be provided to establish a ΔT across the thermoelectric elements.
- For the SiGe system, the hot loop temperatures are a minimum of 1300°F. Hence, hermetic sealing of the PbTe elements, or use of SiGe elements for the pumps, would be necessary. These approaches have not been proven for the thermoelectric pump.
- Since permanent magnet materials such as Alnico V are limited to temperatures of about 1050°F, cooling for the magnet of the thermoelectric pump is required. Note that electromagnet materials have a higher temperature capability; 1250°F

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for silicon-iron and 1600⁰ F for cobalt-iron magnet alloys. Therefore, a pump which is series-excited is not so limited by its magnet temperature.

- The thermoelectric pump is not easily controlled. The controlability is necessary to change the flow rate of the power flattening loop as the isotope decays.
- The weight of the thermoelectric pumps is high, even considering the bus connections and power supplies required for the dc conduction pumps.

By evaluation of the characteristics mentioned above, the dc pump was chosen. Table 4-2 lists performance and configuration data for some of the pumps considered in the study.

Table 4-2. Pump Characteristics

Type	Flow GPM	ΔP psi	Fluid	Pump Wt, Lb	Efficiency	Fluid Temp °F	Excitation Power, %	Efficiency PM
Helical Induction	16	30	K	26	10	1200		
	31	20	Li	33	13	1200		
	11	30	K	20	10	1200		
	16	3	K	3	11	1200		
	30	25	NaK	51	11	1200		
	31	10	Li	21	8.5	1200		
DC Conduction (series excited)	16	30	K	9	13.4	1200	10 2.4	15.4 12 7.2
	9.8	1.2 (with bus losses)	NaK	4.7	9	1425		
	31	20	Li	11	6	1200		
	11	30	K	13	15	1200		
	16	3	K	7	12	1200		
	16	3	K	6	3	1200		
	30	25	NaK	11	13	1200		
	31	10	Li	8	12	1200		
Thermoelectric PbTe Chromel Const	12	1	NaK	17	—	1200		
	13	1.6	NaK	45	—	1200		

Notes: Magnets of Alnico V limited to 1050°F in 1000 hours at 1022°F 5% change in magnetic strength

Thermoelectric pumps are not controllable by external means

Series excited pump magnet temperatures can be as high as 1600°F for CoFe magnets

The limitations on magnet temperature are such that while permanent-magnet pumps can be used in the cold converter loop, series-excited pumps are required in the converter hot loop and the power-flattening loop. A typical series-excited pump is shown in Figure 4-4.

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Figure 4-4. DC EM Pump

4.2.4 PUMP POWER CONDUCTORS

The selection of dc electromagnetic pumps necessitates the use of relatively large conductors to supply the low voltage power. To minimize the transmission losses without incurring undue weight penalties, it is desirable to use a material of low electrical resistivity and density. Further consideration must be given to the temperature/strength characteristics of the material since structural integrity must be maintained at elevated temperatures. In light of these factors, copper, silver and aluminum were considered candidate materials for this application. An analysis of the system constraints and material properties led to the selection of silver. Considerations leading to this selection are:

- The operating temperatures at the busbar terminations will very likely approach 600° F. This is too high for aluminum on a strength basis. Also, copper would require a protective coating to prevent serious oxidation while operating in the earth's atmosphere.

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- Silver has a somewhat lower resistance (96 percent that of copper) at the operating temperature considered.
- Silver has adequate strength at the temperatures involved.
- Silver can be sprayed with a high-emissivity coating such as iron titanate to improve its emissivity and enhance radiative cooling.

4.3 RELIABILITY CONSIDERATIONS

Consistent with the study guidelines, the Pu-238 and Po-210 systems were evaluated for the probability of supplying a minimum of 2 KWe over this mission which includes:

- a. A 30-day prelaunch period
- b. Boost, transit to the moon, and landing on the moon's surface
- c. A 90-to-120 day wait on the lunar surface for the arrival of astronauts
- d. A 14-day period of supplying power for various lunar experiments.

An objective of the analysis was that recommendations be provided for:

- a. Achieving a goal of .95 probability of supplying full rated power over the mission given that the estimate fell short of this value.
- b. With a more complex system, achieving a .99 probability of supplying full rated power over the mission
- c. Achieving a .98 probability of supplying at least 25 percent of full-rated power over the mission.

Reliability estimates for the two basic Pu-238 and Po-210 system configurations shown in Figures 4-2 and 4-3 are .9826 and .9700, respectively. It is clear that the simpler Pu-238 power system configuration of Figure 4-2 is the more reliable of the two systems. Additional complexity is incorporated into the Po-210 system (Figure 4-3) because of the necessity for a power flattening system to dissipate the excess heat generated by the Po-210 heat source.

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The reliability block diagrams for the Pu-238 and Po-210 systems of Figures 4-2 and 4-3 appear in Figure 4-5. These diagrams show that any single component failure will result in a failure of the entire system.

Figure 4-5. Reliability Block Diagrams for Pu-238 and Po-210 Systems

The reliability of each system, or probability of zero functional failures, is given by:

$$R(\text{Pu-238 System}) = R^2(\text{LIHS}) \cdot R(\text{Converter}) \cdot R(\text{EM Pump 1}) \cdot R(\text{plumbing; hot loop}) \cdot R(\text{EM Pump}) \cdot R(\text{plumbing; cold loop}) \cdot R(\text{Radiator; primary}) \cdot R^2(\text{Pressure Regulator}) \cdot R(\text{Shorting Regulator})$$

$$R(\text{Po-210 System}) = R^2(\text{LIHS}) \cdot R(\text{Converter}) \cdot R(\text{EM Pump 1}) \cdot R(\text{EM Pump 2}) \cdot R(\text{plumbing; hot loop}) \cdot R(\text{Radiator; Power Flattening}) \cdot R(\text{EM Pump}) \cdot R(\text{Plumbing; cold loop}) \cdot R(\text{Radiator; primary}) \cdot R^3(\text{Pressure Regulator}) \cdot R(\text{Shorting Regulator})$$

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The component reliability values are summarized in Table 4-3 and the computations and methods are presented in the following subparagraphs:

Table 4-3. Summary of Component Reliabilities

Component	Failure Criterion	Method of Analysis	Estimated Reliability (mission = 3200 hours)
LIHS	(a) Rupture at tubing weldment permitting loss of Nak. (b) Premature bursting of diaphragms in over-temperature sensor permitting fuel cask ejection.	Probability that applied stress at tube weldment does not exceed material strength was computed; R = .999999 per weld. Probability of .9999, for each diaphragm, of premature burst was computed. Ref: ER11862, Martin-Marietta Corporation.	.9984
Radiators	Same as (a) for LIHS leakage		.99994
Plumbing	Same as (a) for LIHS leakage		.99999
PM Pump	(a) Magnet deterioration (b) Loss of electrode connection, resulting in failure to pump fluid.	Failure rate of 0.3×10^{-6} failures/hour used in estimating reliability, (Ref: Document GE65SD4497A)	.99904
EM Pump 1	(a) Open coil (b) Same as PM pump, resulting in failure to pump fluid.	Failure rate of 1.0×10^{-6} failures/hour used in estimating reliability (Ref: Document GE65SD4497A)	.98678
EM Pump 2	(a) Same as for EM pump 1 (b) No output from Control Unit.	Failure rate of 4.1×10^{-6} failures/hour used in estimating reliability, (Ref: Document GE65SD4497A)	.98678
Converter (SiGe)	(a) Any triplet (group of 3) open circuit (b) 5% or more couples open circuit	Probability of no triplet failure and survival of 95%. Determine couple reliability based on 15,000,000 failure free test hours. (Ref: Document NYO-3582-1)	.99999
Pressure Regulator	Both bellows rupture permitting loss of fluid	Failure rate of $.7 \times 10^{-5}$ failures/cycle based on 100,000 failure free cycles. (Ref: Document NAA-5R-11732)	.99999
Shorting Regulator	No output	Failure rate of 3.1×10^{-5} failures/hour used to estimate reliability. Ref: (Document GE65SD418)	.99007

4.3.1 THERMOELECTRIC CONVERTER

The schematic electrical arrangement used in deriving these values for the RCA SiGe converter appears in Figure 4-6. Failure of this device is defined as: (1) any group of three couples (triplet) open-circuiting, or (2) a 5 percent or greater loss in output power (with no triplet failures).

Document NYO-3582-1 reports a total of 15,000,000 failure-free couple hours of testing. The failure rate of a couple is computed using the following relationship:

$$\lambda \leq \chi^2 \alpha_1^2 \left[\frac{F+1}{2T} \right]$$

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Figure 4-6. Reliability Block Diagram for SiGe Converter

where:

λ = Failure rate

α = 1-Confidence level

$2 [F+1]$ = Degrees of freedom

F = Number of observed failures

χ^2 = Value of chi-squared distribution

T = Total part testing hours

For a 50 percent confidence level and two degrees of freedom (F = 0),

$$\lambda \leq \frac{1.386}{2 \times 15 \times 10^6} = 0.046 \times 10^{-6} \text{ failure/hour}$$

The reliability of a couple is:

$$R (\text{Couple}) = e^{-\lambda t}$$

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where t = mission time = 3216 hours,

$$R (\text{Couple}) = e^{-0.046 \times 10^{-6} \times 3216} = .99984$$

Under the failure criteria established for the converter, its reliability is closely approximated by:

$$R (\text{Converter}) = \sum_{x=0}^W \binom{n}{x} P_1^{n-x} \cdot \left(P_{2-3} \right)^x = .99999$$

where:

n = number of triplets = 960 for Pu-238 system
= 530 for Po-210 system

The Westinghouse PbTe module is undergoing active development to produce a reliable, long-lived module. Although it is not significant, the data generated to date can be utilized to make a reliability estimate for the present module with the result described below. As expected, the reliability estimate based on the development data is very low. Generally, until additional operational data on modules more comparable to the expected final design is available, a meaningful reliability estimate for the module cannot be made.

The Westinghouse converter employs 16 modules, each module consisting of 66 thermocouples, to deliver the required power. Document NYOO-3584-1 reports the following life test data:

Module	Test Time (Hours)	Δ Power (%)
TEM-1, S/N-1	1989	-30
TEM-1, S/N-2	1987	-27
TEM-1, S/N-4	1512	-22
TEM-3, S/N-1	1366	-13

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The above represents 253, 598 couple-hours of testing where each module consisted of 37 couples. Using the method described above for calculating failure rate (which assumes that all failures are due to couple factors):

$$\lambda \leq 1.386/2 (254,000) = 0.27 \times 10^{-5} \text{ failures/hour}$$

The configuration of the Westinghouse converter is such that no couple open or short circuit is permitted. For a mission of 3216 hours, the reliability of the converter, or probability of zero couple failures, is estimated as:

$$R (\text{Converter; Westinghouse}) = e^{-0.27 \times 10^{-5} \times 1056 \times 3216} = .00012$$

where:

$$\lambda = 0.27 \times 10^{-5} \text{ failures/hour}$$

$$n = 1056 = \text{number of couples}$$

$$t = 3216 \text{ hours} = \text{mission time}$$

This estimate has no significance since it is based upon development data and, in addition, it is assumed that all failures are a result of couple failures. In fact, many failures can be traced to the difficulties of module assembly, which when eliminated, would not affect the inherent reliability potential of the module.

For computing the system reliability estimates, only the RCA converter was considered.

4.3.2 HOT LOOP EM PUMPS

The failure rate for the hot loop EM pumps were estimated at $\lambda = 1.0 \times 10^{-6}$ failures/hour for the power flattening loop pump (EM Pump 1) and $\lambda = 4.1 \times 10^{-6}$ failures/hour for the hot loop pump (EM Pump 2) (reference document GE 65SD4497A). For this failure rate, the reliability for the mission is:

$$R (\text{EM Pump 1}) = e^{-1.0 \times 10^{-6} \times 3216} = .99678$$

$$R (\text{EM Pump 2}) = e^{-4.1 \times 10^{-6} \times 3216} = .98678$$

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4.3.3 COLD LOOP EM PUMP

The failure rate of the permanent magnet cold loop EM pump was estimated at $\lambda = 0.3 \times 10^{-6}$ failures/hour (reference document GE 65SD4497A). Using the relationship in Paragraph 4.3.2, the reliability of the pump is:

$$R (\text{EM Pump}) = .99904$$

4.3.4 SHORTING REGULATOR

The failure rate of the shorting regulator was estimated at $\lambda = 3.1 \times 10^{-6}$ failures/hour (reference document GE 65SD4318).

Using the relationship in Paragraph 4.3.2, the reliability of the shorting regulator is:

$$R (\text{Shorting Regulator}) = .99007$$

4.3.5 PRESSURE REGULATOR

Document NAA-SR-11732, Volume II, reports a total of 100,000 failure free cycles of testing for the SNAP-10A regulator. Using the method in Paragraph 4.3.1 to determine failure rate and for a mission of 1 cycle, the reliability of the pressure regulator is:

$$R (\text{Pressure Regulator}) = .99999$$

where

$$\lambda = 0.7 \times 10^{-5} \text{ failures/cycle}$$

4.3.6 RADIATOR (PRIMARY)

The criterion for failure of this device and other devices in the system carrying fluid is rupture of any tube permitting loss of fluid. For purposes of this analysis, failure was assumed to occur most likely at joints and that the failure probabilities of the joints were statistically independent.

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The method of analysis assumes that the stresses imposed at the joints and the material strengths are normally distributed and that failure (rupture) will occur if a given joint experiences a stress beyond its capability or strength. This is illustrated in Figure 4-7 where the shaded area represents the intersection of stress and strength. The reliability of a joint is determined as follows:

$$X = \frac{M_S - M_L}{\sqrt{\sigma_S^2 + \sigma_L^2}}$$

where:

M_S = Mean strength of the material

M_L = Mean load at the joint

σ_S^2 = Variance of the material strength

σ_L^2 = Variance of the load

X = Number of standard deviations separating strength and load.

Figure 4-7. Stress-Strength Frequency Distributions

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The reliability for a given value of X is obtained from Figure 4-8.

The above method is presented in the "Structures Reliability Report," document ER 11862, The Martin-Marietta Corporation.

The primary radiator uses stainless steel tubing which is estimated to have a mean ultimate strength (tension) of 80,000 psi at the expected temperature and a variance of 20 percent was assumed for the material. A load of 600 psi is estimated with a variance of 20 percent. Under these conditions, a reliability per joint of much greater than .999999 is obtained. The total number of joints in the system is approximately 60. The reliability for the radiator is therefore given by:

$$R (\text{Radiator; Primary}) = (.999999)^{60} = .99994$$

Figure 4-8. Reliability vs Number of Standard Deviations Associated with Stress/Strength Distributions

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4.3.7 POWER FLATTENING RADIATOR

This radiator utilizes Haynes-25 for its tubing and experiences a temperature of approximately 1400°F. An $M_s = 45000$ psi with a $\sigma_s^2 = 15\%$ of M_s is estimated for this material. The loads are assumed to be the same as for the primary radiator and a total of 60 joints is estimated. The reliability per joint is much greater than .999999 for the strength and load relationship. Using .999999 for each joint, the reliability for the device is:

$$\begin{aligned} R (\text{Power Flattening Radiator}) &= (.999999)^{60} \\ &= .99994 \end{aligned}$$

4.3.8 LARGE ISOTOPE HEAT SOURCE

Using the method given in Paragraph 4.3.6 under the same conditions as for the power flattening radiator for a total of 1400 joints (estimated) the probability of non-leakage failure becomes:

$$\text{Pr (non-leakage)} = (.999999)^{1400} = .9986$$

Included within a LIHS is a temperature sensor consisting of a high pressure vessel with two diaphragms separated by an expansion fluid. If the temperature within the LIHS rises beyond a prescribed limit, the fluid expands and bursts the diaphragms permitting the gas to eject the fuel cask. Failure of this device is defined as premature ejection. For the diaphragms a ratio of M_s to M_L of 3.0 was selected and a 20 percent effective variance; i. e.,

$$\sqrt{\sigma_s^2 + \sigma_L^2} = 0.20 \times M_s .$$

Under these conditions, the reliability using the method in Paragraph 4.3.6 of each diaphragm is found to be:

$$R (\text{Diaphragm}) = .9999$$

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The reliability of the LIHS is

$$\begin{aligned} R (\text{LIHS}) &= P (\text{non-leakage}) \cdot R^2 (\text{Diaphragm}) \\ &= (.9986) \cdot (.9999)^2 = .9984 \end{aligned}$$

4.3.9 PLUMBING (HOT LOOP)

Using the method given in Paragraph 4.3.6, and under the same strength/load conditions as for the heat source the reliability of the plumbing for an estimated 10 joints is:

$$R (\text{Plumbing; hot loop}) = (.999999)^{10} = .99999$$

4.3.10 PLUMBING (COLD LOOP)

For an estimated 10 joints and under the same strength/load conditions as for the primary radiator the reliability for the cold loop plumbing is:

$$R (\text{Plumbing; cold loop}) = (.999999)^{10} = .99999$$

4.3.11 SYSTEM RELIABILITY

Substituting the component reliabilities into the appropriate model, the reliability estimate for each system becomes:

$$R (\text{Pu-238 System}) = .9826$$

$$R (\text{Po-210 System}) = .9700$$

These reliability estimates are the inherent reliabilities and do not reflect the probability that the radiators will suffer meteorite puncture. The radiator reliability reflecting this factor is given by:

$$R (\text{Radiator}) = \text{Pr} (\text{no meteorite puncture}) \cdot \text{Pr} (\text{no leakage failure})$$

where:

$$\text{Pr} (\text{no leakage failure}) = .99994$$

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The required armor protection can be determined so that the total system reliability is .95. For the Pu-238 system:

$$R(\text{System}) = .95 = P(\text{no meteoroid puncture}) \cdot (\text{no radiator leakage}) \cdot R(\text{all other system components})$$

Substituting the appropriate values, and re-arranging gives

$$P(\text{no meteoroid puncture}) = \frac{.95}{.9826} = .967$$

For the Pu-238 systems, where a power flattening radiator is required, the meteoroid protection requirements are slightly higher. Since both these radiators are series components in the reliability model, it is necessary to apportion the available failure probability between them; this is done on an equal basis. For each radiator then,

$$P(\text{no meteoroid puncture}) = \left(\frac{.95}{.9700} \right)^{1/2} = .990$$

4.4 CONSIDERATIONS FOR IMPROVED RELIABILITY

The systems investigated in the parametric analysis, as well as the 2 KWe designs, use radiators whose meteoroid protection is sized to provide no-puncture probabilities of .997 for 3200 hours for the primary radiators and .999 for 3200 hours for the power flattening loop radiators. These systems, then, have reliabilities of approximately .975 and .965, for Pu-238 and Po-210, respectively. To adjust the weights of 2 KWe designs to the .95 reliability level, the curve of Figure 4-8 can be used to approximate the change in radiator weight. This curve illustrates the behavior of radiator weight with variations of meteoroid protection requirements. On the ordinate is plotted the dimensionless weight ratio, W/W_0 , which is defined as

$$\frac{W}{W_0} = \frac{\text{actual weight of radiator}}{\text{weight of radiator with MTTF} = 10^6 \text{ hr}}$$

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A change in survival probability from the reference value of .997 for 3200 hours, where W/W_0 is unity, to .99 for 2200 hours, gives $W/W_0 = .8$. The radiator so armored, therefore weighs about 80 percent of a similar radiator armored to provide a .997 probability of no puncture.

Consider, now, the Pu-238 SiGe 2 KWe reference design. Table 8-1 indicates a total system weight of 2661 lb and a primary radiator weight of 242 lb. In the previous paragraphs it was shown that, to achieve a system reliability of .95, a radiator meteoroid survival probability of only .967 is required. Using the curve of Figure 4-9, a weight ratio of about 70 percent is found. Hence, the system of .95 reliability, if all this additional failure probability were allotted to the radiator, would weigh approximately:

$$\text{Total Weight} = 2661 - (1 - 0.70) (242) = 2588 \text{ lb}$$

Similar calculations for the Po-210 SiGe 2 KWe system gives a system weight of 3213 lb for the systems of .95 reliability. Changes in the weight of the power flattening radiators are small and are therefore neglected in these computations.

To raise the estimated reliability of the systems to .99, redundancy in those areas where it is technically feasible, is considered. A review of the individual component reliabilities, presented in Table 4-3, shows that the obvious choices for redundancy are the pumps and shorting regulator. Fortunately, these components are minor contributors to the system weight total, hence the weight penalty incurred will be small.

The approach used here is to compute the system reliability with the appropriate redundant components while assuming the meteoroid survival probability is unity, then adjust the resulting system probability to .99 by lowering the meteoroid protection requirements to the appropriate value. To illustrate, the calculations are presented for Po-210 SiGe 2 KWe system.

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Figure 4-9. Radiator Weight Function vs. Reliability

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Referring to Table 4-3, the reliabilities of the components to which redundancy is applied are:

EM Pump 1	.99678
EM Pump 2	.98678
EM Pump (cold loop)	.99904
Shorting Regulator	.99007

Previously it was shown that the total system reliability, with meteoroid survival probability taken as unity, was .99660 for the Po-210 system with the power flattening loop. The components to which redundancy is applied are all series components in the reliability model, hence the system reliability can be written as

$$R(\text{System}) = R(\text{EM Pump 1}) \cdot R(\text{EM Pump 2}) \cdot R(\text{PM Pump}) \\ \cdot R(\text{Shorting regulator}) \cdot R(\text{all other components})$$

Inserting the proper values, and rearranging,

$$R(\text{all other components}) = \frac{.99660}{(.99678) (.98678) (.99904) (.99007)} \\ = .99703$$

In the redundant system, the probability that both components of a given type, say EM Pump 1, will fail, is given by

$$R(\text{EM Pump 1}) = 1 - \left[1 - (.99678)^2 \right] \\ = .99982$$

Similarly, for the other redundant components:

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$$R \text{ (EM Pump 2)} = .99999$$

$$R \text{ (PM Pump)} = .999999$$

$$R \text{ (Shorting regulator)} = .999902$$

The revised system reliability, still with the meteoroid puncture probability as zero, is

$$\begin{aligned} R \text{ (system)} &= (.99703) (.99982) (.99999) (.999999) (.999902) \\ &= .99674 \end{aligned}$$

Now, including the meteoroid puncture probability term, the system reliability is reduced to the desired level. The corresponding level of meteoroid protection is

$$P \text{ (no meteoroid puncture)} = \frac{.99}{.99674} = .9932$$

Since the Po-210 system uses the power flattening radiator, the available failure probability must be split between this radiator and the primary radiator. The split is made equally and the required reliability for each is

$$P \text{ (no meteoroid puncture)} = \left(\frac{.99}{.99674} \right)^{1/2} = .9966$$

The radiator weight, for this survival probability is just that given in Table 8-1. The additional weight for pumps, power conditioning and bus bars is 134 lb, bringing the total to 3404 lb. The system configurations with the redundant components are shown schematically in Figures 4-10 and 4-11.

With the exception of the converter, any single component failure in either system appearing in Figures 4-2 and 4-3 would result in catastrophic failure. However, if in the basic systems each LIHS is incorporated into a separate and independent system to supply 1 KWe each, then with two such systems, a high probability would exist that at least one-half the required power of 2 KWe would be delivered over the mission. Such a system is shown in Figure 4-12 for Po-210. Adjusting the reliability of the 1 KWe

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Figure 4-10. Basic Pu-238 System with Redundant Components

Figure 4-11. Basic Po-210 System with Redundant Components

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Figure 4-12. Dual System without Redundancy (Po-210)

system to reflect the use of one only isotope heat source, the original value of .95 is increased to .9515. The probability of the combined systems delivering 2 KWe over the mission life is:

$$R (\text{System}; 2 \text{ KWe}) = (.9515)^2 = .9054$$

The probability that the combined systems will deliver at least 1 KWe is given by:

$$R (\text{System}; \text{at least } 1 \text{ KWe}) = 1 - (1 - .9515)^2 = .9976$$

It is to be noted that the use of two such systems implies the use of two converter assemblies each consisting of one-half as many modules as required for the nominal 2 KWe system. Similarly, the radiator area required for each 1 KWe system is halved. For both these components, then, the reliability will be slightly higher than in the original system. The

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change, however, is of minor significance and is not calculated here. To reduce the system probability of producing at least 1 KWe to the desired level of .98, the radiator armor may be reduced. The probability that each system will produce 1 KWe throughout the mission is given as:

$$R (1 \text{ KWe from each system}) = 1 - (1 - .98)^2 = .86$$

For the Pu-238 system, the revised radiator material survival probability is computed by further reducing the original value of .967 in the following manner:

$$P (\text{no meteoroid puncture}) = (.967) \left(\frac{.86}{.9515} \right) = .874$$

For the Po-210 systems with the power flattening radiator, the appropriate value of meteoroid protection is slightly higher at .943.

Proceeding a step further in the direction of redundant loop systems, a three-loop arrangement was investigated. With this arrangement, two of the three 1 KWe loops are operational and the third loop is maintained on stand-by. The probability of this system producing at least 2 KWe throughout the mission is given by:

$$R (\text{System; 2 KWe}) = \sum_{x=1}^3 \binom{n}{x} R^x (1-R)^{n-x} = .997$$

In this equation, the reliability of each 1 KWe system to produce 1 KWe for the mission life (R) is taken as .86. There is, of course, a reliability associated with switching in the stand-by unit (this is assumed unity for this calculation). The system schematic for this arrangement is illustrated in Figure 4-13.

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Figure 4-13. Triple System Without Redundancy (Po-210)

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The final systems arrangement considered for the purpose of attaining high reliability is the dual 1 KWe system with redundant components in each loop. Systems sized for 1 KWe output, using one isotope heat source with redundant pumps and shorting regulators, have inherent reliabilities of

$$R (\text{Pu-238 system: 1 KWe}) = .9984$$

$$R (\text{Po-210 system: 1 KWe}) = .9983$$

Adjusting the meteoroid armor to give no-puncture probabilities of .9966 and .9983 for the Pu-238 and Po-210 systems, respectively, results in a reliability estimate for both systems of .995 to produce 1 KWe for the 3200 hour mission. The probability of delivering 2 KWe for the same time is:

$$R (\text{System: 2 KWe}) = (.995)^2 = .99$$

and the probability of delivering at least 1 KWe is:

$$R (\text{System: 1 KWe}) = 1 - (1 - .995)^2 = .99998$$

This arrangement is illustrated for a Po-210 system in Figure 4-14. Weights and reliabilities associated with these various system arrangements are summarized in Table 4-4. Note that for purposes of developing these configuration comparisons, the reliability of the PbTe converters was assumed equal to that of the SiGe converters. A review of Table 4-4 shows that the system weight penalty associated with increasing the reliability of producing 2 KWe from .95 to .99 for the basic system is approximately 5 percent for all fuel/converter combinations and that this arrangement affords no partial power capability. Of the redundant loop systems, the dual system with redundant components provides a high measure of reliability, for producing both full and partial power, for a modest weight increase. Compared to the basic systems, the system weight penalties for the dual system with redundancy lie in the 15-to-30 percent range. From a reliability viewpoint, parallel operation of the dual system with redundant components is concluded as the optimum design for meeting the higher system reliability requirements.

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Figure 4-14. Dual System with Redundancy (Po-210)

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Table 4-4. Weight Summary for Redundant Systems

System	Po-210 Fuel			Pu-238 Fuel		
	PbTe	SiGe	Reliability for 2 KW for 1 KW	PbTe	SiGe	Reliability for 2 KW for 1 KW
Thermoelectrics						
Basic system weight	2412	3213	.95 0	1822	2588	.95 0
Single loop system with redundant components	2588	3404	.99 0	1962	2719	.99 0
Dual system without redundant components	2461	3242	.905 .9975	1874	2625	.905 .9975
Dual system with redundant components	2887	3709	.99 .99998	2197	2910	.99 .99998
Triple system without redundancy	3772	4961	.95 .997	2879	3983	.95 .997

Notes:

1. PbTe System Weights are based on the assumption that the PbTe and SiGe converters have approximately equal reliabilities.

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5. HEAT SOURCE AND SHIELD

5.1 CONFIGURATION SELECTION

The three heat source configurations examined during the previous Large Isotope Heat Source Study⁽¹⁾ are shown in Figure 5-1. While these do not represent all possible configurations, the heat source for use in this study was selected from these three to make maximum use of previous work. The "torus" configuration was chosen on the basis that it has the simplest heat transfer system, is a good structural shape, provides unscattered group re-entry of the capsules, and was shown in the previous LIHS study to be lighter than the compact individual capsule configuration and very nearly equal to the weight of the re-entry body configuration.

Figure 5-1. Large Isotope Heat Source Configurations

(1) Preliminary Design and Safety Studies of Large Radioisotope Heat Sources for Space Power (U), Final Technical Progress Report, Vol 1, GEMS 3526-2, Contract No. AT(30-1)-3526, January 24, 1966.

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Maximum power limits of 40 and 50 KWt (EOL) were established for the Pu-238 and Po-210 single torus configurations, respectively. Larger power heat sources are formed by grouping two or more heat sources together. This concept allows the use of a smaller torus which can be more easily handled and loaded into the spacecraft and results in a more flexible configuration for integration with the LEM vehicle than would a source consisting of a single torus. All tori in a heat source are of equal size and power, and the following illustrates the number of tori used for the various power sources:

POWER LEVEL - KWt		NO. OF TORI
<u>Po-210</u>	<u>Pu-238</u>	
15- 50	15- 40	1
50-100	40- 80	2
100-150	80-120	3
150-200	120-160	4
200-250	160-200	5

Using a Po-210 source as an example, the multiple tori are used as follows: In the parametric evaluations, a single torus is increased in size, by adding more fuel capsules as the power increases from 15 to 50 KWt. At 50 KWt, the single torus is replaced by two 25 KWt tori and these are increased in size until each torus is a 50-KWt module and the total source power is 100 KWt. At this point, these two tori are replaced by three 33-1/3 KWt tori and similar additions are made at 50-KWt intervals up to 250 KWt.

5.2 Po-210 HEAT SOURCE

The Po-210 heat source shown in Figure 5-2 is a 40-KWt (EOL) version of the configuration used as the basis for the analytical model for parametric analysis of the heat source. Layers of capsules are arranged in a circular array to form the torus. The fuel capsules are 5/8 inch diameter by 3-3/4 inches long ($L/D = 6$) and the capsule material is 80-mil Haynes 25. The capsules are attached to and supported by a cylindrical structure of Haynes 25. The

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Figure 5-2. Po 210 Torus Configuration

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outside of the torus is covered with a layer of re-entry protection material made of a matrix of Haynes 25 and an ablative salt. The thickness of the layer is sized for super critical re-entry at 36,000 feet per second. The torus is seated on supports at the inboard end of the annular space between the two concentric sections of the heat exchanger and is locked into place by a latching mechanism in the emergency ejection device. The latch grips a piston rod that is attached to the outboard end of the torus. The emergency ejection device throws the torus of re-entry protected capsules out of the heat exchanger when allowable fuel capsule temperatures are exceeded due to heat exchanger or other system failures. This permits the torus to reject its heat by direct radiation to space to prevent capsule rupture or meltdown. The ejection device consists of a spherical pressure vessel containing nitrogen gas at a high pressure, a pair of rupture discs, and the latching mechanism. Excessive temperature creates high pressures which rupture the discs where upon the high-pressure gas releases the latch and pushes on the piston, ejecting the torus from the heat exchanger.

The coolant flow passages in each of the concentric heat exchanger sections are parallel to the axis of the torus and are formed by a corrugated sheet that is sandwiched between two thin cylindrical shells. The thickness of these passages was limited to a minimum of 1/8 inch to prevent plugging, and cross flow between passages is prevented and structural integrity provided by brazing the corrugated sheet to the cylindrical shells. The flow passages are manifolded into headers which are attached to both ends of the concentric sections, and the inboard headers are connected together by elliptical pipes. The NaK coolant enters the outboard header on the outside of the heat exchanger, flows parallel to the torus axis, along the outside to the inboard headers, then back along the inside of the torus to the header on the inside of the heat exchanger from where it is piped down past the emergency ejection gas sphere and out of the torus. The various headers provide separate, redundant, and parallel cooling systems that may be connected to separate cooling systems for power flattening, emergency cooling, etc., or may be manifolded together as a single cooling system.

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The heat exchanger and torus are surrounded by a radiation-baffle-type insulation which is made up of multiple layers of polished tantalum. The layers are separated by small insulating ceramic beads. The insulation attached to the outboard end of the torus is ejected with the torus. The remainder of the insulation, the heat exchanger, torus supports, and emergency ejection device are anchored to the shield or spacecraft structure. The dimensions, and weights of the fuel capsules and other components are listed in Table 5-1 as a function of heat source power level.

5.3 Pu-238 HEAT SOURCE

The Pu-238 heat source shown in Figure 5-3 is a 40 KWt version of the configuration used as the basis for the analytical model. It is basically the same design as the Po-210 heat source shown in Figure 5-2 with the following differences:

- a. The fuel capsules are larger (2 to 2-1/2 inches in diameter), and the size of the fuel element varies with power and temperature conditions, whereas the same size Po-210 capsule is used for all powers and temperatures.
- b. A poison diluent is used to prevent criticality in the event of source configuration changes due to impact or meltdown. The diluent is germanium oxide which is mixed with an equal volume of fuel.
- c. A vented capsule is used. This permits the helium produced by decay of the isotope to be continuously bled off through a filter and eliminates the need for a gas volume inside the capsule or a thick pressure vessel.
- d. A 30 lb weight limit is set on the fuel capsules for convenience of handling and assembly and for impact survival. The fuel capsule weights increase with increasing capsule-to-heat-exchanger ΔT , and the setting of an upper weight limit restricts the capsule-to-heat exchanger ΔT that can be achieved.

The dimensions and weights of the full capsules and other components are listed in Table 5-2 as a function of heat source power.

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Table 5-1. Summary of Heat Source Parameters (Po-210)

Heat Source Power, Kw	10	20	30	40	60	80	100	150	200
Heat source capsule temp, °F					1800				
Coolant inlet temp, °F					1400				
Coolant exit temp, °F					1500				
Capsule diameter, in.					0.625				
Capsule length, in.					3.750				
Number of capsules					405				
Capsule weight, lb					0.300				
Total capsule weight, lb	22.2	44.1	64.8	84	122	155	194.4	290.4	388.8
Re-entry protection thickness, in.	1.009	0.919	0.829	0.739	0.559	0.408	0.408	0.408	0.408
Re-entry protection weight, lb	20.3	33.5	41.4	49.3	51.7	46.203	60.3	86.5	116.7
Torus diameter - "A", in.	11.2	13.9	14.8	18.5	20.8	21.7	26.9	30.0	35.6
Torus length - "B", in.	10.0	13.8	17	17.4	21.1	24.8	24.8	32.8	36.8
Torus weight, lb	42.5	77.6	106	133	173	201	254	376	505
Torus drag coefficient	1.22	1.18	1.12	1.20	1.17	1.13	1.21	1.14	1.16
Torus side area, ft ²	0.77	1.33	1.82	2.24	3.04	3.7	4.63	6.83	9.07
Torus W/C _D A	44	49	52	49	48	47	45	48	47
Heat exchanger weight lb.	14.3	24.3	33.5	41.5	58.4	76.3	94.6	154.3	214.4
Insulation and support structure wt, lb	33.8	54.9	72.7	92.4	124.3	151.7	192.1	273.9	362.8
Heat source diameter - "D", in.	13.9	16.6	17.6	21.2	23.5	24.4	29.7	32.9	38.4
Heat source height - "C", in.	11.5	15.3	19.1	18.9	22.6	26.3	26.3	34.3	38.3
Heat source weight, lb	91	157	213	268	356	430	542	806	1083
NOTE: Dimensions A, B, C and D refer to Figure 5-2.									

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Figure 5-3. Pu 238 Torus Configuration

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Table 5-2. Summary of Heat Source Parameters (Pu-238)

Heat Source Power ~ Kw	10	20	30	40	60	80	100	150	200
Heat source capsule temp, °F					1800				
Coolant inlet temp, °F					1400				
Coolant exit temp, °F					1500				
Capsule diameter, inches	2.095	2.716	2.778	2.790	2.778	2.790	2.780	2.782	2.790
Capsule length, inches	12.57	16.30	16.67	16.75	16.67	16.75	16.70	16.71	16.75
Number of capsules	10	10	13	17	13	17	15	16	17
Capsule weight, lb	13.3	27.5	29.3	29.6	29.3	29.3	29.5	29.5	29.6
Total capsule weight, lb	133	275	380	505	380	505	442	473	505
Re-entry protection thickness, inches	2.3	2.0	1.7	1.4	1.7	1.4	1.6	1.5	1.4
Re-entry protection weight, lb	111	138	141	141	141	141	147	141	141
Torus diameter - "A", inches	15.2	17.3	19.6	22.7	19.6	22.7	21.2	21.9	22.7
Torus length - "B", inches	17.3	20.4	20.2	19.6	20.2	19.6	20.0	19.7	19.6
Torus weight, lb	244	414	521	646	521	646	590	615	646
Torus drag coefficient	1.13	1.12	1.17	1.24	1.17	1.24	1.20	1.22	1.24
Torus side area, ft ²	1.80	2.45	2.74	3.09	2.74	3.09	2.95	3.01	3.09
Torus W/C _D A	119	150	161	167	161	167	165	166	167
Heat exchange weight, lb	23.3	32.1	37.8	44.4	37.8	44.4	41.1	42.8	44.4
Insulation and support structure wt, lb	39.9	55.5	66.7	79.9	66.7	79.9	72.9	76.5	79.9
Heat source diameter - "D", inches	17.5	19.8	22.1	25.2	22.1	25.2	23.7	24.4	25.2
Heat source height - "C", inches	18.3	21.4	21.1	20.6	21.1	20.6	21.0	20.7	20.6
Heat source weight, lb	308	502	627	771	627	771	705	735	771

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5.4 SHIELDING

The shielding criteria established from the mission model were as follows:

- a. Total mission dose..... 25 Rem
- b. Percent of time spent inside LEM..... 82.2
vehicle cabin
- c. Dose allowed inside LEM vehicle cabin 20 Rem
- d. Dose allowed for extravehicular 5 Rem
activities

The astronauts' cabin activities are divided equally between two average locations, one at 1 meter and the other at 3 meters from the source. The self shielding of the Pu-238 source provided full protection from its low gamma flux and the full 20 Rem was received from neutrons. The Po-210 gamma flux is much higher and required tungsten shielding to limit the gamma dose to 15 Rem. The remaining 5 Rem was received from neutrons.

The shield arrangement shown in Figure 5-4 was used in the analytical model of the parametric analysis. However, for ease of analysis, simple unshaped plates replaced the minor contouring. These are the shield arrangements which are appropriate for a source located at the rear of the LEM cabin on the same level with the working area.

The figure illustrates the two-torus, 80 Kw (EOL) heat sources and shows the use of both tungsten and lithium hydride around the Po-210 heat source and the use of only lithium hydride around the Pu-238 heat source.

Only scatter shielding was used on the sides of the cylinders and was assumed to be 3 attenuation lengths thinner than the direct radiation shielding which covers the ends of the cylinders.

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Figure 5-4. Shield Configuration A

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The following expression relates shield thickness to thermal power for Pu-238 sources:

$$Pe^{-.16t} = 1.66 \times 10^3$$

where

P = thermal power (watts)

t = thickness of LiH (cm)

and is based on:

- A neutron emission rate of 2.1×10^4 neutrons/sec-gm fuel
- Thermal power of 0.4 watts/gm-fuel
- LiH removal cross section = 0.16 cm^{-1}
- Flux to dose conversion factor = $0.094 \frac{\text{mrem hr}^{-1}}{\text{n-cm}^{-2} \text{sec}^{-1}}$ for 2.5 Mev neutrons
(see ANL-5800, p. 466)

For Po-210 the equations are:

$$Pe^{-0.16t} = 3.48 \times 10^3 \text{ for Lithium Hydride}$$

where

P = thermal power (watts)

t = thickness of LiH (cm)

$$(3.234e^{0.06846t} - 2.234e^{-0.18804t}) Pe^{-1.44t} = 3.22 \times 10^2 \text{ for Tungsten}$$

where

P = thermal power (watts)

t = thickness of tungsten (cm)

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and are based on:

- a. Neutron emission rate of 200 neutrons/sec-curie
- b. 4500 curies/gm
- c. Thermal power of 144 watts/gm
- d. Gamma emission rate at 1.42×10^7 of 0.8 Mev photons/watt-sec.
- e. LiH removal cross section = 0.16 cm^{-1}
- f. Tungsten gamma attenuation coefficient = 1.44 cm^{-1}
- g. Flux to dose conversion factor of $0.094 \frac{\text{mrem/hr}}{\text{n/cm}^2 \text{ sec}}$ and $1.67 \times 10^{-6} \frac{\text{Rads(c)/hr}}{\text{Mev/cm}^2 \text{ sec}}$

Densities of 0.033 lb/in^3 and 0.697 lb/in^3 were used for lithium hydride and tungsten, respectively, in the weight calculations.

Figure 5-5 illustrates a heavily sculptured shield for a heat source located between the structural webbing on the descent stage of the LEM, underneath and off to the rear side of the cabin.

5.5 ANALYTICAL MODEL

The analytical model for the heat source and shield parametric analysis is schematically illustrated by Figure 5-6. The model permits calculation of the number, size, and weight of the heat source and shield components as a function of the following variables:

- a. Source power
- b. Torus maximum power
- c. Capsule temperature
- d. Coolant ΔT
- e. Heat exchanger average temperature

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Pu 238 TORUS

STAINLESS STEEL #347

LITHIUM HYDRIDE

0 5 10 15
INCHES

Pu 10 TORUS

STAINLESS STEEL #347

LITHIUM HYDRIDE

0 5 10 15
INCHES

TUNGSTEN

Figure 5-5. Shield Configuration B

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Figure 5-6. Heat Source and Shield Analytical Model

The physical properties of the heat source and shield do not vary greatly over the range of temperatures considered in this study and were assumed, for the sake of simplicity, to remain constant.

The model computes the following parameters as a function of the variable listed above.

- Number of tori
- Power per torus
- Number of capsules
- Number of capsule layers
- Re-entry protection thickness
- Capsule diameter
- Capsule length
- Heat exchanger thickness

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- Heat source overall length
- Heat source overall diameter
- Torus length
- Torus diameter
- Gamma shield thickness
- Neutron shield thickness
- Heat exchanger pressure drop
- Torus $W/C_D A$
- Weights
 - Capsule
 - Re-entry protection material
 - Torus
 - Heat exchanger
 - Insulation and structure
 - Gamma shield
 - Neutron shield

5.6 HEAT SOURCE AND SHIELD EVALUATIONS

Shielded Po-210 and Pu-238 heat source weights for single and multiple torus heat sources are compared as a function of power in Figures 5-7 and 5-8. The shields are 2π shields with only scatter shielding on the sides of the cylinders. The multiple torus system is shown to be lighter for a 3 torus configuration but heavier for the other multiple torus configurations. The shielded heat source weights of multiple torus Po-210 and Pu-238 sources are illustrated in Figure 5-9 as a function of power. These curves do not consider the mission time or decay of the Po-210 source but are merely point designs. However, these factors are considered in the parametric analysis of the total heat source compact converter system and results in a larger size Po-210 heat source and a heavier shield for a given mission power level due to the excess heat source volume (and hence shield size) which must be included to compensate for decay prior to the mission.

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Figure 5-7. Comparison of Single and Multiple Torus Shielded Source Weights, Po-210

Figure 5-8. Comparison of Single and Multiple Torus Shielded Source Weights, Pu-238

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Figure 5-9. Weight vs Power for Shielded Po-210 and Pu-238 Multiple Torus Heat Sources

Unshielded Po-210 heat sources are lighter than unshielded Pu-238 heat sources of the same power. However, the shielding for a Po-210 heat source is heavier than for Pu-238. This difference in source and shield weights is illustrated by Figure 5-10. These results indicate that Po-210 heat sources would provide lighter systems for unshielded or lightly shielded missions of short duration, but that Pu-238 heat sources would have the weight advantage for heavily shielded missions of long duration.

The heat source weight decreases as the difference between the heat exchanger and fuel capsule temperatures increase. This results from the decreasing heat transfer area requirements which reduce the size of the torus and heat exchanger. This variation in shielded heat source weight is illustrated in Figure 5-11, where the two curves sloping downward to the right represent weight versus capsule temperature for a constant heat exchanger average temperature of 1450 °F. The curves sloping downward to the left represent weight versus heat exchanger average temperature for a constant fuel capsule

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Figure 5-10. Comparison of Po-210 and Pu-238 Heat Source and Shield Weights

Figure 5-11. Effect of Heat Exchanger and Capsule Temperature on Shielded Heat Source Weight

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temperature of 1800°F. The Pu-238 capsule size is increased to provide the necessary heat flux and power as either the fuel capsule temperature is increased or the heat exchanger temperature is decreased. The greater power density attained in the heat source results in a decrease in weight until the capsule weight limit of 30 pounds is reached.

The Po-210 heat source does not reach a similar limit because the high-power density of the fuel allows an increase in capsule power without a significant increase in capsule weight.

The effect of capsule temperature on the number of capsules required and the size and weight of the capsules is shown in Tables 5-3 and 5-4 for Pu-238 and Po-210, respectively.

Figure 5-12 shows that, with a constant heat exchanger average temperature and a constant coolant flow velocity, the shielded heat source weight and heat exchanger pressure drop are relatively insensitive to variations in the coolant ΔT . The size of the flow channels was varied with flow rate to maintain a coolant velocity of 2 fps.

Table 5-3. Variation of Capsule Parameters With Capsule Surface Temperature (Pu-238)

Capsule Temperature, °F	1600	1700	1800	1900	2000
Heat Source Power, Kw	40	40	40	40	40
Coolant Inlet Temp, °F	1400	1400	1400	1400	1400
Coolant Exit Temp, °F	1500	1500	1500	1500	1500
Capsule Diameter, Inches	1.06	1.91	2.78	2.78	2.78
Capsule Length, Inches	6.37	11.46	16.68	16.68	16.68
Number of Capsules	305	53	17	17	17
Capsule Weight, lb	2.09	10.35	29.70	29.70	29.70
Total Weight of Capsules, lb	638	549	505	505	505

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Table 5-4. Variation of Capsule Parameters With Capsule Surface Temperature (Po-210)

Capsule Temperature, °F	1600	1700	1800	1900	2000
Heat Source Power, Kw	40	40	40	40	40
Coolant Inlet Temp, °F	1400	1400	1400	1400	1400
Coolant Exit Temp, °F	1500	1500	1500	1500	1500
Capsule Diameter, Inches	0.625	0.625	0.625	0.625	0.625
Capsule Length, Inches	3.750	3.750	3.750	3.750	3.750
Number of Capsules	749	420	280	207	159
Capsule Weight, Lb	0.399	0.399	0.399	0.399	0.399
Total Weight of Capsules, lb	225	126	84.0	62.1	47.7

Figure 5-12. Effect of Coolant ΔT on Shield Heat Source Weight and Heat Exchanger ΔP

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6. ANALYTICAL MODELS

6.1 SYSTEM CONFIGURATION

The diagram illustrates a power system architecture. At the top, four rectangular blocks are arranged horizontally: 'POWER FLATTENING RADIATOR', 'HEAT SOURCE', 'TE CONVERTER', and 'RADIATOR'. A 'SHIELD' trapezoidal block is positioned between the 'HEAT SOURCE' and 'TE CONVERTER'. Below these, three small squares labeled 'P' represent pumps. A 'PUMP CONTROL' block is connected to the first pump. A 'POWER CONDITIONING' block is connected to the second and third pumps. Arrows indicate the flow of power and fluid. A 'BUSBAR' is shown at the bottom, connected to the 'POWER CONDITIONING' block and the third pump. Labels 'PUMPS' and 'PIPING PUMPS' point to the respective components.

Figure 6-1. System Block Diagram

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6.2 COMPONENT MODELS

The system components considered in the analytical model are:

- a. Heat source (Po-210 or Pu-238)
- b. Radiation shield
- c. Thermoelectric converter (Westinghouse PbTe or RCA SiGe)
- d. Primary radiator
- e. Pumps
- f. Piping
- g. Power conditioning
- h. Bus bars
- i. Power flattening system.

The following sections describe the component models used in the system program.

6.2.1 HEAT SOURCE AND RADIATION SHIELD

Analytical models for these components are described fully in Section 5 of this report.

6.2.2 RADIATORS

The empirical radiator model developed for use with the compact converter system is derived from the output of a detailed radiator design computer program. Outputs from this program were arranged parametrically and by means of curve fitting and tabular methods and reduced to concise analytic expressions relating the radiator weight and area to the selected independent variables. The parameters selected as independent variables in the radiator model are those interfacing with the system. Specifically, these parameters and the ranges over which the model was developed are:

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- a. Radiator thermal load (5 - 800 KW)
- b. Coolant inlet temperature (300 - 700°F)
- c. Coolant temperature drop (25 - 300°F)
- d. Radiator pressure drop (0.5 - 6 psi).

Since these variables represent only a fraction of the independent parameters necessary to define a complete radiator, it is necessary to select and hold constant the remaining factors. The most significant of these fixed parameters are:

- a. Effective sink temperature: 26°F
- b. Working fluid: NaK (eutectic)
- c. Meteoroid survival probability: 0.99 for 10,000 hours
- d. Surface emissivity: 0.9
- e. Material: aluminum armor and fins with stainless steel tube lines and headers
- f. Geometry: flat or curved panel radiating from one side.

Each of the design points generated by the radiator computer code was subjected to an optimization procedure which minimizes the radiator weight by varying selected input parameters within prescribed limits. The parameters optimized in each design are:

- a. Radiator tube inside diameter
- b. Fin thickness
- c. Tube spacing.

Of these three variables, only the tube inside diameter is restricted from reaching its optimum value, and this occurs only for the higher pressure drop designs. Consideration of manufacturing difficulties and the potential clogging associated with decreased diameters

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indicate a practical lower limit of diameter to be in the 0.15 to 0.20 inch range; a value of 0.18 inch I. D. was used here.

The analytical radiator model is developed in two distinct parts: the weight correlation and the area correlation. In both instances it was found convenient to employ a combination of curve fitting and tabular methods. Where double tables are used, the interpolation is linear; in the single tables, second order Lagrangian interpolation is used.

In performing the area correlation, it is found that the area associated with optimum designs is essentially independent of the available pressure drop. The general form of the correlation is then reduced to

$$\text{AREA} = f(Q, \Delta T, T_{IN})$$

where

Q = radiator thermal load (kw)

ΔT = coolant temperature drop ($^{\circ}\text{R}$)

T_{IN} = coolant inlet temperature ($^{\circ}\text{R}$)

AREA = radiator panel area (ft^2)

The form of the correlation is:

$$\text{AREA} = G_1 (\Delta T) + G_2$$

$$G_1 = e^{(1.05 \ln Q + G_3)}$$

$$G_2 = e^{(0.9796 \ln Q + G_4)}$$

$$G_4 = 34.42 - 4.804 \ln (T_{IN})$$

G_3 is obtained from the following table:

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TIN	G3	TIN	G3
760	-3.21	960	-4.42
785	-3.07	1000	-4.65
820	-3.44	1050	-4.89
860	-3.78	1110	-5.11
900	-4.07	1160	-5.25
930	-4.26		

A graphic representation of the area model is given by Figure 6-2. Maximum deviation from the points generated by the radiator design program is approximately 5 percent and this occurs at the extremities of the model.

Figure 6-2. Radiator Area Model

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The general relation for radiator weight is:

$$WT = f (Q, \Delta T, T_{IN}, \Delta P)$$

where

Q = radiator thermal load (kw)

T = coolant temperature drop ($^{\circ}$ R)

TIN = coolant inlet temperature ($^{\circ}$ R)

ΔP = pressure loss in radiator (psi)

WT = total radiator weight (lb)

The empirical model is found to be

$$WT = C (0.8 + 0.0048 (\Delta P - 6)^2)$$

and the value of C is found from the following table

TIN	C
760	C1
960	C2
1160	C3

The values of C1, C2, and C3 are dependent upon Q and ΔT and are found from the following double tables:

C1 TABLE

Q

		20	100	200	300	400	500	600	800
ΔT	300	925	6900	15100	29000	43000	57000	74000	50700
	200	470	3520	8300	14050	20800	27900	35300	28000
	100	295	2180	5200	8600	12300	16100	20100	24350
	50	261	1900	4580	7570	10780	14050	17500	25400
	25	278	2000	4780	7820	11180	14700	18200	10600

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C2 TABLE

		Q							
		20	100	200	300	400	500	600	800
ΔT	300	155	1300	3050	5000	7920	10000	12200	16150
	200	111	887	2020	3400	4950	66000	8275	11800
	100	96	760	1675	2780	4010	5350	6680	9520
	50	102	780	1770	2850	3980	5100	6300	8750

C3 TABLE

		Q							
		20	100	200	300	400	500	600	800
ΔT	300	75	540	1280	2125	3310	4400	5550	7820
	200	50	381	915	1540	2205	2915	3630	5130
	100	45	352	840	1410	2010	2640	3300	4690
	50	53	390	940	1560	1990	2850	3560	5050
	25	60	425	1075	1890	2825	3800	4800	6800

Behavior of the radiator weight model is illustrated graphically by the curves of Figures 6-3, 6-4 and 6-5.

Figure 6-3. Radiator Weight Model (Fluid Inlet Temperature = 760°R)

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Figure 6-4. Radiator Weight Model (Fluid Inlet Temperature = 960°R)

Figure 6-5. Radiator Weight Model (Fluid Inlet Temperature = 1160°R)

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The following paragraphs give a brief description of the radiator design program used to generate the data for the empirical model. A brief discussion of the salient features such as the optimization technique, meteoroid criteria, and some of the input/output quantities are presented.

The meteoroid armor thickness is based on the 1963A Whipple criterion. With the various data on meteoroid velocity, density, flux, and other pertinent factors, the armor thickness may be expressed as:

$$t = \frac{S}{2.54} \sigma \left(\frac{6}{\pi} \right)^{1/3} (\rho_p)^{-1/3} \left(\frac{624 \rho_p}{\rho_t} \right)^{\phi} \left(\frac{\bar{v}}{C} \right)^{\theta} \left(\frac{\alpha A \tau}{-\ln P_o} \right)^{1/3 \beta} \left(\frac{2}{3 \eta \theta \beta + 2} \right)^{1/3 \beta}$$

where

t = required armor thickness (in.)

S = thin plate spalling factor (1.75)

σ = material proportionality constant (2.0)

ρ_p = meteoroid particle density (0.44 gm/cc)

ρ_t = target material density (lb/ft³)

$\bar{v}$ = average meteoroid velocity (98,400 ft/sec)

C = sonic velocity in target material $(12 \sqrt{\frac{E_t g}{\rho_t}})$

where E_t = Young's Modulus at operating temperature and

g is the gravitational constant (32.2 ft/sec²)

φ = penetration constants (1/2)

θ = penetration constants (2/3)

α = constant for flux distribution curve (5.3 x 10⁻¹¹)

β = constant for flux distribution curve (1.34)

A = external surface area of components (ft²)

τ = exposure time (days)

P_o = probability of no meteoroid penetration

η = damage factor for oblique impact (1.0)

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Reduction of this equation yields the more convenient form

$$t = \frac{0.256S}{\rho_t^{1/6} E_t} \left(\frac{A \tau}{-1 \ln P_o} \right)^{0.249}$$

in which the variables have the same definition as above.

Consistent with NASA-Lewis recommendations, the vulnerable area of the tubes is defined as the external surface area of the armor. In computing the armor requirements, the vulnerable area is taken as the total external surface area of all tubes, headers, and feed lines.

To protect radiator headers, feed lines, and parts of the tubes themselves, a meteoroid bumper criterion is required. Figure 6-6 illustrates the criterion used ⁽¹⁾. The protected wall thickness (tw) is shown related to the bumper thickness (tb) and the spacing(s) between the bumper and the wall. All quantities are expressed dimensionlessly in terms of the equivalent armor thickness (ta). The equation shown in the figure is a curve fit relating the criterion to the test data ^(2, 3). In applying this criterion to a design, the first step is the determination of the required armor thickness by means of the armor criterion as though bumpers are not being used. Following this, the relative thickness of bumper and wall are determined using this reference armor thickness and Figure 6-6 as a basis. The vulnerable area is not considered to be altered by the use of a bumper, since the damage to the bumper by a meteoroid which would not normally have impacted the wall is of secondary concern. In the normal context of a bumper as applied to the outer shell of a space station, for example,

(1) "Research on Spacecraft and Powerplant Integration Problems", GE DIN 64SD892, NASA Contract NAS NO. CR54159, July 1964.

(2) Wallace, R.R. et al, "Effects of Hypervelocity Particles on Shielded Structures", ARS Journal, Vol 23, No. 8 August 1962, pp 1231-1237.

(3) Nysmith, C.R. and Summers, J. L., "Preliminary Investigation of Impact on Multiple-Sheet Structures and an Evaluation of Meteoroid Hazard to Space Vehicles", NASA TN D-1039, Sept 1961.

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this vulnerable area philosophy would not be important; however, in the case of a radiator the general reference is to the situation of a small diameter pipe (e.g., a 2-inch diameter feed line) enclosed within a large diameter shell (e.g., a 260-inch diameter radiator or vehicle).

To illustrate the scope and detail of the radiator design code used for this application a partial list of the factors considered in a design are presented.

a. Thermal Requirements

1. Heat rejection rate
2. Fluid inlet temperature
3. Fluid temperature drop

b. Geometric Factors

1. Number of radiator panels
2. Number of tubes per panel
3. Tube spacing
4. Tube inside diameter
5. Fin thickness

Figure 6-6. Meteoroid Bumper Criterion

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c. Environmental Factors

1. Meteoroid protection requirements
2. Incident heat flux
3. Surface emittance
4. Surface absorptance
5. View factors

d. Physical Property Data

1. Young's Moduli
2. Material densities
3. Thermal conductivities
4. Fluid viscosity
5. Fluid specific heat

e. Configuration Factors

1. Fin-tube design (offset or central tube)
2. Header shape (parabolic or constant diameter)
3. Length and diameter of feed lines
4. Pressure loss coefficients

With this input data, the mechanics of the program are such as to satisfy simultaneously, the thermal requirements and the meteoroid protection considerations. The relationships for meteoroid armor requirements include allowances for bumper effects where applicable and are consistent with the criteria described in this section. Thermal balance for the radiator is effected by varying the length of the tube-fin elements.

Outputs from the program include the following:

a. Temperature Distribution

1. Fin root temperature at tube inlet
2. Fin root temperature at tube outlet
3. Effective average fin root temperature
4. Fin efficiency
5. Effective sink temperature

b. Vulnerable Areas and Armor Requirements

1. Total thickness of armor required
2. Reduction in armor thickness due to fin bumper
3. Vulnerable areas of components (tubes, headers, etc.)

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c. Radiator Geometry

1. Fin length
2. Tube length
3. Header diameter
4. Radiator area

d. Flow Characteristics

1. Mass flow rate
2. Fluid velocity in tubes and headers
3. Reynolds number in tubes and headers
4. Pressure drop in feed lines
5. Pressure drop in headers
6. Pressure drop in tubes
7. Pressure drop at tube inlet
8. Pressure drop at tube outlet
9. Total pumping power

e. Weight Summary

1. Fluid weight
2. Feed line weight
3. Header weight
4. Tube weight
5. Fin weight
6. Armor weight

For purposes of optimization, a parameter called "radiator effective weight" is introduced. This is the parameter minimized and is defined as

$$\text{Eff Wt} = \text{Radiator Weight} + K1 (\text{Hydraulic Power}) + K2 (\text{Area})^{K3}$$

The constants K1, K2, and K3 can be manipulated to bias the selection of an optimum design with respect to radiator area and hydraulic power requirements. The constant K1 is generally used to reflect the "cost" of pumping power on system performance by defining it as

$$K1 = \frac{\text{System Specific Weight}}{\text{Pump Efficiency}}$$

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To arrive at an optimum radiator design, those independent parameters not constrained by the specified boundary conditions are varied until a combination yielding a minimum value of "effective weight" is achieved. Incorporated in the optimization logic is the facility to impose an upper limit on radiator area, pressure drop, total hydraulic power or a combination of these parameters. With this feature, it is possible to obtain, for example, an optimum design satisfying certain thermal and reliability requirements while not exceeding either the available surface area nor the available pressure drop.

6.2.3 THERMOELECTRIC CONVERTERS

Analytical representations of both the RCA Silicon Germanium converter and the Westinghouse lead telluride converter are based on the data presented in the final and midterm reports (4, 5, 6) of the respective compact converter study programs. The interface of these component models with the system program is identical for both converters; the geometry and operating temperatures of the converter are specified, and the dependent parameters computed include power output, efficiency, thermal requirements, and flow rates. The methods used to determine the desired output quantities for each converter design differ considerably and are described in the following paragraphs.

6.2.3.1 RCA Silicon Germanium Converter

The analytical model used to represent the Silicon Germanium converter performance is a rather complex computer code which considers the many details of the module design. This program was developed by General Electric under sub-contract to RCA in support of the Compact Converter Phase I study program and is the same code used to predict the

-
- (4) Compact Thermoelectric Program First Quarterly Report NYO-3582-5, Contract No. AT(30-1)-3582, June 28, 1965 to October 1, 1965.
 - (5) Compact Thermoelectric Program Final Phase I Report NYO-3582-12, Contract No. AT(30-1)-3582, June 28, 1965 to December 31, 1965.
 - (6) Compact Thermoelectric Converter Final Progress Report WANL-PR(CC)-006, NYOO-3584-1, Contract No. AT(30-1)-3584, January 15, 1966.

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module performance presented in Reference 4. In this reference, a complete and detailed description of the computational procedures, scope and basic assumptions are given.

The silicon germanium converter selected as the reference module for use in this study is that illustrated by Figure 6-7. This converter consists of two of the basic submodule units as defined by Figure 2.3.3-1 of Reference 5. This submodular unit consists of two tiers of thermoelectric elements, each tier containing 36 P-N couples. The reference module used for this study consists of 144 couples and has a power output in the 120 to 180 watt range, depending upon the imposed temperature profile.

To provide a reasonably high output voltage from the T/E converter, thereby allowing the use of more efficient power conversion efficiency, the couples were assumed to be connected in three parallel electrical strings, each of forty eight couples, yielding a module output voltage in the vicinity of 7 volts. To enhance the module reliability, intercouple laddering was also assumed. Electrical connections to the modules were taken as parallel so that the gross electrical power supplied to the power conditioning was at a nominal level of 7 volts.

Pressure drops through the converter were computed on the basis of having all plates arranged hydraulically in parallel. This configuration was selected to minimize the flow resistance and hence the associated pump power. The small diameter tubes connecting the hot and cold plates to the manifold system are considered to have a nominal inside diameter of 0.26 inch and be of a geometric configuration which results in a pressure loss of four dynamic heads for each fluid path. This parameter, tube inside diameter, and the thermoelectric element length are the only geometric module parameters varied in the study.

Degradation of the silicon germanium thermoelectric elements is based on the curve shown in Figure 6-8. This relation assumes a linear form when plotted against the logarithm of operational time and is characterized by a 5 percent loss in efficiency after 10,000 hours operation.

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Figure 6-7. RCA Silicon Germanium Reference Module

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Figure 6-8. Degradation Characteristic for Silicon Germanium

6.2.3.2 Westinghouse Lead Telluride Converter

The analytical model used to describe the Westinghouse lead telluride converter performance is derived from the tabular data presented in the appendix of Reference 6. The data presented in the tables was coded and appropriate table look-up and interpolation techniques applied to provide a continuous model. The reference module geometry is illustrated by Figure 6-9.

The independent parameters for the model are:

- Average hot side fluid temperature
- Average cold side fluid temperature
- Module outer diameter
- Module open circuit voltage

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Figure 6-9. Westinghouse PbTe Reference Module

With these inputs the following parameters are output from the model:

- a. Module weight
- b. Power
- c. Efficiency.

The factors assumed constant in this model are:

- a. Inner tube diameter - 0.5-inch I. D.
- b. Module active length - 15 inches
- c. Pressure drop on hot and cold sides - 0.19 psi

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Using this data as the basis, correction factors are introduced to account for end heat leak, end weight, fluid weight, degradation, outer jacket weight, and manifold weights.

Heat losses through the module ends are assumed to be 5 percent of the total heat input to the module; the power and efficiency of the module are corrected accordingly.

Degradation at constant hot- and cold-side temperatures are introduced to establish converter end-of-life performance. The relations used for this purpose are those supplied by Westinghouse and illustrated by Figure 6-10. The curves of this figure illustrate the change in power output with time. In addition, it is necessary to apply a factor to reflect the changes in module efficiency. The analytical model accounting for degradation is:

Figure 6-10. Degradation Characteristics of Lead Telluride

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$$\text{POWER DEG} = (e^{4.6 \times 10^{-4} \text{ THOT} - 0.278} - e^{2.27 \times 10^{-3} \text{ THOT} - 5.7}) \ln (\text{TIME} + 500)$$
$$\text{EFF DEG} = 1 - (1 - \text{POWER DEG})^2$$

where

POWER DEG = fraction of initial power output

EFF DEG = efficiency degradation factor

THOT = average hot fluid temperature, °F

TIME = mission time, hours

The end weights for the modules are taken as:

$$\text{End Weight} = 2 \left(\frac{\text{WT}}{\text{L}} \right)$$

where

WT = weight of active length of converter, (lb)

L = active length of converter

Fluid weight in the converter is assumed constant at 0.25 lb. The outer fluid channel is assumed to be 15 inches long, 30 mils thick and the diameter equal to the module outer diameter. The end manifold weight is assumed to be 0.25 lb each, and the lead lines from the feed lines to the end manifold are assumed to be 15 inches long with 0.25 inch I.D. and 20 mil wall thickness. The material for this extra module plumbing is considered to be stainless steel.

6.2.4 POWER FLATTENING SYSTEM

An inherent problem associated with isotope systems whose design life is a significant fraction of the isotope half life is that of thermal power dissipation at the beginning of life. In the present study, the use of Po-210 fueled systems for missions of up to 150 days duration

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required the inclusion of such an auxiliary cooling system in the designs. The arrangement selected is shown schematically in the diagram of Figure 6-1 and the basis for the selection of this configuration is discussed in Section 4 of this report.

For purposes of analytical modeling, the power flattening system is considered to consist of the following components: radiator, pump, busbars, and pump control. The radiators considered for this cooling function are similar in design to those discussed in paragraph 6.2.2, and are considered to be constructed of Haynes 25 for systems with heat source outlet temperatures above 1300°F and of beryllium for systems operating below this level. A meteoroid survival probability of 0.999 for 10,000 hours is incorporated in the designs. The analytical representation of the power flattening radiator is slightly different, in that the power available for coolant circulation is an independent input parameter. This results from the fact that the power flattening system is sized to use all the excess electrical energy available due to the overdesign necessary to accommodate the thermoelectric degradation. Other independent variables of the power flattening system are the beginning of life thermal load, heat source outlet temperature, and the busbar transmission efficiency. Outputs from this subprogram include weights of the components considered, required radiating area, flow rates, pressure drops in the various components, and the resulting temperature distribution.

For each system design point analyzed, the busbar transmission efficiency and pressure drop distribution to the various components in the power flattening loop are optimized.

6.2.5 PUMPS

Previous analytical studies have yielded a correlation of pump efficiency with the parameter

$$\left[(Q)^{1/4} (\Delta P)^{1/5} \left(\frac{\rho_{\text{wall}}}{\rho_{\text{fluid}}} \right)^{1/2} \right] \text{ for dc conduction pumps where}$$

Q = volume flow rate (gpm)

ΔP = pressure rise (psi)

ρ_{wall} = electrical resistivity of duct wall material

ρ_{fluid} = electrical resistivity of the fluid.

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A plot of the efficiencies for ~~dc~~ conduction pumps as given in References 1 and 2 shows a reasonable correlation with the equation

$$\eta = 0.026 \left[(Q)^{1/4} (\Delta P)^{1/5} \left(\frac{\rho_{\text{wall}}}{\rho_{\text{fluid}}} \right)^{1/2} \right]$$

This is shown by Figure 6-11, where of the correlation "K" factors used, a value of 0.026, best matches the NaK pump performance.

In Reference (7), pump weight had been correlated with the parameter $\left[(Q) (\Delta P) (\rho f) \right]$ for all types of electromagnetic pumps. Using the data from References (7, 8 and 9) for dc conduction pumps, a better correlation was found, using the parameter $\left[(Q) (\Delta P)^{1/2} (\rho f) \right]$ where:

Figure 6-11. Pump Efficiency Correlation

- (7) Electromagnetic Alkali Metal Pump Research Program NASA CR-380.
- (8) Design of Two DC Electromagnetic Pumps - Internal GE Report by A.P. Ferro.
- (9) Conduction and Induction Pumps for Liquid Metals - L.R. Blake, U.K. Atomic Energy Research Authority, Paper No. 2111U

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Q = volume flow rate (gpm)

ΔP = pressure rise (psi)

ρf = electrical resistivity of fluid (μ ohm - in)

As shown in Figure 6-12, a semi-logarithmic relation was used to approximate the actual curve and the resulting equation is:

$$W_P = \frac{\ln[(Q)(\rho)(\Delta P)^{1/2}] - 4.114}{0.405}$$

where

W_P = weight of pump (lb)

Figure 6-12. DC Conduction Pump Weight

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This is the relation used in the analysis with the further restriction that, from practical considerations, the minimum weight of pump would be 10 pounds.

6.2.6 BUS BARS

Calculation of bus bar weight and transmission efficiency yield the curves of Figure 6-13.

Assumptions made in these calculations are:

- Internal ohmic heating of the conductors was considered, with only conduction through the bus to remove the heat. Resistivity was taken as the resulting average for the length of the bus.
- The ends of the bus were at a temperature of 600°F .
- A constant cross-section area was assumed throughout the length of the bus.

Figure 6-13. Busbar Specific Weight vs Transmission Efficiency

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The results show:

$$\frac{W}{P_p} = \frac{\rho L^2 \gamma}{V_p^2} \frac{\eta}{1-\eta}$$

where

- W = weight of bus (grams)
P_p = power delivered to pump (watts)
ρ = average resistivity (ohm-cm)
L = Total length of bus (cm)
V_p = voltage at pump (volts)
γ = density of bus material (gm/cc)
η = transmission efficiency defined as

$$\frac{\text{power delivered to pump}}{\text{power input to bus}}$$

The efficiency of the pump control unit, as required by the power flattening loop, is dependent on the voltage drop in the output transistors. Since a significant portion of the output voltage is dissipated in the transistors, the control unit efficiency depends also on the voltage required by the pump, and hence on the transmission efficiency. Assuming an overall circuit efficiency of 95 percent exclusive of the output circuit, the efficiency of the control unit is

$$\eta_c = \frac{0.95 (\eta_{TR} V_P)}{\eta_{TR} V_P + 0.1}$$

where

- η_c = efficiency of pump control unit
η_{TR} = busbar transmission efficiency
V_P = voltage required at pump (volts)

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The constant, 0.1, is considered to be the total voltage drop in the output circuit, including the stepdown transformer.

6.2.7 COST MODEL

In addition to performing weight optimizations over the parametric range of 1-5KWe, a cost model for the isotope/compact converter systems was developed to provide the ability to design a minimum cost system. The development of such a cost model, by its very nature, poses some unique problem particularly since some of the system components are still in the preliminary design stages and may even require advances in technology before hardware can be realized. With these facts in mind, it was decided to proceed on the basis of relating the cost of such components to similar types of existing hardware for which cost can least be speculated. For example, the large isotope heat source model was formulated with consideration given to costs of the SNAP-8 reactor. It should be noted that the model presented here does not reflect the development costs associated with the various system components; rather it considers the cost of assembling a system from previously developed components.

The effective cost of the isotope heat source is given by:

$$\begin{aligned} \text{COST OF SOURCE} = & \left[\text{TOTAL WEIGHT} \right] \times \left[\text{SPECIFIC LAUNCH COST} \right] \\ & + \left[\text{THERMAL POWER} \right] \times \left[\text{SPECIFIC ENERGY COST} \right] \times \left[\text{INTEREST} \right. \\ & \quad \left. \text{CHARGE} \right] \times \left[\text{YEARS OF USE} \right] \\ & + \left[\text{THERMAL POWER} \right] \times \left[\text{SPECIFIC ENERGY COST} \right] \times \left[\text{PROBABILITY} \right. \\ & \quad \left. \text{OF LOSS} \right] \\ & + \left[\text{TOTAL WEIGHT} \right] \times \left[\text{SPECIFIC FABRICATION COST} \right] \end{aligned}$$

The first term in this equation represents the cost of launch; the specific launch cost is taken as \$ 4000/lb, a figure representative of the Saturn V class booster. The second term is intended to reflect the cost of "use" of a long-life isotope such as Pu-238; this is essentially a rental charge for the period during which the fuel is unavailable for other applications. In the case of short-life isotopes, such as Po-210, this term is omitted. The magnitude of this quantity is dependent upon the system fuel inventory, the specific energy cost of the fuel, i. e., the cost of producing a pound of the fuel, and the factors determining the rental rate,

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namely, the interest rate and the years of use. For this study, the specific energy cost Pu-238 was taken as \$1,000,000/KWt and that of Po-210 as \$25,000/KWt, the interest rate as 8 percent, and the time of use was assumed to be 5 years. The third term in the model represents an "insurance cost" and consists of the total cost of the fuel and a probability of loss factor. This probability factor will, of course, be mission-related and for this study was taken as 1 percent. For the nonreusable fuels, this loss factor is set at unity, indicating that the total cost of the fuel must be charged entirely to that particular mission. The final term in the model reflects the cost of fabrication and is assumed proportional to the physical mass of the component; the specific fabrication cost was taken as \$2000/per lb.

The cost model for the thermoelectric converters is:

$$\begin{aligned} \text{COST OF CONVERTERS} = & \left[\text{TOTAL WEIGHT} \right] \left[\text{SPECIFIC LAUNCH COST} \right] \\ & + \left[\text{GROSS ELECTRIC OUTPUT} \right] \left[\text{SPECIFIC POWER COST} \right] \end{aligned}$$

The first term is the cost associated with launching the converters, and the second term is a fabrication cost which is proportional to the gross electric output of the converters. The specific power cost for the converters is taken as \$100,000/KWe.

The remaining system components can be classified in one of the following categories:

- a. Components whose effective cost is made up of a fixed cost plus a launch cost
- b. Components whose effective cost can be described by a fabrication cost and a launch cost

The respective cost models for these components are:

- a. $\text{COST} = \text{FIXED COST} + \left[\text{TOTAL WEIGHT} \right] \left[\text{SPECIFIC LAUNCH COST} \right]$
- b. $\text{COST} = \left[\text{TOTAL WEIGHT} \right] \left[\text{SPECIFIC FABRICATION COST} \right] + \left[\text{TOTAL WEIGHT} \right] \left[\text{SPECIFIC LAUNCH COST} \right]$

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Components assigned to the fixed cost category include pumps, busbars, and power conditioning. The remaining category includes the radiators, radiation shield, and piping. The values assumed for the fixed and fabrication costs of these items are listed in Table 6-1. Although the exact values of the constants used, and in some cases possibly the form or scope of the model itself, are subject to discussion, it is felt that any salient effects of cost optimizing will be uncovered.

Table 6-1. Assumed Component Cost Factors

Component	Specific Fabrication Cost	Fixed Cost
Shield	500	-
Piping and manifolds	2000	-
Radiators	1000	-
Pumps	-	200, 000
Busbars	-	50, 000
Power conditioning	-	600, 000

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6.3 SYSTEM COMPUTER PROGRAM

To facilitate the analysis of the isotope/compact converter power system, with its many independent variables, a digital computer program was developed. This program, coded for use on the IBM 7094, incorporates all the component analytical model previously described in addition to an extremization routine which automates the selection of the independent variables necessary to attain a minimum weight or minimum cost system.

Figure 6-14 illustrates the interrelationship of the various component models and gives a simplified logic diagram of the program. Listed on the left side of this figure are some of the more significant program input parameters. A brief review of these listings and an understanding of program sequential operations give some insight to the flexibility and scope of the program.

With the specified values of converter geometry, such as element length, the number of converter modules in the system, and the imposed temperature profile, the converter analytical model computes the thermal loads of the heat source and radiator, the resultant flow rates and pressure drops, gross electrical power output, and the converter weights. Using the appropriate computed values from the converter subroutine and input quantities such as available pressure drop and radiating area, the primary heat rejection radiator is sized. Similarly, the heat source, piping, and pumps are configured to accommodate the requirements of the converters and other system components as well as the specified geometric inputs. After determining the electrical power required for pump operation, the converter gross electric output is adjusted to account for thermoelectric module degradation. At this time, power available for the power flattening loop pump is computed, and the components of the loop are sized accordingly. Pump electrical requirements for the primary coolant loops are further modified by the assumed busbar efficiency and deducted from the converter output. The resulting quantity of available electric power is used to size the power conditioning and net system power computed. The weights of the various system components are summed and used in computing the system specific weight and effective component costs which ultimately result in the computation of the system specific cost. At this point, depending on the program option selected, the optimization routine may be used or execution terminated and the computed

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Figure 6-14. System Logic Diagram

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parameters printed. In the latter case, the abbreviated sequence described represents the complete performance analysis of a specified system arrangement. If the optimization option had been selected, the appropriate computed quantities, depending on whether a weight or cost optimization is desired, would be stored and the optimization process initiated. The extremization technique employed in this program is a stepwise binary search routine which adjusts the initially estimated values of those input parameters indicated by an asterisk. All or any combination of these variables may be manipulated simultaneously to arrive at the desired optimum design. In addition, provision is made to specify constraints on the ranges of these independent variables. The input parameters to which the optimization procedure can be applied are:

- a. Heat source outlet temperature
- b. Heat source inlet temperature
- c. Radiator outlet temperature
- d. Radiator pressure drop
- e. Hot-and cold-loop pipe diameters
- f. Bus bar efficiencies
- g. Thermoelectric element length (or module O.D.) .

The estimated values of these parameters are incremented by a predetermined step size, and the system is re-analyzed. The resultant specific system weight or specific cost, if that option is selected, is compared to the previously stored value, and a discrimination procedure used to readjust both direction and stepsize of the increments of the variables being optimized. This process is repeated until no further improvement is possible with system constraints imposed.

6.4 OFF-DESIGN PERFORMANCE PROGRAMS

To estimate the off-design performance of the isotope/compact converter systems a simple digital computer program was generated. The program is intended to approximate performance

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variations for: (1) changes of the effective sink temperature and, (2) variations of the thermal power available. This program is not intended as a detailed analysis tool, but considers only the first-order effects in the system to predict approximate off-design performance. A brief description of the program is presented in the following paragraphs.

The complete two loop power system can be represented, in its simplest form, by the schematic illustrated in Figure 6-15. As shown in this diagram, the only system temperatures considered are:

TCAP = average fuel capsule surface temperature

TH = average hot fluid loop temperature

TC = average cold fluid loop temperature

TS = effective sink temperature

Figure 6-15. System Schematic For Off-Design Performance

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The equivalent electric analog for this thermal network is also illustrated in Figure 6-15 and is seen to consist of three series resistances, the physical interpretation of which are:

R1 = resistance due to radiation from capsule surface to heat source receiver

R2 = resistance due to conduction through thermoelectrics

R3 = resistance due to radiation from heat rejection radiator to sink.

Some of the basic assumptions included in this simplified representation are:

- a. The average hot loop fluid temperature, T_H , is equal to the effective heat source receiver temperature.
- b. The average cold loop fluid temperature is equal to the effective heat rejection radiator temperature.
- c. The electrical power used by the pumps in the off-design mode is not changed from that of the design point.
- d. The effective thermal conductivity of the thermoelectric modules remains constant.

To account for changes in the efficiency of the thermoelectric converters, the T/E characteristics shown by the curves (Figures 6-16 and 6-17), for silicon germanium and lead telluride respectively, were incorporated into the program. The converter efficiency then is scaled as material theoretical efficiency for changes in the temperature levels; this method amounts to assuming a constant device efficiency.

With this model, iteration techniques are used to find the temperature profile resulting from a change of sink temperature or heat source thermal output, and predict the off-design performance.

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Figure 6-16. Material Theoretical Efficiency For Silicon Germanium

Figure 6-17. Material Theoretical Efficiency For Lead Telluride

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7. PARAMETRIC STUDIES

7.1 GUIDELINES

The parametric results presented in this section are representative of systems of the basic two-loop configuration as schematically illustrated in Figure 6-1. The total system weights and system specific weights presented include only those components illustrated in the diagram, namely, the following:

- a. Isotope heat source
- b. Radiation shield
- c. Thermoelectric converters
- d. Primary radiator
- e. Power flattening radiator (where applicable)
- f. Pumps
- g. Piping, manifolds, and fluid inventory
- h. Power conditioning
- i. Bus bars

The reference design, about which the parametric examinations are made, is the LEM application discussed in Section 3. The various geometric factors, such as pipe lengths and bus bar lengths, associated with the LEM configuration are used for the parametric studies. Where a shielded power system is specified, the shield weights are based on the stringent requirements of the reference mission and account for the relatively high weights of these systems. Similarly, the heat source size and weights are representative of designs which supply the indicated power at the end of a 135 day mission; in the case of a Po-210 fueled system, the heat source is essentially twice the required capacity at the beginning of life. The sink temperature is taken as 26°F. The range of the parametric evaluation is as follows:

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Power level: 1 to 5 KWe

Fuels: Pu-238 and Po-210

Thermoelectric converters: RCA SiGe and Westinghouse PbTe

Fuel capsule surface temperature: Po-210, 1700[°]F to 1900[°]F

Pu-238, 1600[°]F to 1800[°]F

Converter inlet temperature: SiGe, 1300[°]F to 1600[°]F

PbTe, 1100[°]F to 1300[°]F

For convenience of presentation, the parametric studies are separated into two sections, depending on the type of thermoelectric converter used: Section 7.2 describes the behavior of systems using the SiGe converter and Section 7.3 the PbTe converter.

7.2 PARAMETRIC ANALYSIS OF SiGe SYSTEMS

The curves of Figure 7-1 illustrate the variation of system specific weight with changes of converter inlet temperature over the power range of interest. In these designs, the radiator area is not restricted, but allowed to attain the optimum value required to minimize the system specific weight. The curves representing the Po-210 fueled systems are based on a fixed fuel capsule surface temperature of 1900[°]F and those for the Pu-238 systems on a temperature of 1700[°]F. These capsule surface temperatures were selected as the nominal values for the respective fuels in view of the present technology levels and what might be practical levels of temperature to achieve by the selected mission time.

In general, the curves of Figure 7-1 indicate that, over the 1 to 5 KWe power range, the system specific weight is essentially constant. The upper set of curves, those for the Po-210 fueled systems, show a marked decrease in specific weight with increases in converter inlet temperature as might be expected due to the increased Carnot efficiency. Examination of the curves for the Pu-238 fueled systems shows a somewhat different result, in that a

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Figure 7-1. Effect of T/E Converter Inlet Temperature

minimum is observed in the vicinity of the 1400°F curve. The difference in the two sets of curves results from the differences in the fuel capsule surface temperatures; as the converter inlet temperature is raised, the decreased temperature difference between the capsule surface and the receiver increases the area requirements for heat transfer within the heat source, and the resultant increases in heat source and shield weight more than offset the increases in cycle efficiency. A close examination of the curves for the Po-210 fueled systems shows that the system weight reduction per degree of converter inlet temperature increase is diminishing as the temperature level approaches that of the fuel capsules. Had the parametric range of converter inlet temperature been increased, say to 1800°F, a similar effect would be noted with Po-210 systems.

The difference in the absolute levels of specific weights of the Po-210 and Pu-238 fueled systems is attributable to the radiation shielding requirements of the isotopes. The gamma

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shielding necessitated by the use of Po-210 accounts for a significant fraction of the total power system weight; this effect is covered more fully in the discussion of the following curves.

In the development of the curves of Figure 7-1, all of the remaining system independent variables, as described in Section 6.4, were optimized with only the restriction that the temperature drops in both loops be the same. The resulting values of these parameters, and some of the more significant dependent parameters, are illustrated in Figures 7-2 through 7-6.

The element lengths found to be optimum for the various combinations of converter inlet temperatures, fuels, and power levels are indicated by Figure 7-2. A general trend toward greater element lengths is noted with increasing values of converter inlet temperature and power level. The length variation with respect to temperature is due, in part, to the

Figure 7-2. Optimum Element Length for Minimum Specific Weight

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fact that the cross-section area of the couples are held constant and the length change is tending to hold constant the geometry/temperature relation which determines the efficiency and power output of the elements.

Although the total variation of element length shown in Figure 7-2 is quite large, almost 50 percent, it should be pointed out that the weight penalty incurred for holding the element length at a compromise value, say 0.75 inch, is small, and in practice other factors such as manufacturing considerations may dominate the length selection.

Figure 7-3 shows the values of fluid loop temperature drop and radiator inlet temperatures resulting from the optimization process. In the case of the loop ΔT 's, it should be noted that both hot and cold loops were constrained to have the same values and upper limit of this parameter was set at 300°F. For all combinations of converter inlet temperatures, fuels, and power levels, the optimization process resulted in the selection of the greatest available

Figure 7-3. Optimized System Parameters for Minimum Specific Weight

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temperature drop in the loops, a result which indicates the relative "cost" of high flow rates in a low-efficiency system.

The lower curves of this figure show the resulting values of radiator inlet temperature. No distinction is made here for the various values of converter inlet temperature, as the variations observed were of the same order of magnitude as the nominal "noise level" of the computer code. There is, however, a discernable variation of this parameter with respect to the isotope used; the lower temperature occurring for the Po-210 systems result from the tendency towards increased cycle efficiency and a corresponding decrease in the heat source power level. Also of significance is the fact that, independent of power level, converter inlet temperature, and fuel, the optimum inlet temperatures are well within the allowable range of aluminum radiators.

An important consideration from the aspect of power system integration is the radiator area. Figure 7-4 shows the optimum radiator specific areas associated with the various designs. As might be expected, the higher converter inlet temperatures yield the lower values of specific radiator area; this results primarily from increased cycle efficiency as the optimum radiator inlet temperature is nearly independent of converter inlet temperature. The areas for Po-210 systems are seen to be higher than the Pu-238 systems, since the radiator inlet temperatures of Po-210 systems are slightly lower than the Pu-238 system as shown in Figure 7-3.

The areas shown here are those corresponding to the minimum weight systems with no area limitations imposed. Accepting a slight penalty in the system weight would allow a considerable reduction in the specific areas associated with each power level and converter inlet temperature.

The curves of Figures 7-5 and 7-6, for Pu-238 and Po-210, respectively, show the weight fractions attributable to the major system components. In both cases, the weight fractions are essentially constant over the 1 - 5 KWe power range and the heat source and shield

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Figure 7-4. Radiator Specific Area for Minimum Weight Systems

Figure 7-5. Major Component Weights of Pu-238 Systems

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Figure 7-6. Major Component Weights of Po-210 Systems

combined account for some 75 percent of the total system weight. For the Pu-238 systems, the heat source contributes about 41 percent to the total, while the Po-210 heat source, with its 100 percent excess thermal output at beginning of life, accounts for only 14 percent of the total weight. For the selected application, with its very stringent shielding requirements, the Po-210 fueled systems are penalized approximately 1000 pounds/KWe for shielding purposes while the Pu-238 systems are somewhat less affected, the addition being about 400 pounds/KWe. In both systems, the weight of converters, pumps, piping, etc., is on the order of 10 percent of the system total, indicating that changes in these components which increase efficiency at the expense of weight would certainly be beneficial.

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The curves of Figure 7-7 illustrate the reductions in specific weight as the shielding requirements are reduced. For the LEM applications, the allowable dose rate is quite high; however, the effective separation distance is small-somewhat less than 4 feet. To illustrate this weight change, the dose rate is held constant at 72.6 mrem/hr, and the separation distance increased to the point where no shielding is required. The 2 KWe reference design point was selected as the basis for this comparison, and, at each point, the system parameters are reoptimized. At the prescribed dose rate, shielding requirements are seen to vanish at separation distances of approximately 20 and 50 feet for Pu-238 and Po-210, respectively. As indicated by the weight breakdown curves of Figures 7-5 and 7-6, the unshielded, or even moderately shielded Po-210 systems, will be of substantially lower specific weights than Pu-238 fueled systems. Variations of the allowable dose rate would, of course, change the distances at which shielding is not required and the cross-over point at which the Po-210 systems have lower weights; however, the general shape of the curves and the unshielded specific weights will remain as indicated.

Figure 7-7. Effect of Separation Distance on System Specific Weight

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Figure 7-8, shows the system specific weights, over the power range of 1 to 5 KWe, for optimized systems with the shielding requirements removed. For both fuels considered, the specific weights are nearly constant over the power range with only a slight decrease at the higher power levels. The similar curves of Figure 7-1 showed an increase of specific weight with power level, a result attributable solely to the shield.

The optimum thermoelectric element lengths for both Po-210 and Pu-238 fueled systems are found to be approximately 0.7 inch for the weight-optimized unshielded systems. Figure 7-9 shows the sensitivity of the system specific weight to this factor. The curves illustrated are for the 3 KWe power level and are typical over the range investigated.

Using the cost model described in Section 5 as a basis for optimization, the unshielded systems were reoptimized to attain minimum specific cost. The resulting curves are presented in Figure 7-10. As expected, the Pu-238 systems result in a higher cost; however,

Figure 7-8. Weight Optimization of Unshielded Systems

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Figure 7-9. Sensitivity of System Specific Weight to T/E Element Length

Figure 7-10. Cost Optimization of Unshielded Systems

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the ratio of costs is considerably less than the ratio of 40 to 1 normally assumed on fuel cost alone. The costs are also relatively independent of power level; however, at the lower power, where the fixed costs become significant, an increase is noted.

The purpose of the cost optimization was not to predict the actual cost of the power system but rather to compare the values of the system independent parameters resulting from an optimization of this type to those resulting from a weight optimization. Such a comparison was made, and, with the exception of the thermoelectric element lengths, no significant changes were observed. The change noted in the optimum element length was a tendency towards increased values of this parameter. In the case of Po-210 fueled systems, optimum values were found to be in the vicinity of 0.9 to 1.0 inch; or the Pu-238 systems, an optimum value was not reached for lengths below the 1.0-inch upper limit placed on this parameter. The curves of Figure 7-11 show the sensitivity of the cost parameter to element length. Although the sensitivity is quite low, there is a discernable trend toward greater element lengths than was not found in the weight optimization.

Figure 7-11. Sensitivity of System Specific Cost to T/E Element Length

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To assess the effect of the thermoelectric module weights on the total system, the 2 KWe design points were reoptimized considering the module weight to be various fractions of its actual weight. Figure 7-12 illustrates the resulting values of system specific weight for Pu-238 and Po-210 fueled systems, both shielded and unshielded. For all combinations, the specific weight shows relative insensitivity to changes in the converter weight. The abscissa of this curve plots the module weight ratio which is defined as the assumed module weight/actual module weight. At a value of unity, the actual module weight is used; at a value of 2.0, the module weight is double the actual weight, and so forth. The slope of the curves is such that an increase of T/E module weight of 100 percent results in an increase of system specific weight of about 40 lb/KWe, or, for the lightest system, the unshielded Po-210 designs, a 100 percent increase in T/E module weight causes an approximate 10 percent increase in system specific weight. With these proportions, it becomes obvious that increases in the module conversion efficiency, such as reduction of thermal losses, at the expense of increased module weight will provide a net improvement to the total system.

Figure 7-12. Sensitivity of System Specific Weight to T/E Module Weight

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The sensitivity of system weight to converter pressure drop is illustrated by Figure 7-13. This curve shows an influence of about 150 lb/KWe per psi drop in the converter. As indicated, the reference module configuration with all hydraulic passages in parallel, yields an extremely low-module pressure drop, and it is doubtful that satisfactory flow distribution through the modules could be maintained at such a low level. A practical solution, from the standpoints of both flow distribution and thermal gradients in the module, would be to connect two or more modules hydraulically in series to produce a greater pressure drop, say 0.2 psi. Such a change would yield only minor penalties in the system performance.

Figure 7-13. Sensitivity of Specific Weight to Converter Pressure Drop

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7.3 PARAMETRIC ANALYSIS OF PbTe SYSTEMS

The response of specific weight of systems using the Westinghouse lead telluride converter to changes in converter inlet temperatures and fuels is illustrated in Figure 7-14. These designs are characteristic of systems of unlimited radiator area and shielding as required for the selected LEM shelter mission. The fuel capsule surface temperatures are held at the selected reference values of 1700°F and 1900°F for Pu-238 and Po-210, respectively. Since these temperatures are considerably higher than the converter inlet temperatures used with lead telluride, the effective radiation temperature drop in the heat source is large for all cases considered, and the higher converter inlet temperatures yield lower weights for both fuels. In systems where the heat source and shield account for the majority of the total weight, the lower converter inlet temperature of lead telluride produces a distinct advantage; the greater temperature differential in the heat source allows higher radiation flux densities, thereby reducing the heat source size. A comparison of the curves of Figures 7-1 and 7-14 shows the lead telluride systems to be about 300 to 400 lb/KWe lighter across the entire power range; this is almost entirely attributable to the reduced mass of the heat source and shield which results from the greater heat source temperature differential and somewhat higher cycle efficiencies.

Figure 7-14. Effect of T/E Converter Inlet Temperature

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Figures 7-15 through 7-19 illustrate the behavior of some of the significant system parameters resulting from the weight optimization. For these designs, all the independent variables, with the exception of fluid loop temperature drop, were subjected to the optimization process. The loop temperature drops were maintained at 200°F in both hot and cold loops to correspond with the converter performance data available in the Westinghouse report.

Figure 7-15 shows the converter outside diameters found to be optimum for the shielded systems. For all designs examined, the optimum converter diameters fall in a relatively narrow band, from approximately 1.55 to 1.85 inches, a range which brackets the reference module diameter of 1.75 inches quite closely. Trends similar to these noted for silicon germanium systems are also evident here; increased converter diameter with increasing power level is a tendency toward increased efficiency and reduced heat source weights, and the variation with temperature level is due to the geometry/temperature relation described previously.

Figure 7-15. Optimum Converter O.D. for Minimum Specific Weight

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The optimum values of radiator inlet temperature are shown in Figure 7-16. Again, no distinction is made for the various converter inlet temperatures as the values resulting from the optimization were virtually independent of this parameter. The slight difference in preferred radiator inlet temperatures with respect to the type of fuel is attributable to the shielding involved; the lower value selected for the Po-210 systems shows a tendency to increase cycle efficiency thereby reducing the heat source and shield size.

Figure 7-16. Optimized Radiator Inlet Temperature for Shielded Systems

The radiator area requirements for the shielded, weight-optimized systems are presented in Figure 7-17. As indicated, the specific radiator area is nearly constant with power level and fuel type. The increased cycle efficiencies achieved at the elevated converter inlet temperatures translate into reduced area requirements for these systems. The values of area given by these curves correspond to those systems having no area restrictions; for slight increases in the system specific weight, the area requirements can be substantially reduced from those shown.

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Figure 7-17. Radiator Specific Area for Minimum Weight Systems

In Figures 7-18 and 7-19, the component weight fractions are shown. While the heat source and shield still dominate the systems, their fractional values of the total weight are considerably reduced from those of the silicon germanium systems shown in Figures 7-5 and 7-6. In the Pu-238 systems, the heat source itself accounts for the greatest fraction of the system weight, while in the Po-210 systems, the shield is the greatest contributor. The lead telluride converters account for a slightly greater percentage of the total than do the silicon germanium converters; however, the absolute value is still quite small, and weight increases to enhance cycle efficiency would almost certainly result in favorable changes to the system.

Specific weights of the unshielded lead telluride systems for a converter inlet temperature of 1300°F are given by Figure 7-20. Here the Po-210 fueled systems, with the high-power density heat source, are considerably lighter than comparable Pu-238 fueled systems. Associated with these optimized unshielded systems are the converter diameter indicated by Figure 7-21. Comparison with the similar curves for shielded systems, Figure 7-15, shows that the optimum diameter for the Po-210 fueled systems is reduced nearly 0.5 inch,

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while in the Pu-238 fueled systems only a minor reduction is noted. In view of the relative shield weight fractions, as shown by Figures 7-18 and 7-19, this effect is readily explained; removal of the Po-210 shield reduces the system weight by some 60 percent and shifts emphasis to the remaining system components, while a similar change in the Pu-238 systems effects a change of some 15 percent in the system weight and requires little or no change in values of the independent system variables. It is further noted that, with the shield omitted, the optimum converter diameter is less sensitive to power level.

Changing the optimization figure of merit to specific cost, rather than specific weight, yields the results shown in Figures 7-22 and 7-23. The conclusions indicated are substantially the same as those for silicon germanium systems; the Pu-238 fueled systems are more costly due to the isotope costs, and larger converter diameters are selected for the Pu-238 systems in attempt to increase cycle efficiency and reduce the necessary isotope inventory.

Figure 7-18. Major Component Weights of Pu-238 Systems

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Figure 7-19. Major Component Weights of Po-210 Systems

Figure 7-20. Weight Optimization of Unshielded Systems

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Figure 7-21. Optimum Converter O.D. for Minimum Weight Unshielded Systems

Figure 7-22. Cost Optimization of Unshielded Systems

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Figure 7-23. Optimum Converter O.D. for Minimum Cost Unshielded Systems

Figure 7-24 illustrates the sensitivity of the system weight to the fuel capsule surface temperature. The Po-210 systems display a marked dependence on this parameter, approximately 200 lb/KWe/100°F change in this temperature. The Pu-238 systems show a similar, though less pronounced response - about 50 lb/KWe reduction in specific weight for a 100°F increase in capsule surface temperature. The variation of sensitivity for the two types of fuels results from the differences in shielding requirements and power densities.

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Figure 7-24. Effect of Fuel Capsule Temperature on Specific Weight

The sensitivity to converter pressure drop of systems using the Westinghouse lead telluride converters is shown in Figure 7-25. The slope of the curve indicates a penalty of about 100 lb/KWe for each psi increase in converter pressure drop; however, the reference value of 0.19 psi is relatively low and, if for manufacturing or flow distribution considerations it were necessary to increase this two-fold, the consequences would be of minor significance.

The preceding parametric results for the lead telluride converters are based on the use of the 7 volt matched load design, four of which are connected electrically in series to produce 28 volts at the power conditioning. The results of varying this voltage, and consequently the number of modules connected in series to supply the 28 volt power, are shown in Figure 7-26. In practice, this curve obviously would be discontinuous if it were desired to maintain the 28 volt output, due to the discrete numbers of modules involved; however, for convenience it is shown as a continuous function. As illustrated in the figure, there is very

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little variation in the specific weight for the entire range of voltages examined, and the reference design value of 7 volts is nearly optimum.

Figure 7-25. Sensitivity of Specific Weight to Converter Pressure Drop

Figure 7-26. Effect of Converter Voltage on Specific Weight

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8. DESIGN OF 2 KWe SYSTEMS

The selection of the 2 KWe reference designs is based on the results of the parametric studies described in Section 7 and the power system integration aspects discussed in this section. In the development of these reference designs, consideration was given to factors such as radiator area limitations, heat source location, structural interfaces, and methods of heat rejection during the shrouded post-launch period of the mission. Detailed discussions of these factors, and their influence on the design point selections, are presented in the remainder of this section.

8.1 PARAMETRIC ANALYSES FOR 2KWe DESIGNS

Configuration studies of the LEM vehicle were performed to determine the most satisfactory arrangement of the power system within the spacecraft. From these studies, piping lengths and available radiator areas were determined and factored into the parametric analyses. The ground rules upon which the 2 KWe design point parametric studies are based are:

- a. Radiator surface area: 180 ft^2
- b. Fuel capsule temperatures: Po-210 - 1900°F
Pu-238 - 1700°F
- c. Converter inlet temperatures: SiGe - 1500°F
PbTe - 1300°F
- d. Mission life: 134 days
- e. Effective sink temperature: 26°F

8.2 2 KWe REFERENCE DESIGNS USING SiGe CONVERTERS

The variation of system specific weight of the optimized silicon germanium systems for changes of thermoelectric element length are shown in Figure 8-1. Optimum element lengths for both Po-210 and Pu-238 fueled systems are approximately 0.8 inch, thus the inclusion of a radiator area limit does not significantly alter the values found in the para-

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Figure 8-1. SiGe Optimum Element Length for 2 KWe

metric study of unlimited area systems. On the basis of cost optimization, the optimum element lengths are slightly greater as illustrated by Figure 8-2. For the systems using Pu-238, a length of 0.9 inch gives minimum cost systems. The sensitivity to element length is seen to be slight until the length is decreased beyond 0.6 inch, at which point further reductions impose significant penalties.

Due to the incremental nature of power additions to the compact converter power system, it may not be possible to arrive at an optimum system of a fixed power level using a specified converter configuration. In Figure 8-2, this is illustrated for cost optimized systems using a Pu-238 heat source. From this plot it is seen that a minimum cost 2 KWe system occurs with an element length of 0.9 inch and using slightly more than 20 modules. In such situations, it is necessary to select either a 20 or 21-module system and accept the resulting power. At the temperature levels being considered, the reference module net power output is about 100 watts, thereby allowing the desired power level to be matched quite closely.

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Figure 8-2. Selection of Optimum Element Length for 2 KWe Design SiGe Pu-238

A typical distribution of the component weights of an area limited 2 KWe system is given in Figure 8-3. Comparison with the analogous curve for unlimited area systems, Figure 7-6, shows the radiator weight is slightly lower, and the shield and converter weight percentages somewhat higher in the area limited designs. The reduction in available radiator area forces the selection of higher radiator inlet temperatures and results in reduced converter efficiency. To maintain a fixed power level, the number of converters must be increased as must the heat source, and consequently, shield sizes. The weight attributable to the remaining system components is approximately the same as for the unlimited area designs.

To illustrate the sensitivity of specific system weight to the optimized parameters, the curves of Figure 8-4 are presented. Although the curves illustrated are specifically for a silicon germanium system using Po-210 fuel, they are typical of both fuels and both converter designs. As illustrated, the systems show a marked sensitivity to radiator outlet

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Figure 8-3. SiGe Po-210 Weight Fraction for System Components 2 KWe Design Point

Figure 8-4. SiGe Po-210 System Weight Variation with Optimized Parameters (2 KWe System)

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temperature, fluid loop ΔT and radiator pressure drop while the pipe diameters and bus bar efficiencies are less influential.

Off-design performance of the silicon germanium systems for changes in effective sink temperature and isotope decay is given in Figures 8-5 and 8-6. The variation of effective lunar sink temperatures is dependent upon radiator orientation and coatings used. However, it is generally expected to fall in the -300°F to $+150^{\circ}\text{F}$ range. As shown in Figure 8-5, the resulting changes in net power output are small and under the worst conditions the available power does not drop below 90 percent of the design value. A similar performance curve predicting the variation of electrical power due to changes in available thermal energy is shown in Figure 8-6. This deduction of heat input can be considered to result from isotope decay, insulation deterioration, or other system contingencies producing such an effect. The power response to changes in this parameter are much more significant than variations of the sink temperature.

Figure 8-5. Effect of Sink Temperature - SiGe 2 KWe Reference Designs

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Figure 8-6. Off-Design Performance of 2 KWe SiGe Reference Design Systems

8.3 2 KWe REFERENCE DESIGNS USING PbTe CONVERTERS

The curves of Figure 8-7 illustrate the variations of net electrical power, specific weight, and module diameter as functions of the number of converter modules for weight optimized lead telluride systems. For the 2 KWe system using a Po-210 heat source, 16 converter modules of 2 inch O.D. are selected and a specific weight of 1195 lb/KWe results. Similar data for the Pu-238 system is presented in Figure 8-8; the 2 KWe design again uses 16 modules of approximately 2 inch diameter and a specific weight of 940 lb/KWe is indicated. Comparison of these designs with the 2 KWe unlimited area designs of Figure 7-14 shows slightly higher specific weights due to the radiator area limitation imposed.

The sensitivity of the specific weight of the area limited 2 KWe designs to converter module diameter is given by Figure 8-9. For either isotope, a converter diameter in the 1.8 to 2.0 inch range yields the lowest weight systems and a reduction to the reference diameter of 1.75 inches would not impose a significant penalty.

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Figure 8-7. PbTe Po-210, Selection of 2 KWe Design Point

Figure 8-8. PbTe Pu-238, Selection of 2 KWe Design Point

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Figure 8-9. PbTe 2 KWe, Effect of Module O. D.

Off-design performance of the lead telluride systems is similar to that of the silicon germanium system and is given in Figures 8-10 and 8-11. A summary of the 2 KWe system characteristics is presented in Table 8-1.

In the work statement received from the AEC, it was specified that the 2 KWe designs using the Westinghouse lead telluride modules be developed at a converter inlet temperature of 1100°F. Discussions with Westinghouse indicated that the inlet temperature of the reference design was 1300°F. To comply with the work statement, and to use the most recent designs estimates of converter inlet temperature, 2 KWe reference designs were prepared for inlet temperatures of 1100°F, 1200°F, and 1300°F. A summary comparison of these designs is presented in Table 8-2. The variation of inlet temperature does not alter the general conclusions of the preceding paragraphs; the primary differences of the designs are the resulting temperature profiles of the optimized systems and the associated

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Figure 8-10. Effect of Sink Temperature, PbTe 2 KWe Reference Designs

Figure 8-11. Off-Design Performance of 2 KWe, PbTe Reference Design Systems

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Table 8-1. Summary of 2 KWe System Characteristics

	Units	W-PbTe Pu-238	W-PbTe Po-210	RCA-SiGe Pu-238	RCA-SiGe Po-210
Net Electric Power (EOL)	KWe	2.01	2.04	1.96	1.99
No. of Modules	-	16	16	18	20
Element Length or Mod Dia.	inches	1.96	2.00	0.8	0.8
Module Efficiency (EOL)	-	6.9	6.9	5.4	5.1
Overall System Efficiency (EOL)	%	5.2	5.8	4.9	4.7
Capsule Surface Temperature	°F	1700	1900	1700	1900
Heat Source Outlet Temperature	°F	1300	1300	1500	1500
Heat Source Inlet Temperature	°F	1100	1100	1288	1201
Radiator Inlet Temperature	°F	502	491	540	584
Radiator Outlet Temperature	°F	302	291	328	285
Radiator Sink Temperature	°F	26	26	26	26
Thermal Power Generated by Source at BOL	KWth	38.3	73.7	42.4	94.7
Thermal Power Generated by Source at EOL	KWth	38.2	34.7	42.2	44.7
Thermal Load of PF Radiator at BOL	KWth	-	34.5	-	47.50
Radiator Heat Load	KWth	32.38	32.17	37.95	40.26
Mass Flow Rate through Source	lb/hr	2826	2812	3026	2283
Mass Flow Rate through Radiator	lb/hr	2549	2527	2820	2127
Mass Flow Rate in PF Radiator	lb/hr	-	1720	-	2342
Pressure Drop through Source	Psi	0.105	0.183	0.103	0.189
Pressure Drop Across Module-Hot	Psi	0.19	0.19	0.060	0.028
Pressure Drop Across Module-Cold	Psi	0.19	0.19	0.056	0.022
Pressure Drop in Radiator	Psi	0.50	0.50	0.06	0.06
Total Pressure Drop in Hot Loop	Psi	0.371	0.445	0.164	0.217
Total Pressure Drop in Cold Loop	Psi	0.926	0.893	0.648	0.623
Total Electric Power to Pumps	Watts	129	129	92	78
Heat Source Torus Dia	in.	24.16	18.75	31.10	20.30
Heat Source Torus Length	in.	20.50	17.85	18.16	24.0
No. of Fuel Capsules/Torus	-	17	248	29	350
Actual Area of Primary Radiator	ft ²	180	180	180	180
Area of PF Radiator	ft ²	-	7.8	-	10.3
Hot Loop Pipe Diameter	inches	1.60	1.62	0.75	0.75
Cold Loop Pipe Diameter	inches	1.39	1.43	0.75	0.75
Cold Loop Pump Bus Bar Efficiency	-	0.56	0.56	0.550	0.550
Hot Loop Pump Bus Bar Efficiency	-	0.56	0.56	0.550	0.550
Weight of LIHS	lb	805	302	1114	478
Weight of Shield	lb	414	1399	1002	2084
Weight of Primary Radiator	lb	233	265	242	284
Weight of Hot Loop Pipes	lb	22	26	9	9
Weight of Cold Loop Pipes	lb	48	57	24	25
Weight of Converter Manifolds	lb	21	25	36	40
Weight of Hot Loop Pump	lb	10	10	10	10
Weight of Cold Loop Pumps	lb	10	10	10	10
Weight of Power Conditioning	lb	38	38	39	39
Weight of Converter	lb	246	254	138	153
Weight of Cold Loop Pump Bus Bar	lb	26	29	23	18
Weight of Hot Loop Pump Bus Bar	lb	19	25	12	45
Weight of PF Loop Pump Bus Bar	lb	-	1	-	2
Weight of PF Loop Radiator	lb	-	14	-	63
Weight of PF Loop Pump	lb	-	10	-	10
Total Weight of System	lb	1892	2465	2659	3270
System Specific Weight (EOL)	lb/KWe	938	1196	1362	1628
Specific Radiator Area	ft ² /KWe	89.36	88.20	89.05	87.88
Specific Cost	\$/KWe	1.68x10 ⁷	6.16x10 ⁶	1.64x10 ⁷	9.49x10 ⁶

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Table 8-2. Comparison of 2 KWe PbTe Power System

	Units	Pu-238			Po-210		
T/E Module							
Inlet Temp.	(°F)	1100	1200	1300	1100	1200	1300
No. of Modules		32	22	16	34	22	16
Net Elect. Power	(KWe)	2.031	2.09	2.01	2.07	2.096	2.04
Unshielded							
SPWT	(lb/KWe)	847	827	733	752	571	512
Shielded							
SPWT	(lb/KWe)	1132	1077	940	1652	1352	1200
Capsule							
Temp.	(°F)	1700	1700	1700	1900	1900	1900
Specific Cost	(\$/KWe)	1.86x10 ⁷	1.54x10 ⁷	1.08x10 ⁷	9.5x10 ⁶	7.9x10 ⁶	6.16x10 ⁶
Hot Side T/E							
Temp.	(°F)						
Inlet Temp.		1100	1200	1300	1100	1200	1300
Outlet Temp.		900	1000	1100	900	1000	1100
Cold Side T/E							
Temps.	(°F)						
Inlet Temp.		367	345	302	351	313	291
Outlet Temp.		567	545	502	551	513	491
Heat Source							
Power*	(KWt)						
BOL		55.8	41.5	38.3	114	92.2	73.7
EOL		55.6	41.4	38.2	53.5	43.5	34.7
Area Limit							
T/E Module Dia	(in.)	1.71	1.79	1.96	1.98	1.98	1.99
Sys. Eff.	(%)	3.76	5.05	5.24	3.88	4.82	5.88
Weight T/E							
Converters	(lbs)	408	282	246	528	344	254

*Includes allowance for 5% heat loss

system specific weights. At the lowest value of converter inlet temperature, 1100°F, the shielded system specific weights are almost identical to those of the silicon germanium systems given in Table 8-1.

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8.4 SHIELD AND HEAT SOURCE LOCATION

As indicated in Section 3, the power system will be located in the LEM Shelter which will be delivered to the lunar surface some 90 to 120 days prior to the arrival of the exploration crew. Several alternate locations for the shield and heat source within the LEM were considered with the results summarized in Figure 8-12. These locations were evaluated with respect to:

- a. Growth potential
- b. Remote fueling access
- c. Shielding
- d. Structural support
- e. Affect on vehicle center of gravity

to determine the compromise location that would be most attractive. These relatively qualitative factors are discussed in the following paragraphs.

	CONFIGURATION	GROWTH POTENTIAL	ACCESS FOR REMOTE FUELING	PROXIMITY TO CREW COMP SHIELDING	STRUCTURAL SUPPORT	AFFECT ON C G VERT/HORIZ
1.		FAIR	POOR	POOR	POOR	POOR FAIR
2.		FAIR	FAIR	POOR	FAIR	FAIR FAIR
3.		POOR	GOOD	FAIR	POOR	FAIR POOR
4.		FAIR	FAIR	FAIR	GOOD	GOOD FAIR

Figure 8-12. Alternate Shield and Heat Source Locations

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8.4.1 GROWTH POTENTIAL

The growth potential of three of the locations are rated as only "Fair" because the heat source and shield for the 2 KWe power system are near the limit of the volume available on the LEM. Configuration 3 is rated as "Poor" because the heat source is located outside the octagonal outline of the LEM and additional increases in the horizontal plane are not possible because of interference with the Saturn shroud in the launch configuration.

8.4.2 REMOTE FUELING ACCESS

It is expected that the heat source will not be loaded into the spacecraft until just a few hours before launch. Since the spacecraft would be in the launch configuration, an access panel would be required through the Saturn shroud to allow for the loading of the heat source. The heat source analyses indicate that it is desirable to provide the necessary thermal power by two heat sources, and if Configuration 1 were utilized, two access panels would be required on opposite sides of the shroud to allow for loading. Configurations 3 and 4 are rated as "Fair" as they require only one panel; however, the distance between the face of the heat source and the shroud is greater than that of Configuration 4, thus a greater traverse is required in the insertion of the heat source. Configuration 3 is rated "Good" as the heat source is placed immediately adjacent to the shroud.

8.4.3 PROXIMITY TO CREW

The relative size of the crew compartment and the overall LEM vehicle is such that it is difficult to place the heat source more than 3 to 8 feet from the astronaut living quarters. This is reflected in the ratings shown in Figure 8-12. Configurations 1 and 2 are rated "Poor" because the heat source is located immediately adjacent to the crew compartment. Configurations 3 and 4 provide locations in the descent stage and are somewhat more attractive. A location not considered, but one that could result in significant reductions in shield weight, would be placement of the heat source below the LEM and away from the descent engine exhaust plumes.

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	CONFIGURATION	GROWTH POTENTIAL	STRUCTURAL SUPPORT	HEAT REJECTION IN SHROUDED CONFIG	AFFECT ON C. G.	RADIATING TO LEM STRUCT.
1.		POOR	GOOD	FAIR	MINIMAL	FAIR
2.		POOR	GOOD	FAIR	MINIMAL	POOR
3.		GOOD	FAIR	GOOD	MINIMAL	GOOD

Figure 8-13. Alternate Radiator Locations

- a. Growth potential
- b. Structural support
- c. Shrouded heat rejection
- d. Affect on vehicle center of gravity
- e. Thermal radiation to the LEM

for both low temperature radiators and the high temperature power flattening radiator.

8.5.1 GROWTH POTENTIAL

Of the four octagonal faces not covered by the LEM legs, one face will be utilized for the heat source and shield assembly and the other three may be utilized for radiator locations. The small, high temperature power flattening radiator is less than 10 ft² in area and may be located without interference on the same face and above the heat source as shown in Configurations 1 and 3. The three available octagonal faces can provide a total area of only 120 to 130 ft² which is less than the minimum required for the 2 KWe power systems.

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Thus, in Configuration 1, the radiators are extended above the ascent stage about two feet to increase the area to 150 ft². A significantly greater area cannot be attained because the radiators would interfere with the astronauts' view of the lunar surface during landing and the radiators would be exposed to the exhaust of the attitude control jets. In Configuration 2, a cylindrical radiator that encircles the entire LEM is provided; however, its height and therefore its area, is limited for the same reasons as Configuration 1. The available area is about 130 ft². Configuration 3 provides three radiator panels that are supported away from the LEM structure. This results in a radiator area of 180 ft² with no extension above the ascent stage and growth is thus available in this configuration if a power system of greater than 2 KWe were ultimately required.

8.5.2 STRUCTURAL SUPPORT

The structural requirements are not expected to be a serious consideration because of the relatively small size of the radiators (60 ft² per panel) and their inherent strength. Configurations 1 and 2 would have some advantages as the radiators would be located adjacent to the spacecraft and the length of the structural ties would be minimized.

8.5.3 HEAT REJECTION IN SHROUDED CONFIGURATION

As discussed in Paragraph 8.7, an auxiliary heat rejection system is required to dissipate the power system energy when the LEM is enclosed by the shroud in the launch configuration. An evaluation of the requirements of that auxiliary system indicates that a system of radiators that face the LEM power system radiators will satisfy the heat rejection requirements. These auxiliary radiators would be attached to the shroud, and thus Configuration 3, in which the power system radiators are located away from the vehicle and adjacent to the shroud would be most attractive.

8.5.4 SPACECRAFT CENTER OF GRAVITY

The effect of the radiators on the spacecraft center of gravity is expected to be minimal because of their near uniform distribution around the spacecraft and their low total weight (200 to 300 lb).

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8.5.5 THERMAL RADIATION TO LEM STRUCTURE

The thermal radiation from the radiators to the LEM structure (primarily the legs) is minimized in Configuration 3 in which the radiators are located outboard of the spacecraft with a minimum view of the legs.

8.5.6 SELECTION OF LOCATION

Configuration 3 was selected for the location of the radiators because it was rated good in all respects except structural support, and this was judged to be a minor deficiency that would result in negligible penalty to the system.

8.6 VEHICLE/POWER SYSTEM ARRANGEMENT

The vehicle/power system arrangement is shown in detail in Figure 8-14 and in perspective in Figure 8-15. The configurations are the same for both Po-210 and Pu-238 power systems with the exception of the high temperature radiator that is required for the Po-210 fueled systems.

The thermoelectric converters and the maximum possible number of other system components are located on the side of the spacecraft opposite to the shield and heat source assembly in an attempt to minimize the effect of the power system on spacecraft center of gravity. Both the SiGe and PbTe modules are mounted externally to the present LEM octagonal outline. Their relatively low total volume and weight is such that they may actually be mounted without interference in a variety of locations. This particular location will minimize the modifications to the LEM.

The main EM pumps are located immediately adjacent to the T/E modules to minimize the electrical bus length and losses. The EM pump for power flattening is necessarily located adjacent to the heat source and power flattening radiator and an electrical bus of about 15 feet and weighing 2 lb is required for power.

As discussed in Section 4, a manual shut-off valve is provided on the power flattening system to minimize the heat loss that will occur through the system at end of life. This valve is located below the heat source and approximately 4 feet from the lunar surface for easy access by the astronaut.

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Figure 8-14. Power System LEM Vehicle Configuration

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Figure 8-15. Power System/Vehicle Arrangement

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The radiators are insulated on the back face to limit heat rejection to the spacecraft. The three power system radiators are connected in parallel, receive flow from a common pump, and are constructed of stainless steel tubes with aluminum fin material. The single power flattening radiator is also insulated on the back side and is constructed of Haynes-25 tubes and fin substrate with a copper plating for high fin conductivity.

The layout of the system piping was generally selected to limit the perturbations to the LEM. The piping is placed external to the vehicle and between the ascent and descent stages.

8.7 AUXILIARY HEAT REJECTION

The LEM spacecraft is shown in the launch configuration in Figure 8-16. The spacecraft is enclosed by the shroud, which according to the planned mission profile, will normally be ejected at about 2 hours after launch. This assumes a normal mission with only one earth orbit prior to translunar ejection. However, the mission will allow up to 6 earth orbits prior to translunar injection, in which case, the time to shroud ejection could be as much as 9.5 hours.

Since the heat source is included in the power system, provision must be made for auxiliary heat rejection during this period. An evaporative system with water could be used; however, even based upon the lowest heat source power level of 38.3 KWt (PbTe with Pu-238), the weight of water would exceed 1380 lb exclusive of tankage, control system, and boiler. This weight is prohibitive and other systems were examined.

A heat pipe radiator system as illustrated in Figure 8-16 can provide the necessary heat rejection. In the system shown, a heat pipe radiator is located adjacent to each of the power system radiators mounted on the spacecraft. The heat pipe radiators extend through and around the shroud to form a radiator that receives heat from the power system radiator on the interior of the shroud, transfers that heat via the heat pipe to the exterior of the shroud, and rejects the heat to the environment. The low temperature heat pipes are constructed of stainless steel tubes with aluminum fins. The heat pipes are sloped in the horizontal plane toward the heat input end to allow gravity to assist the wicking action.

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Figure 8-16. Auxiliary Heat Rejection System

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Either water or one of the stable organic coolants would be an adequate fluid for the expected operating temperature of 460°F. With the power system radiator enclosed in the shroud, the radiator operating temperatures will be increased approximately 100°F, and this increased temperature level will apply over the entire system with the exception of the fuel capsules, whose temperature will increase only 40 to 60°F. At these temperatures, the external heat pipe radiator will be 22 percent larger than the power system radiators.

The Saturn shroud is constructed of 2024 aluminum honeycomb and since it is enclosed on both sides by heat pipes, it cannot be effectively insulated and will operate at the 460°F heat pipe temperature. The shroud is a major load-carrying member and its strength would be reduced to approximately 50 percent of room temperature under these conditions. Depending upon the present shroud design margins, shroud strengthening may be required.

In the case of the Po-210 power system, a high temperature heat pipe radiator is also located adjacent to the power flattening radiator as shown in Figure 8-16. This radiator is constructed entirely of stainless steel to operate at a temperature of 1125°F. Sodium vapor will serve as an adequate heat transfer medium at the low heat fluxes required. The operating temperature of the power flattening radiator will also be increased by 100°F when enclosed in the shroud and the external heat pipe radiator will be 87 percent larger than the power flattening radiator. The radiator configuration is different from that of the low temperature heat pipe radiators because of the higher operating temperature. At 1125°F, the aluminum honeycomb would melt and, consequently, the radiator is placed in different locations on the interior and exterior to allow the radiators to be insulated from the shroud surfaces.

These are major modifications to the shroud, and if such modifications are necessary, it may prove more attractive to replace panels of the present shroud with sections similar to those shown in Figure 8-17. For the low temperature radiator, a honeycomb aluminum structure consisting of rectangular cross section tubes located circumferentially around the vehicle could provide the necessary heat pipe action. A wick within the tube would allow heat input on the interior surface, heat rejection from the exterior surface, and

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Figure 8-17. Alternate Auxiliary Radiators

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capillary fluid return. For the high temperature radiator, a stainless steel section supported by ribs would act as a structural member, receive heat from the power system radiator, and reject the heat to the environment.

8.8 EMERGENCY HEAT REJECTION

As previously discussed in considerations of large radioisotope heat sources, it is considered essential that the heat source be provided with a system that will throw it free of the spacecraft in the event of a mission abort. This is necessary to reduce the probability that the heat source will be trapped in its insulated heat exchanger with inadequate cooling and thereby, result in a partial meltdown of fuel or its cladding. If heat source ejection is required prior to ejection of the shroud, the shroud would present an interference. To prevent this occurrence, an ejection chute may be incorporated in the shroud as shown in Figure 8-16. The chute will serve to guide the ejected heat source through the shroud access door which will be released as illustrated by the ejected heat source.

The combined shroud modification of heat pipe and emergency ejection chute will result in the weight increases listed in Table 8-3.

Table 8-3. Shroud Heat Pipe Radiating System

Item	<u>Po System</u>		<u>Pu System</u>	
	Area Ft ²	Weight Lb	Area Ft ²	Weight Lb
Radiators				
Low Temp	180	400	180	400
High Temp	22	126	15	90
Insulation	-	30	-	28
Ejection Chute	-	22	-	25
Ejection Mech	-	11	-	11
Hardware	-	<u>59</u>	-	<u>59</u>
Total Weight		648		613

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