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MASTER

LARGE RADIOISOTOPE COMPACT CONVERTER
POWER SYSTEM STUDY FINAL REPORT
TO THE
U. S. ATOMIC ENERGY COMMISSION
(Title Unclassified)

AEC Research and Development Report

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ISOTOPIC SNAP PROGRAM,
ADVANCED CONCEPTS
FOR FUTURE APPLICATION
CONVERSION DEVICES
M-3679 (44th Ed.)

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TO THE
U. S. ATOMIC ENERGY COMMISSION
(Title Unclassified)

Prepared by
Atomsics International
Technical Staff

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SECTION I. INTRODUCTION

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I. INTRODUCTION

A. PROGRAM SCOPE AND OBJECTIVES

A study of large radioisotope electric power systems utilizing compact thermoelectric converters has been completed by Atomics International for the U. S. Atomic Energy Commission. The study consisted of a three-month engineering and design effort. Four specific systems were designed using two fuels and two different compact converters.

The objective of this study was to examine the use of compact thermoelectric converters with large radioisotope heat sources as complete power systems in order to gain information which can be used by the AEC in direction of its on-going compact converter programs and future heat source development programs.

In order to give the study a mission base for configuration and integration evaluations the AEC established the specifications shown in Table I-1. The reference systems were to provide 2.0 kwe at end of life for manned missions of 90 days and 2 years, using Po^{210} and Pu^{238} , respectively. The manned mission specified was the Apollo Applications Program (AAP) which appears to be the next generation NASA manned space flight program.

TABLE I-1
STUDY SYSTEM AND MISSION SPECIFICATIONS

Mission Type	Manned Earth Orbital (up to Saturn V)
Mission Spacecraft	Apollo Applications Program (CM, SM, LEM, SLA, MM)
Mission Life	
With Po^{210} Systems	90 days in orbit plus 14 days launch pad hold, with 30 days between fuel encapsulation and delivery to launch site
With Pu^{238} Systems	Two (2) years total mission duration
Mission Launch Date	1972
Electrical Power Level	
Reference Systems	2.0 kwe at end of life
Parametric Evaluation	1.0 to 5.0 kwe at end of life

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The entire study was built upon past and present AEC radioisotope heat source and thermoelectric conversion programs. The work statement specified that the results of the Large Radioisotope Heat Source Study* be used along with the Radio Corporation of America (RCA) and Westinghouse Corporation compact converter designs. The resulting power systems were studied at 2 kwe and parametrically examined between 1.0 and 5.0 kwe to establish the effects of changes in conversion subsystem and heat source parameters on total system performance.

B. FINAL REPORT FORMAT

This document presents the information generated in the study, together with the recommendations and conclusions which have resulted. Specifically, Section II contains a summary of the system designs, parametric analysis, and the recommendations concerning heat source and compact converter development.

Section III contains a comprehensive discussion of the AAP program based on the most current, available NASA planning information. This section is of prime importance from the standpoint of the logic for key design and integration decisions which are included later in the report.

The polonium systems analysis and designs (the reference 2-kwe systems) are included and discussed in Section IV. This section contains component descriptions, subsystem tradeoff studies, heat transfer analysis, mechanical design work, system integration, operational analysis, operational safety, and system reliability sections. The plutonium systems are presented in a similar manner in Section V.

Section VI contains a detailed parametric analysis of system performance characteristics. The system characteristics vs power level in the range of 1.0 to 5.0 kwe are presented. Section VI also contains the results of off-design performance and effects of changes in reliability.

In Section VII an alternate system is presented; this consists of cascading the RCA and Westinghouse converters for maximum performance within the specified operating envelope of each. The system utilizes the full capability of each converter and the heat source.

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C. REFERENCE DOCUMENTS

This study is based extensively on past component and subsystem study and/or development work. The principal technical references for this work are included below. A number of documents related to the AAP mission were used and are also referenced. This study was closely coordinated with the Reactor-Compact Converter Study which was performed concurrently by Atomics International for the AEC.

Heat Source References

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Large Radioisotope Heat Source Study Mid-Term Report to the NYOO of AEC, AI-65-144 (CRD), August 20, 1965

Large Radioisotope Heat Source Study Final Report to the NYOO of the AEC, AI-65-221, Volumes I, II, and III, December 17, 1965

Preliminary Design of a Pu²³⁸ Isotope Brayton Cycle Power System for MORL, SM-48835 Volume IV, Book 1, Nuclear Systems

Thermoelectric Converter References

Final Phase I Report for Compact Thermoelectric Program, NYO-3582-12 Radio Corporation of America, January 1966

Final Progress Report, Compact Thermoelectric Converter, WANL-PR(cc)-006, Westinghouse Astronuclear Laboratory, January 15, 1966

Mission Analysis and Vehicle References

Preliminary Definition Phase (PDP), Apollo Extension System (AES), Master Program Plan, NA-SID-65-1145, December 20, 1965

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Final Report, PDP, AES, Subsystem Summary, SID-65-1519, January 17, 1966

"Extended Apollo Systems Utilization Study, Prolonged Missions Final Report, Volume 3. Subsystems, Appendix B, Isotope Dynamic Power System for Prolonged Missions Apollo," SID-65-968-3B, July 22, 1965

PDP, AES, Manufacturing Plan (Preliminary), SID-65-1146, December 10, 1965

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SECTION II. SUMMARY, CONCLUSIONS,
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II. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

A. SUMMARY OF RESULTS

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Summaries of results and conclusions are presented below in three categories: mission requirements, system integration, and overall system performance.

1. Mission Requirements

A detailed discussion of mission requirements, sequence, and philosophy is presented in Section III of this report. It has been concluded that a 2- to 3-kwe radioisotope power supply will be needed in the 1971 time period for a series of 90-day earth orbital missions. These isotope systems will provide prime power for both the AAP command and service modules (CSM) and a dependent mission module (MM). The mission module for prolonged missions will change as the program proceeds, but probably will be composed initially of the CM-Lunar excursion module (LEM)-SIV-B propellant tank combination. By using the LEM as an air lock between the CM and the exhausted SIV-B stage propellant tanks a large volume laboratory can be made available in the early 1970's.

Based on present planning, the sequence of missions leading to the above laboratory concept is summarized as shown in Table II-1. It can be seen that as early as 1971 a 90-day power system is required. It can also be seen from this table that early importance is being placed on increasing mission duration as opposed to simply using many 14- to 28-day spacecraft.

2. System Integration

Since the CSM must contain a power system regardless of the type of laboratory and since it is logical to provide one power system for both vehicles, it was concluded that the most desirable location for the power supply relative to a 90-day mission is in the service module (SM) of the Apollo spacecraft. In this manner a power-dependent laboratory concept is achieved, the Po^{210} EOL disposal is quite easy, extension of the laboratory life by CSM resupply at 90-day intervals is accomplished by Po system resupply, and a minimum number of integration problems and interfaces are achieved.

It was concluded that a 2-year Pu^{238} system is not required by the near-term NASA missions. However, as the AAP mission grows into either a

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TABLE II-1
PRESENT AAP MISSION SEQUENCE

Schedule	Estimated Number of Flights	Mission Type	CSM* Designation	Mission Duration (days)	Power System
1968 to 1971	6 to 8	Earth-Orbital	Block IIA	28 to 56	P&W Fuel Cells (400-hr life)
1970 to 1971	3 to 5	Lunar-Orbit and Surface	Block IIA	14 to 28	P&W Fuel Cells (400-hr life)
1970 to 1972	5 to 7	Lunar-Orbit and Surface	Block IIB	28 to 45	Modified Fuel Cells (~1000-hr life)
1971 to 1973	12 to 15	Earth-Orbital	Block III	45 to 90	Radioisotope Power/Solar Cells (90-day life)

*Block II is the present manrated Apollo CSM.

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TABLE II-2
AREA AVAILABLE ON APOLLO SERVICE MODULE*

Location	Approximate Area (ft ²)	Desirability
1. Sector IV Only	70	Most Desirable
2. Sector IV + Sector I of SM	140	Acceptable (1)
3. Sector IV + 4 ft extension on SLA [†]	250	Acceptable (2)
4. Sector IV + Sector I + 4 ft of SLA	320	Acceptable (3)
5. Deployable Radiators on SM	-	Undesirable
6. More than 4 ft extension on SLA	180 to 500	Probably Unacceptable

*Based on discussion with NAA-Space and Information Systems Division

[†]SLA is Spacecraft LEM Adapter

() Order of Acceptability

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Manned Mars/Venus flyby or a medium-sized long-life earth orbital laboratory (1 to 5 years) a 2- to 5-kwe Pu²³⁸ system will be of interest. For the purposes of this study the Pu²³⁸ systems were also integrated into the CSM. This was done because the integration constraints are typical of those which would be found in a Mars/Venus mission. Further, no details are available for a mission module design.

The recurring conclusion relative to radiator area was again apparent. That is, prime radiator area is at a premium on spacecraft of the AAP type. Table II-2 shows the available service module area as additional liberties are taken with the spacecraft.

With both the RCA and Westinghouse converter systems, care was taken in the design point selection to pick Carnot efficiencies which were on the low area side of minimum weight. It was found that the system which used the RCA converter could be operated within the combined area of Sectors I and IV, and within the volume limits of Sector IV only. The Westinghouse compact converter system was integrated into the service module, Bay IV, and by use of a three-foot radiator, laid over the SLA, can meet its integration requirements. This left Sector I open for experiments while remaining within the limits of the extension over the SLA. These decisions and area allocations are based on the intangible penalties associated with area increases. In the present Apollo spacecraft only Sector IV is used. The fuel cells require nearly all of the Sector IV volume but only slightly over half of the Sector IV area. The most desirable replacement power supply would be one which also stayed within these constraints. Neither of the thermoelectric systems, however, can operate with a 70-ft² limit. Therefore the next "most acceptable" approach is the combined utilization of Sector IV plus Sector I. In the present Apollo mission Sector I is unused, though plans are being made to make this sector an experimental bay where various space experiments can be placed. It is therefore concluded that a minor penalty is incurred by requiring Sector I for the power supply. This penalty is overcome by the advantages of the increased life and power output and decreased weight of the radioisotope power supply.

Systems using both the RCA SiGe and Westinghouse PbTe converters can be made to fit within the 140-ft² limit (including power-flattening area) of Sectors I

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plus IV. However, the PbTe system would be compromised both in weight and efficiency by the limited area, and therefore additional area locations were examined.

There is no additional surface area available on the SM. Deployable radiators are undesirable from the standpoints of system reliability, view factors to the lower temperature ECS radiators, and additional projected drag area. In conjunction with S&ID, it was therefore decided not to consider deployable radiators further.

The spacecraft LEM adaptor (SLA) is the structural skin which provides the transition from the bottom of the SM to the Saturn IV-B stage. The SLA houses the LEM during launch. On Apollo it opens in petals to allow CSM access to the LEM. This same sequence of events will be used in AAP. It becomes obvious that to integrate into the SLA results in a major perturbation to both the qualified structure and the mission sequence. Therefore, area on the SLA can only be obtained on the surface with no permanent structural ties. Provision must be made for attachment of any extended SLA wraparound radiators to the SM. This allows SLA/SM separation to take place at the presently designed interface. There is a limit on the extension of the radiator area below the SM, this limit being set by the SM propulsion engine, which is radiation cooled. Any wrap-around, extended radiator must not reduce the view factor to space to such an extent that engine overheating occurs. In conjunction with NAA-S&ID, it was determined that a 3- to 4-ft extension is acceptable.

It was decided to place part of the Westinghouse radiator over the SLA. The remaining area, along with the power-flattening radiator, was placed on the surface of SM Sector IV. Sector I was left unused. An intangible penalty is acquired by the Westinghouse system by use of the SLA wraparound radiators; however, an offsetting benefit is derived by leaving Sector I empty and free of radiators. The different approach for each system allows integration at more nearly the optimum operating point of each.

3. System Performance

a. Reference 2-kwe System Performance

The four system designs, namely systems using Po and Pu coupled with both the RCA and Westinghouse converters, are summarized in Table II-3. The

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TABLE II-3
SYSTEM DESIGN AND PERFORMANCE SURVEY

Parameter	Po ²¹⁰ RCA	Po ²¹⁰ Westinghouse	Pu ²³⁸ RCA	Pu ²³⁸ Westinghouse
Electrical power (kwe)	2.0	2.0	2.0	2.0
System orbital life	90 day	90 day	2 yr	2 yr
Prime radiator area (ft ²)	120	200	135	250
Power flattening area (ft ²)	15.0	12.5	0	0
Total system weight (lb)	1664	1618	3265	2870
Shielded heat source weight (lb)	1070	807	2605	1930
Power conversion subsystem weight (lb)	594	811	660	940

weights and areas are based on the derived and specified operating parameters given in Tables II-4 and II-5. It can be seen that the system utilizing the Westinghouse converter requires more area than the RCA system but is somewhat lighter in weight. Both systems can physically meet the weight, area, and volume constraints of the AAP spacecraft.

The specific data points given in Table II-3 are from the system optimizations performed at 2.0 kwe for each fuel and converter. The weight, area, and efficiency parameters are given in Figures II-1 through II-4. Indicated on the figures are the selected design operating points.

In Figure II-1 it can be seen that the RCA Po²¹⁰ system operating point was selected as a compromise between minimum weight, maximum efficiency, and the SM area restriction. The selected 4-1/2% efficiency could be pushed to 5-1/2% but this would require that the radiation area be increased to 350 ft² or a factor of 3 increase to achieve the 20% increase in system efficiency.

The 2-kwe Po²¹⁰ RCA converter system shielded for a total mission dose of 10 rem has a weight of 1664 lb, as indicated in Table II-3. Because of the efficiency difference between the RCA and Westinghouse systems the RCA converter system heat source is the heavier of the two at 1070 lb. However, the smaller radiator area associated with the RCA converter results in that system having the lowest PCS weight (594 lb).

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TABLE II-4
HEAT SOURCE AND TE CONVERTER OPERATING
PARAMETERS FOR Po^{210} 2-kwe
REFERENCE SYSTEMS

	Heat Source	RCA Converter	Westinghouse Converter
Primary coolant inlet temperature ($^{\circ}\text{F}$)	1300/1000	1500*	1100*
Primary coolant exit temperature ($^{\circ}\text{F}$)	1500/1100	1300	1000
Secondary coolant inlet temperature ($^{\circ}\text{F}$)	-	405	290
Secondary coolant exit temperature ($^{\circ}\text{F}$)	-	605	390

*Specified by the AEC

TABLE II-5
HEAT SOURCE AND TE CONVERTER OPERATING
PARAMETERS FOR Pu^{238} 2-kwe
REFERENCE SYSTEMS

	Heat Source	RCA Converter	Westinghouse Converter
Primary coolant inlet temperature ($^{\circ}\text{F}$)	1300/1000	1500*	1100*
Primary coolant exit temperature ($^{\circ}\text{F}$)	1500/1100	1300	1000
Secondary coolant inlet temperature ($^{\circ}\text{F}$)	-	380	285
Secondary coolant exit temperature ($^{\circ}\text{F}$)	-	580	385

*Specified by the AEC

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Figure II-1.
 Po^{210} RCA System
 Performance vs Carnot
 Efficiency

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Figure II-2.
 Po^{210} Westinghouse
 System Performance vs
 Carnot Efficiency

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Figure II-3.
Pu²³⁸ RCA System
Performance vs
Carnot Efficiency

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Figure II-4.
Pu²³⁸ Westinghouse
System Performance
vs Carnot Efficiency

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The Westinghouse converter Po^{210} system performance is shown in Figure II-2. At the reference design point it weighs 1618 lb. This is composed of 807 lb of shielded heat source and 811 lb of PCS.

It can be concluded that at this design point there is an insignificant weight difference between the two systems. The Westinghouse system exhibits the best efficiency and hence fuel economy, while the RCA converter results in a system with the most attractive radiator area.

The Pu^{238} systems evaluated exhibit considerably different characteristics from those of the Po^{210} systems. With Pu^{238} systems the shielded heat source will be between 70 and 85% of the total system weight, as opposed to Po^{210} systems where it is between 55 and 70%. For this reason the minimum-weight point will be reached at a higher radiator area and Carnot efficiency. Whereas the RCA and Westinghouse Po^{210} system minimum weights occurred at 52 and 48% Carnot, the minimum Pu^{238} system weights were reached at 57 and 52% Carnot. Because of the area, Carnot efficiency, and total system weight it was necessary to allow an increase in radiator area in the Pu^{238} system designs. Instead of the 120 and 200 ft^2 associated with the Po^{210} RCA and Westinghouse converter systems, the Pu^{238} system areas were increased to 135 and 250 ft^2 , respectively. These area allocations were again compromises between a desirability for high efficiency, minimum area, and minimum weight, as can be seen in Figures II-3 and II-4. The system using the RCA converter can still fit within Sectors IV and I because no power-flattening radiator is required. The Westinghouse converter also is integrated in a fashion similar to that employed with the Po^{210} system.

The Pu^{238} system weights are about double those of the Po^{210} . They vary from 3265 lb using the RCA converter to 2870 lb with the Westinghouse converter. These weights are for the reference 2-kwe, 2-year systems at the design conditions specified in Tables II-4 and II-5.

The above reference systems are based on the heat source designs from the Large Radioisotope Heat Source Study. The individual capsule re-entry protection which exhibits a high weight is used. Further the Pu^{238} capsules are designed for 5 years at operating temperatures rather than 2 years. These factors all add weight to both Po^{210} and Pu^{238} systems. If refined heat source

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Figure II-5.
 Po^{210} RCA System
Weight vs
Power

Figure II-6.
 Po^{210} RCA System
Area vs Power

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design was done using either capsule or source block concepts, considerable weight could be removed from the systems.

Several additional areas for potential weight reduction exist. The first is in the radiator. In order to simplify integration and operation the power system radiators were designed to survive the aerodynamic launch loads directly. Weight reduction could be achieved by a more integral or an externally shrouded concept. Another interesting weight reduction potential exists in the heat source shielding. If the spacecraft materials were taken into account in the shielding evaluation a major shield weight reduction would occur. The Apollo CSM has an effective thickness of between 6.0 and 110.0 gm/cm² of Al. Approximately 80 gm/cm² would completely replace the depleted U shield. The total system weight would be reduced by 300 to 400 lb for the same 10 rem/mission dose. This effect is quite mission-dependent and therefore no credit was taken in the shielding calculations.

b. Parametric Performance

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In addition to the four reference system designs discussed above, the study included evaluation of system characteristics as power output was changed between 1.0 and 5.0 kwe. Figures II-5 through II-8 show the effect of power variations on total system weight and radiator area for the Po²¹⁰ RCA and Po²¹⁰ Westinghouse systems. It can be seen that the area is strictly a linear function of power with a constant efficiency while system weight has a slight nonlinear characteristic due to the nonlinear variations of shield weight with heat source thermal power.

The key parameter of interest is radiator area because of the very tight spacecraft area constraint. If one were to use all available area, that is, Sector I and IV and a 4 foot extension over the SLA, the total available area is 300 ft². With 300 ft² and 5.0% system efficiency an RCA converter system of up to 4.8 kwe could be integrated into the spacecraft. With the Westinghouse converter the same area allows growth to 3.1 kwe with an overall efficiency of 6.0%.

It can be concluded that both systems have the capability for meeting the 2 to 3 kwe estimated power requirement for AAP without a major integration problem.

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Figure II-7.
Po²¹⁰ Westinghouse
System Weight
vs Power

Figure II-8.
Po²¹⁰ Westinghouse
System Area
vs Power

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The parametric analysis includes system performance as a function of hot junction temperature, loop pressure drops, element lengths, off-design performance, and different reliability requirements in the range of 0.95 to 0.99.

c. Cascaded RCA/Westinghouse System

An evaluation was performed of the characteristics and variations in performance of a cascaded system using the RCA converter coupled to a Westinghouse converter by an intermediate liquid-metal loop. The rationale for studying this system was the increased efficiency and hence decreased fuel and weight expected from such a system for a limited radiator area. Figure II-9 shows the variation of weight, area, and efficiency with Carnot for the reference RCA and Westinghouse converter inlet temperature conditions. These curves are based on the reference temperatures and 2.1 kwe EOL power.

The Pu^{238} system at minimum weight would require 220 ft^2 of radiator to provide the 2.1 kwe EOL power at a net system efficiency of 8.9%. This minimum occurs at 60% Carnot and yields a Pu^{238} system weight of 2120 lb. The key effects are a reduction in system weight of from 700 lb to 1150 lb, and reduction in fuel inventory by 15 to 20 kw. This is between 30 and 50% reduction in inventory for the same power output as compared to either single converter system.

Figure II-9.
Cascaded System
Performance

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Figure II-9 also shows the cascaded Po^{210} system. In this case minimum weight occurs at a Carnot efficiency of 59%, with a resulting area of 155 ft^2 . The total system weight is a very attractive 1208 lb for 2 kwe. With this system the efficiency is also 8.9% at minimum weight. A significant point can be seen from Figure II-9 relative to the sensitivity of the Po^{210} system to parametric variations. It can be seen that the weight is quite flat as radiator area or Carnot efficiency is changed. Thus, this system could actually be integrated into the CSM Bay IV only (70 ft^2) and still weigh only 1375 lb. Using 70 ft^2 the overall system efficiency is 6.9%, which is higher than either of the single converter systems.

It was found that the intermediate loop temperature between the RCA SiGe-Westinghouse PbTe was not critical. Weight, area and overall efficiency were quite flat for variations in intermediate temperature. This leads to the conclusion that the PbTe could be operated at a very conservative hot loop temperature in such a system with little effect on system performance.

The conclusion of this portion of the study has major significance to isotope applications. It places the TE conversion concept in completely different perspective relative to efficiency, weight, and area for kwe applications while not introducing direct physical coupling problems with the SiGe and PbTe materials.

d. Summary of Performance

The performance of all three types of systems studied, i. e., RCA, Westinghouse, and Cascade, is shown in Table II-6. This table gives the specific weights, area, powers, and energy for each system with both Po^{210} and Pu^{238} .

The performance characteristics discussed previously appear to be very competitive when compared to solar or fuel cell systems. At the 90-day life point both fuel cells and solar cell systems weigh more than the radioisotope TE systems studied. Further, the solar cell system results in definite mission constraints and significant orientation and attitude maneuvering propellant weights. The fuel cell at 2.0 kwe for 90 days weighs four to five times as much as the isotope system.

It can be seen from Table II-6 that while the Pu^{238} system exhibits a much poorer specific weight than the Po^{210} system, the specific energy is much

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TABLE II-6
OVERALL REFERENCE SYSTEM PERFORMANCE

Performance Parameter	Converter Design		
	RCA	Westinghouse	Cascade [*] RCA/ Westinghouse
<u>90 Day Po²¹⁰</u>			
Specific Weight (lb/kwe)	792	809	580
Specific Power (watts/lb)	1.26	1.23	1.72
Specific Area (watts/ft ²)	17.5	10.0	17.5
Total Energy (kwe-hr)	4536.0	4536.0	4536.0
Specific Energy (kwh/lb)	2.73	2.80	3.74
<u>2 Year Pu²³⁸</u>			
Specific Weight (lb/kwe)	1555	1435	1070
Specific Power (watts/lb)	0.64	0.70	0.94
Specific Area (watts/ft ²)	15.5	8.0	17.5
Total Energy (kwe-hr)	36,288.0	36,288.0	36,288.0
Specific Energy (kwh/lb)	11.1	12.7	16.2

*Based on 120 ft² area limit

better. With Po²¹⁰-RCA and Po²¹⁰ Westinghouse for 90 day missions between 2.8 and 2.9 kwhr of electrical energy are produced per pound of system. This is increased to 3.74 through cascading of both converters. With Pu²³⁸ and its long life capability the specific energy jumps to between 11.0 and 13.0 kwhr/lb for the single converter systems and to 16.2 kwhr/lb for the cascaded system. This jump results from a factor of 8 increase in life (2 years) with Pu²³⁸ and only a factor of 2 weight increase.

A comparison of radioisotope system performance with Apollo fuel cells yields perspective to the above numbers. The Apollo fuel cells operated at a power level of 1.7 kwe for 336 hr. This is a total of 571 kwhr. The gross weight of the fuel cell system is 1500 lb. However, allowing a credit of 400 lb for consumable water gives a net system weight of 1100 lb. Using this net weight the specific energy is 0.52 kwhr of electrical energy per pound of system.

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It can be seen that there is almost an order of magnitude increase in performance in going from the fuel cell to the Po^{210} system. The specific energy increase in going from the short life fuel cell system to the 2 year cascaded Pu^{238} isotope system is a factor of 30.

B. STUDY RECOMMENDATIONS

The Large Radioisotope Compact Thermoelectric System Study contained, as a part of the work scope, an assessment of the present compact converter designs and heat source concepts relative to isotope system optimization. This task was to be done within the real constraints of the AAP missions. Based on Atomics International's study results, the following recommendations and findings were established. These are discussed in some detail after their tabulation.

1. Compact Converter Recommendations

- For best system performance the RCA converter pressure drops should be reduced to the same levels as those of the Westinghouse module.
- The present converter element lengths need not be modified for isotope system applications.
- The basic building block converter module with the RCA design should be what is presently considered a submodule.
- The basic building block converter module with the Westinghouse design should be a single tubular element rather than present "four pack."
- Converter weight reduction does not justify a major effort.
- No additional effort directed at volume reduction in the converter is needed for isotope applications.
- Demonstration of reliable operation of the RCA converter in the 1500°F range will require liquid metals compatibility testing.
- The present converter reliability goals are adequate for manned isotope system applications.

2. Radioisotope Heat Source Recommendations

- The liquid metal inventory of the heat source should be minimized.
- High performance thermal insulation development is important in isotope systems and should be continued.

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- Total system subcooling below 930°F prior to launch is recommended for all vehicles utilizing a hydrogen-fueled launch stage.
- Capsule, source block, and reentry system work should be initiated and directed toward the manned kilowatt class of system.
- Future studies and/or system development should take into consideration the shielding effects afforded by the surrounding spacecraft materials.
- Shadow shielding should be used with manned isotope systems as opposed to 4π shields.
- End-of-life disposal of Po^{210} in missions such as AAP should be by ocean burial through either controlled or semicontrolled intact reentry.

3. Discussion

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The above recommendations and findings are based on the study results, manned mission influences, and the present guidelines and specifications for the development of compact thermoelectric converters. Some discussion of these recommendations is in order and is presented below.

The RCA converter pressure drop is the largest contributor to total loop ΔP in the system. A significant improvement in pumping power, pump weight and heat source inventory and weight can be achieved by decreasing the converter ΔP to a point near that of the Westinghouse module. A reduction in ΔP will cause the optimum flow to increase and hence the optimum loop ΔT to decrease to 100°F. Section VI contains a detailed discussion of this analysis.

It is recommended that the present element lengths not be changed. The present compact converter element lengths are near optimum and changes would not yield significant performance improvement.

With both the RCA and Westinghouse modules it was found that practical 2 kwe designs required working with a single tubular converter or a single RCA submodule rather than with the Westinghouse four-pack and RCA module. With presently defined modules, systems in the low kilowatt region will probably utilize partial converters or dummy submodules in certain converter modules.

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The recommendation concerning weight and volume is based on several data points from manned mission studies. It has been found that, in general, the volume limit is of secondary importance to area and weight. Further, it was found that in AAP the available volume for power system integration is from 2 to 5 times more than is required by the isotope power supply. Converter weight is a small fraction of total system weight. Therefore, reductions are relatively unimportant.

Because of the reference operating temperature of the hot junction of the RCA converter, careful attention must be paid to liquid-metal corrosion. Present data at 1500°F with NaK is somewhat lacking. For the 90-day system NaK corrosion with stainless steel should be acceptable. However, data at 1 to 2 years is not available.

The present converter reliability goals, when coupled with those of the other system components, welds, etc., result in achievement of the total system goal without undue redundancy or complications to the system. For manned earth orbital applications, a total system reliability for full power of 0.95 may be acceptable. However, growth to the 0.99 to 0.997 range will be required for future non-earth orbital manned missions. This will probably be achieved by redundancy rather than "order of magnitude" increases in individual component reliabilities.

It is recommended that total loop liquid-metal volumes be minimized. Specifically, the heat source liquid-metal inventory should be held to a minimum compatible with ΔP objectives. This results in lighter weight systems through compensator size reduction, simplification, and elimination. It does not appear within the operational limits of AAP that pad startup requires a void-free loop. This could further reduce the requirements for volume compensation. However, the reference systems are designed for void-free operation throughout startup and operation.

The operational safety evaluation resulted in recommending disposal in the ocean at the end of life. This disposal method can take advantage of the SM semicontrolled reentry characteristic. Ocean burial has been shown previously to be totally acceptable when polonium release is prevented for about five years.

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The systems designed in this study utilized tailored depleted U and LiH shielding to provide a reference 10 rem/mission in the CM. No credit was taken for shielding which resulted from existing spacecraft materials. It has been found that a significant weight or dose reduction occurs if actual attenuation is considered. In some cases studied the shielded dose of 10 rem/90 days was cut to less than 1 rem/90 days simply by considering the effective thicknesses of the spacecraft materials. On the other hand if 10 rem/90 days is an acceptable dose to the men and experiments, the U and/or LiH shield could be cut to almost zero by consideration of spacecraft attenuation.

This study has pinpointed a problem related to prelaunch operations. The problem exists in all launch operations where hydrogen fuel is loaded into the vehicle. It has been found that during and after fueling the hydrogen concentration in the air is so high that either fires or explosions from the hot power system could result. Based on the analysis completed, it is AI's recommendation that provision be made for cooling all portions of the system open to the atmosphere to below 932°F. This includes radiators, piping, source block (if exposed to the atmosphere), etc. This subcooling can be accomplished by use of launch pad support water through a simple clam-shell heat exchanger.

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SECTION III. APOLLO APPLICATIONS PROGRAM MISSION DEFINITION

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III. APOLLO APPLICATIONS PROGRAM MISSION DEFINITION

A. THE APOLLO APPLICATIONS PROGRAM

1. The Manned Space Program Beyond Apollo

NASA has been considering the use of Apollo hardware for a wide range of space missions during and beyond Apollo. The potential program extends from early experiments using minimal adaptations of Apollo hardware, through extended exploration of the earth-moon systems, establishment of MORL-type earth orbital stations, large research laboratories in near-permanent earth orbit, extended operations on the moon, permanent lunar bases, to manned planetary probes. At present, two basic constraints limit and shape this program; (1) future funding availability, (2) the enormous investment in Apollo and Saturn hardware. Because of these it is understandable that completely new hardware for post-Apollo missions is very undesirable. There appears to be a growing feeling in the scientific community that the Apollo/Saturn hardware could be extended to accomplish many important missions not presently included in the fairly restrictive Apollo program.

Thus it appears that the key to the future manned space program could be Apollo Applications – a program tied closely to present Apollo-Saturn hardware and technology; involving earth-orbital, lunar orbital, and lunar flights; and laying the groundwork for the large earth orbit stations, lunar bases, and planetary exploration that will follow.

The first AA spacecraft would be virtually unmodified Apollo hardware carrying a crew of 2 to 3 for 14 to 28 days. Follow-on vehicles may be progressively modified, from extended Apollo vehicles yielding increased mission lifetime, to modified LEMS serving as orbital laboratories or lunar shelters, to mission modules in the SLA and utilization of the S-IVB tankage to provide greatly increased crew quarters and experimental volume.

Obviously, the scope of the AA program is closely related to the success of the parent Apollo program. The present AA program is predicated on early success of Apollo itself and timely availability of launch vehicles and Apollo hardware.

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2. Apollo Applications Program Mission Objectives

The Apollo Applications program is based on the position that the present Apollo lunar landing program is of limited scope and that AA can use Apollo hardware and technology to lead logically and sequentially into the next phase of the manned space program. Thus, AA mission objectives appear to be: (1) to make full utilization of the presently developed hardware for direct and immediate benefits to earth and, (2) to make a valid operational and technological contribution to the manned space program that will follow, and to do so before obsolescence and unjustifiable costs set in.

Earth-orbital flights are the first scheduled AA flights and indeed make up the bulk of the entire program. Mission objectives for these flights fall into three groups:

- a) Earth-oriented experiments: experiments in atmospheric science and technology, earth sciences and resources, and communications and navigation.
- b) Orbital and outer space experiments: biological and physical science studies in zero-gravity, and astronomy/astrophysics.
- c) Support for long-term space operations: this objective appears to be one of the most important of the AA program. Emphasis would center on rapidly extending mission lifetime. Technological experiments could be conducted to provide the eventual capability for permanent manned orbital stations and lunar flight. Experiments in biomedicine, extravehicular activities, orbit transfer and assembly, space rescue, and maintenance and repair of equipment in orbit would most probably be conducted. Advanced spacecraft subsystems for extended missions will probably be developed and operational experience gained. The AA spacecraft will serve as a technological laboratory in which most of the new equipment and techniques for long-term manned space flight can be tested.

The remainder of the AA program is composed of lunar flights and lunar surface exploration. The basic mission objective is to provide data for planning a permanent lunar base and its functions. Early flights will involve remote surveys of the entire lunar surface. This might be followed by extended lunar

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surface exploration involving the first extensive use of roving vehicles to provide surface mobility.

3. Mission Description and Schedule

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The present Apollo Applications schedule is based on a successful Apollo program leading to an Apollo lunar landing in late 1969. The first AA orbital flight could occur as early as 1968; the first moon landing in about 1970, and the last AA mission would probably be launched in the 1973 to 1974 time period. This is the general framework; most of the details still remain to be filled in. NASA has completed limited contract work to define the scope of the AA effort. Advanced studies on adaptation of the Apollo command and service module (CSM) for the Apollo Applications program have been completed by North American Aviation. Grumman Aircraft has done advanced studies on the necessary modifications of LEM. Similar studies have been done for the Saturn launch vehicle systems. Project definition has been completed.

Thus, at this stage, the AA program still appears quite fluid and subject to further definition. However, it appears that in general the program will follow the general sequence noted below.

1) 1968-1969 — Earth-orbital flights of at least 14 days each using the basic CM and SM. Experiments to be carried on a pallet in the SM. Emphasis will center on extending subsystem endurance to increase mission lifetime. Modifications in the area of environmental control and life support systems may increase spacecraft lifetime in orbit up to 28 days.

2) 1970-1971 — Earth orbital flights, lunar orbital and lunar surface exploration. CM and SM may be extended to provide up to 45 days lifetime in earth orbit. Alternate versions of LEM may be developed. For earth orbital missions, the LEM could be stripped to provide laboratory volume. The LEM shelter — for extended lunar stays — and a LEM "taxi" may be developed. Earth-orbital mission lengths may be extended by CSM rendezvous and resupply. The first attempts may also be made to establish a larger dependent laboratory that could be supplied by a series of CSM rendezvous to give extended laboratory lifetime.

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TABLE III-1
AAP MISSION SEQUENCE

Estimated Flight Period	Mission Type	Estimated Number of Flights	Typical Mission Duration	Booster	Probable Mission Hardware	Experimental Location	Probable Power System
1968-1969	Earth orbital, primarily 200 N. Mi	6 to 8	28-day primary spacecraft capability. Longer missions with rendezvous.	S-IB	Basic CSM with extended life support subsystems. S-IVB Laboratory	Service module pallet, S-IVB Laboratory	Fuel cells
1970-1971	Earth orbital, primarily 200 N. Mi	10 to 12	28 to 45 day primary spacecraft capability, longer with rendezvous.	S-IB	Extended CSM, S-IVB Laboratory, Mission module.	Service module pallet, S-IVB Laboratory, Mission module	Modified fuel cells
	Lunar orbit and surface exploration	3 to 5	14 to 28 days	S-V	Extended CSM, LEM shelter, LEM taxi	Service module pallet, LEM shelter, Lunar Roving Vehicle	Modified fuel cells
1972-1973	Earth orbital, primarily 200 N. Mi	12 to 14	45-90 day primary spacecraft capability. Missions to one year with rendezvous.	S-IB	Extended CSM Mission module	Service Module pallet, Mission module	Isotope systems
	Extended lunar surface exploration	2 to 4	28-or more days	S-V	Extended CSM, LEM shelter, LEM taxi	Service module pallet, LEM shelter, Lunar Roving Vehicle	Isotope systems, modified fuel cells

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3) 1972-1973 — Earth-orbital and lunar exploration missions will probably grow in duration, power, and volume requirements. Increased laboratory volume will be provided by some, as yet undefined, "Mission Module" or by utilization of S-IVB propellant tankage. The mission module would be located in the LEM interstage area and would replace the present LEM. The S-IVB stage may be modified by including air locks in the tankage. By utilizing a modified LEM as an air lock between the S-IVB tankage and the CM, a large volume laboratory could be provided. This program probably phases into large space stations of MORL class.

A summary of the predicted AA mission sequence and description is shown in Table III-1.

B. REPRESENTATIVE MISSION PROFILES

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1. Launch Vehicle and Laboratory Configuration

The reference mission for this study is the establishment, operation, and eventual disposal of various manned earth orbital laboratories using Apollo Applications hardware. The great majority of the projected AAP missions are earth orbital; of these, the great majority are 200-nautical-mile orbits. For this class of mission the launch vehicle will be the S-IB.

It is evident that for the longer earth-orbital lifetime missions (90 days to 2 years) to be considered in this study, additional laboratory volume — both for experiments and living quarters — will be necessary. Provision of this volume is the subject of current AA studies. Three potential alternatives appear feasible:

1) a stripped-down version of LEM

2) the S-IVB stage tankage. By providing the S-IVB propellant tankage with a hatch and using the LEM as an air lock between the CM and the exhausted propellant tanks, a large volume laboratory can be made available. This laboratory version may be used early (1968 to 1970) in the AA program.

3) a "mission module." The module could be located in the LEM interstage area, replacing the present LEM. Airlocks would probably be located on both ends of the module. Under the mission module concept, a number of modules could be interconnected in a variety of configurations to provide a

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laboratory of great versatility. This laboratory version would probably be used later (1970 to 1973) in the AA program. Due to its versatility and availability consistent with the reference 1972 launch date for this study, the mission module concept was selected for the reference laboratory.

As discussed in Section A above, emphasis in the AA program is apparently being placed on rapidly increasing the basic CSM and laboratory lifetime, as opposed to simply using a series of 14-day spacecraft to extend mission lifetime. A 90-day isotope power supply may be required as early as 1971.

Currently NASA is considering both independent and dependent laboratory concepts, i. e., the prime power supply located in the CSM or MM. Since the CSM must contain a power system regardless of the type of laboratory, it is logical to provide one system to satisfy both power requirements. Further, if the dependent lab concept is assumed the resulting space hardware is well defined. With this in mind, the reference heat source position for both the Po^{210} - and Pu^{238} - fueled systems was taken as the aft end of the SM in a dependent lab configuration. This location has a number of advantages:

- 1) Heat source and power conversion volume is readily available.
- 2) Adequate radiator area is available.
- 3) Location is compatible with the dependent laboratory concept.
- 4) Extension of laboratory (MM) life with the Po^{210} heat source is readily accomplished by CSM resupply at 90-day intervals.
- 5) Lab/CSM integration and interface problems are held to a minimum.
- 6) Maximum heat-source-to-crew separation distance is provided during orbit establishment.
- 7) Maximum heat-source-to-crew separation distance is provided during laboratory establishment and operation.
- 8) The inherent semicontrolled, intact reentry capability of the SM is always available to the heat source.

Capability for controlled intact reentry of either the Po^{210} or Pu^{238} heat sources is obtained by a combination of heat source location and design. Location

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of the heat source in the SM provides a semicontrolled reentry probability much greater than the man survival probability. Survival through aeroheating is provided for by the capsule or source block design.

The guidelines established for the power system study as derived from the above discussion of the AA program are summarized in Table III-2 below.

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TABLE III-2
STUDY GUIDELINES ESTABLISHED BY
AA MISSION CONSTRAINTS

	Isotope Heat Source	
	Po ²¹⁰	Pu ²³⁸
Mission class	Manned earth orbit, 200 n.mi	Manned earth orbit, 200 n.mi
Mission lifetime (in orbit)	90 days	2 years
End-of-life power	2 kwe	2 kwe
Mission hardware		
Class	AAP	AAP
Launch vehicle	S-IB/S-V	S-IB/S-V
Logistics/reentry vehicle	Extended CSM	Extended CSM
Laboratory	S-IVB or mission module	Mission module
Year of launch	1972	1972
Power conversion	RCA or Westinghouse compact TE	RCA or Westinghouse compact TE
Reentry mode	Semicontrolled intact reentry	Controlled-intact reentry
Heat source location		
Launch	Bay IV of SM	Bay IV of SM
Operation	Bay IV of SM	Bay IV of SM
Reentry	Bay IV of SM	CM

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PRELAUNCH ACTIVITIES

- a. LOAD ISOTOPE CAPSULES INTO FUEL BLOCK
- b. CHECKOUT SYSTEM ON ISOTOPE POWER
- c. COOL HEAT SOURCE TO 932°F PRIOR TO H₂ FUELING

S-I STAGE IGNITION AND VEHICLE LAUNCH

2-STAGE S-I-B LAUNCH VEHICLE

S-I STAGE CUTOFF AND JETTISON (IGNITE S-I RETRO AND S-IV-B ULLAGE ROCKETS)

S-IV-B STAGE IGNITION AND ORBITAL VELOCITY BUILDUP

LAUNCH ESCAPE SYSTEM JETTISON (AFTER FULL S-IV-B THRUST AND VEHICLE STABILIZATION)

S-IV-B STAGE CONTINUES VELOCITY BUILDUP

HEAT SOURCE REACHES NORMAL OPERATING TEMPERATURE AND FULL POWER

S-IV-B SEPARATION. CSM SERVICE PROPULSION SYSTEM PROVIDES FINAL VELOCITY INCREMENT AND ESTABLISHES ORBIT.

MISSION MODULE LAB IS SENT UP IN UNMANNED VEHICLE

MANNED CSM FROM FIRST LAUNCH DOCKS WITH MISSION MODULE FROM SECOND LAUNCH

JETTISON ADAPTER, I. U., AND S-IV-B

LAB ESTABLISHED AND OPERATING ON NUCLEAR POWER

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Figure III-1. Reference AAP Earth-Orbital Laboratory Mission (Establishment of Orbital Lab)

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2. Mission Operational Sequence

a. Launch Vehicle Capability

The Saturn-IB launch vehicle will be capable of placing a payload of about 33,000 pounds into a 200 nautical-mile altitude, low-inclination orbit, with some assistance from spacecraft propulsion. This means the S-IB has only a limited capability for placing both the CSM and Mission Module into orbit. There would be no significant payload capacity for scientific flights. Therefore, the S-IB launch vehicle will probably be used primarily for rendezvous missions or for missions with the CSM alone.

For the reference mission in this study — a 200-n. mi earth-orbital Mission Module laboratory — two separate launches are required. The CSM and a portion of the experimental payload is orbited by one launch, and the Mission Module and the remainder of the experimental payload is orbited in the second launch. The CSM is sent up with an empty LEM adapter, and the Mission Module, located inside the LEM adapter, is boosted with a CSM shroud to protect it and to mate with the SLA.

A pictorial representation of the establishment of an orbital lab, resupply of the lab, and return of the heat source aboard the Apollo CSM is shown in Figures III-1 and III-2. The reader may find these figures helpful as an outline to the discussion below.

b. Po²¹⁰ Fueled System Sequence

(1) Establishment of Orbital Laboratory

The heat source (without fuel capsules), TE PCS, radiators, and associated piping are integrated into the aft end of the Apollo SM during the normal assembly sequence. This takes place at NAA-S&ID. The isotope fuel capsules are brought to the launch pad and loaded into the heat source up to 14 days before vehicle launch. The power supply is brought up to full power and the entire laboratory/Apollo CSM is checked out on isotope power. Following checkout, and prior to hydrogen loading of the S-IVB tankage, the heat source water boiler coolant supply is turned on and the NaK heat source exit lines are cooled to 900°F. Limiting the maximum temperature of any exposed surface of the system to 900°F or less eliminates the possibility of H₂ propellant ignition.

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Figure III-2. Reference AAP Earth-Orbital Laboratory Mission
(Resupply of Lab and Return of Isotope Heat Source)

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The S-I booster stage is ignited and liftoff occurs. The water boiler umbilical piping is guillotined and heat source temperature begins to rise. With the Westinghouse converter, design heat source temperature and nearly full electrical output power will be reached about 11 minutes after liftoff, during the CSM thrust stage.

With the RCA converter, design heat source temperature is reached about 25 minutes after liftoff, after the initial 80- by 200-n. mi elliptic orbit is established.

Following the S-I stage cutoff and jettison, the S-IVB stage is ignited and the vehicle is accelerated to near-orbital velocity. The S-IVB stage is then jettisoned and the Apollo CSM Service Propulsion System provides the final 5000 ft/sec velocity increment to establish the initial 80 by 200-n. mi elliptic orbit and also to circularize this elliptical orbit at 200 nautical miles.

The Mission Module has been placed in orbit, earlier, by a separate launch in a similar manner, except that a CSM-LEM shroud replaces the Apollo CSM. With this configuration, the S-IVB stage supplies the entire remaining velocity increment to establish the orbit. After the orbit is established, the shroud is explosively separated from the LEM adapter, which peels back to expose the Mission Module.

The CSM, with the isotope power supply, makes rendezvous with the Mission Module and docks, nose first, to one of the air locks of the Mission Module. The LEM adaptor, instrument unit, and S-IVB stage are jettisoned, electrical connections are made from the CSM to the Mission Module, and the laboratory is now established and operational on isotope power.

(2) Laboratory Operation

Following establishment of the laboratory, a variety of mission modes are possible. The simplest is operation of the laboratory for 90 days and then re-entry of the CSM. Other modes possible are resupply of the laboratory by additional CSM's which could dock, connect to the isotope power plant for prime power, and return; rendezvous with additional Mission Modules to form a laboratory complex; 90-day resupply of the Mission Module by CSM's under isotope prime power; etc. Regardless of the laboratory operational mode, it is anticipated that each CSM under isotope prime power will return to earth after 90 days.

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(3) Heat Source Reentry

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To initiate the reentry sequence the CSM will disengage from the Mission Module. The CSM is then oriented for reentry and the SM engine ignited to provide deceleration. Prior to the buildup of reentry aerodynamic heating, the SM is jettisoned and the CM reenters in the normal mode. The Po^{210} heat source remains fixed in the aft end of the SM and continues to provide thermal power to the PCS. The SM reenters in a tumbling mode and impacts in reasonably close proximity to the CM. During the tumbling reentry the power system continues to reject heat from the radiators. Any temperature rise on the radiator surfaces due to reentry aerodynamic heating will be reflected back to the heat source. If reentry heating is sufficient to cause the heat source to rise above 2200°F , a fusible link ejection system will eject the capsules out of the SM. If the capsules do not rise above 2200°F , they will remain in the SM. In either event, the capsules terminate, with high probability, in deep ocean burial.

c. Pu^{238} Fueled System Sequence

(1) Establishment of Orbital Laboratory

The operational sequence is identical to the Po^{210} fueled system.

(2) Laboratory Operation

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Due to the 2-year mission lifetime of the Pu^{238} system, a more optimum laboratory operation and resupply schedule can be obtained. The initial Mission Module and Apollo CSM with the integrated Pu^{238} power supply will form the basic laboratory. Resupply of expendables will be on a nominal 90-day basis. At the end of the first 90 days of operation, a logistics CSM will rendezvous with the laboratory. This vehicle and subsequent vehicles may bring up additional Mission Modules to create a laboratory complex. The logistic CSM vehicles do not require a long-lived power supply since they need only dock with the Mission Module, resupply expendables, possibly exchange crews, and return to earth. Resupply and crew exchange will be on a regular basis throughout the 2-year mission lifetime. During the entire 2-year mission, the original CSM and Pu^{238} power system will supply prime power to the laboratory complex. The original CSM also provides emergency abort capability to the lab crew throughout the entire two years.

(3) Heat Source Reentry

At the end of two years, the present laboratory crew prepares for reentry in the original CSM. Due to the great value of the Pu^{238} inventory in the heat source, the Pu^{238} will be returned with the crew in the CM for reclamation and reuse. The Pu^{238} heat source is transferred to a shielded cask in the CM. A liquid-metal coolant line within the cask is valved into the basic heat-reject radiator on the SM. Thus the original radiator continues to provide capsule cooling. The CSM then disengages and begins the normal reentry sequence. At the time of SM jettison, the coolant lines are severed and the capsules are cooled passively by a beryllium heat sink built into the capsule cask. This heat sink provides capsule cooling from the time of SM jettison until CM splashdown in the ocean — a matter of minutes. Cooling from splashdown until capsule retrieval is by ocean water.

C. APOLLO APPLICATIONS PROGRAM HARDWARE

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1. Launch Vehicles

The space vehicles to be used in the Apollo Applications Program will consist of either of two launch vehicles, together with a spacecraft that may be configured in one of several possible ways. The two launch vehicles, which are being developed initially for the Apollo manned lunar landing program, are the Saturn IB and the Saturn V.

a. Saturn IB Launch Vehicle

The Saturn IB launch vehicle will be capable of placing a payload of about 33,000 pounds into a 200-N. Mi altitude, low-inclination orbit, with some assistance from spacecraft propulsion.

The Saturn IB has two propulsive stages — the S-IB and the S-IVB. The latter is the final stage of both the Saturn IB and Saturn V launch vehicles. It contains the controls and guidance for the total vehicle in an instrument unit (IU) mounted on top of the S-IVB. Each propulsive stage has its own instrumentation and safety systems and receives guidance and control commands from the IU.

The S-IVB stage is powered by a single J-2 engine, burning liquid oxygen and liquid hydrogen, to provide a thrust of 200,000 pounds in vacuum.

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Figure III-3. Apollo Saturn IB Space Vehicle

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The IU is a three-segment, cylindrical, unpressurized structure which houses the instrumentation, including guidance, concerned with vehicle performance from liftoff to insertion of the S-IVB/IU and spacecraft into earth orbit.

Figure III-3 indicates the configurations for rendezvous launches; the CSM is sent up with nothing inside the adapter, and the LEM laboratory or MM, is boosted with a CSM shroud to protect it and to mate with the adapter.

b. Saturn V Launch Vehicle

The Saturn V launch vehicle (Figure III-4) will be capable of placing both the CSM and the LEM, each with large experiment payloads, in lunar orbit or in earth synchronous or polar orbits. The Saturn V has three propulsive stages – the S-IC, S-II, and S-IVB – plus an instrument unit on top of the S-IVB. Each propulsive stage has its own instrumentation and safety systems and receives guidance and control commands from the IU.

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The S-IC stage is powered by five F-1 engines using liquid oxygen and RP-1 (kerosene) fuel to provide a nominal sea-level thrust of 7.5 million pounds. The S-II stage is powered by five J-2 engines, burning liquid oxygen and liquid hydrogen to provide a thrust of one million pounds in vacuum.

The S-IVB stage and the IU for the Saturn V launch vehicle has a restart capability; the vehicle performance functions of the IU extend through translunar injection and the spacecraft transposition phase immediately following (nominally six hours after launch).

Experiment payload performance of the Saturn V cannot be simply expressed. There are various staging concepts for the more difficult missions, and the tradeoffs between laboratory total weight and CSM weight are not of equivalent value in terms of performance. The Saturn V can inject about 245,000 pounds into a 100-nautical-mile earth orbit. But this amount does not represent the weight of the elements above the S-IVB, since the stack limit on top of the S-IVB is 110,000 pounds.

The earth synchronous orbit mission is the most demanding of the alternate Apollo missions in terms of performance. Unlike the lunar orbit mission, the service module cannot perform injection into and out of the synchronous orbit, even if it did not make a plane change to zero degrees inclination. If it proves

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Figure III-4. Apollo Saturn V Space Vehicle

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feasible to relight the S-IVB to start injection into the synchronous orbit, performance capability will provide for about 14,000 pounds of experiment equipment in the LEM laboratory and 2000 pounds in the CSM. Other divisions of equipment weight would, of course, be possible.

For the earth polar orbit at an altitude of 200 nautical miles, and using a yaw steering ascent, the Saturn V would permit an experiment payload of about 24,000 pounds in the LEM laboratory and as much as 38,600 pounds of propellants and experiments in the CSM. This payload capability could permit extensive maneuvering if part of it were used for added propellant.

For the lunar orbital mission, the permissible experiment equipment weight in the laboratory is about 16,300 pounds and 1700 pounds for the CSM, with 3930 pounds of propellant used for in-orbit maneuvers to achieve desired survey coverage.

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2. Command Module

The command module (CM), shown in Figure III-5, will contain crew support systems, displays, control equipment requiring direct access by the crew, and all systems needed for earth entry and landing. In addition, the CM will act as a control center for experiments being conducted in the service module (SM) as well as the CM. The CM is divided into three basic compartments: crew, forward, and aft.

The crew compartment comprises the major portion of the CM. It is an oxygen-pressurized (5 psia), three-man cabin which maintains a habitable environment for the crew during space flights. Spacecraft controls and displays, observation windows, food, water, and sanitation and survival equipment are contained therein.

The forward compartment is located at the apex of the conically-shaped crew module. This compartment is unpressurized, and the center portion is a 30-in. diameter tunnel to permit the crew to enter the LEM laboratory. The major portion of the remaining area is occupied by the earth-landing system.

The aft compartment is a toroidal area located around the lower rim of the conical body. This area also is unpressurized and not accessible to the crew.

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Figure III-5. Cutaway Views of the Command Module

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It contains the CM reaction control motors (which are not used until reentry), impact attenuation equipment, and instrumentation. Storage also is provided for expendables; potable and waste water and reaction control propellants.

The CM exterior is designed to provide shielding against reentry heat. The ablative covering varies from 1.71 inches in a region of high heat load to 0.33 inch in low regions.

3. Service Module

The SM (Figure III-6) is an unmanned and unpressurized vehicle which contains stores and systems not requiring direct crew accessibility. This module contains the propulsion utilized for midcourse correction and for insertion into and from lunar orbit. Also included are fuel cells which in Apollo provide spacecraft power, radiators for spacecraft cooling, and oxygen and hydrogen supplies. The SM remains attached to the CM throughout the space flight; it is separated from the CM just prior to earth reentry, however, and is not recovered.

Provisions have been made in SM Section I for the installation of experimental equipment, such as a self-contained experiment pallet. The pallet is capable of

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Figure III-6. Block II Service Module

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Figure III-7. Existing Lunar Landing LEM Configuration

supporting experiment equipment ranging up to 4000 pounds. The experiment portion of the pallet is equipped with a cover which can be opened or jettisoned after launch in order to expose the experiment activity.

4. Basic LEM

The basic LEM (Figure III-7) is designed to carry two men and required equipment from lunar orbit to the lunar surface, to provide support for the astronauts while on the lunar surface, and to return the men and lunar samples to the CSM in lunar orbit. It consists of two stages: the descent stage, which provides the braking and hover capability needed for landing; and the ascent stage for return to lunar orbit.

The descent stage is the unmanned portion of the LEM. It consists of equipment necessary for landing on the lunar surface and serves as a platform for launching the ascent stage after completion of the lunar stay. The landing gear is attached externally to it.

The ascent stage houses the two crewmen during lunar operations. It provides a pressurized oxygen environment, food, water, communications equipment, and environmental control for the crew for up to 45 hours. It has the necessary propulsion and guidance to return the crew from the lunar surface to rendezvous in lunar orbit with the CSM. It remains in lunar orbit when the CSM departs for earth.

This basic LEM may be modified to provide an alternate Apollo experiments laboratory. These modifications include removal of systems not essential for the experimental missions in order to provide additional volume.

5. Spacecraft LEM Adapter (SLA)

The spacecraft LEM adapter (SLA), shown with the lunar LEM in Figure III-8, consists of the structural interstage between the launch vehicle and the spacecraft. The SLA is required during launch and passage through the atmosphere to support the CSM and to house the service propulsion engine expansion nozzle, SM high-gain antenna, and the LEM.

The SLA is a monocoque structure consisting of panels with linear-shaped explosive charges installed at panel junctions. At the time of SM/SLA separation, the charges are fired, exposing the LEM and permitting the CSM to transpose

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PANEL SEPARATION
BY LINEAR SHAPED
CHARGES

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Figure III-8. LEM/S-IVB Adapter

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180 degrees and dock with the LEM ascent stage. The SLA panels are restrained from opening fully in order not to interfere with the communications of the instrument unit on the S-IVB.

6. Summary

The above provides a general picture of the projected missions, spacecraft, and operational sequence. It should be pointed out that many changes could and probably will occur in the AA program and hardware. However, adequate information was available to study intensively at least one approach to radioisotope system mission integration.

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SECTION IV. P_o²¹⁰ COMPACT CONVERTER
REFERENCE SYSTEM DESIGNS

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IV. Po²¹⁰ COMPACT CONVERTER REFERENCE SYSTEM DESIGNS

This section describes the design and optimization of the reference 2-kwe power systems using the RCA and Westinghouse compact converters with Po²¹⁰ heat sources. The approach used in selecting the reference designs is as follows: The general system configurations and operating limits (e.g. maximum hot-junction temperature) were first established. The system configurations were then examined and the parametric performance of each of the system components was defined. Using the component parametric data, the system performance in terms of total weight and radiator area was determined as a function of the major design point variables, Carnot efficiency (radiator temperature), and flow rate. The selection of system design points was then made on the basis of weight and area considerations involved in the integration of the systems in the Apollo Command and Service Module. The effects of detailed integration requirements, system operational requirements, safety, and reliability were then factored into the design of the reference system at the selected operating point.

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A. COMPONENT AND SYSTEM DEFINITION

The system configuration discussed below defines the components required in a Po²¹⁰ compact converter system, describes the function of each component, and presents the general relationship of the components. The discussion of overall system configuration is followed by a detailed description of each of the system components, the component parametric performance, and its state of development.

1. System Configuration

The general configuration of the systems is essentially established by the specification of the heat source and converter. For this study the heat source has been specified by the AEC to be of the type shown in Atomics International's Large Radioisotope Heat Source Study, that is, a heat source comprised of individual isotope fuel capsules arranged in a compact heat exchanger array. Alternate types of heat sources which could be used in these systems are discussed later in this section. The specifications of a compact heat exchanger geometry for the heat source dictate that heat transfer from the source to the

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thermoelectric converter be by a liquid-metal convection loop. This is consistent with the requirements of a compact converter, the use of which also requires a heat transfer loop between the converter and the waste-heat radiator. The general system configuration, then, is as illustrated in Figure IV-1. The major components are the isotope source, radiation shield, compact converter, and radiator. As indicated by the schematic, heat is transferred from the heat source to the converter by a closed (primary) NaK loop and from the converter to the radiator by a second (secondary) NaK loop. The converter in the system is either the RCA or Westinghouse compact converter. For the reference 2-kwe system designs, the maximum converter hot-junction temperatures have been specified by the AEC as 1500°F for the RCA converter and 1100°F for the Westinghouse converter.

In designing Po^{210} systems, provisions must be made to account for the decreasing power of the Po^{210} heat source. Since Po^{210} decays with a half-life of 138 days, the power at the end of a 104-day mission will be approximately 60% of the power at the beginning of the mission. There are two ways of compensating for the Po^{210} decay. These can be classified as electrical power

Figure IV-1. Po^{210} System Schematic

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flattening and thermal power flattening. With electrical power flattening, the system is designed to produce the required amount of electrical power at the end of life (EOL) and a larger amount of power at the beginning of life (BOL). The excess power at BOL is then consumed in a parasitic load. However, since the system radiator area and internal thermal impedances are fixed in this type of design, the decreasing heat source power over the mission lifetime results in decreasing system temperatures, and the system must be designed to produce rated power at EOL with the converter operating at substantially less than the maximum allowable temperatures. It can be shown that this results in a system weight and area penalty of approximately a factor of two compared to a system designed to produce the rated power at EOL at the maximum allowable converter temperatures. In the second approach, thermal power flattening, a radiator with variable heat rejection capability is inserted in the primary loop and the heat to the thermoelectric converter is maintained essentially constant over the mission life. The converter, therefore, operates at maximum efficiency over the total mission life. The power-flattening radiator is an additional complication to the system; however, it is judged that the substantial improvement in system performance justifies its inclusion.

In the system schematic (Figure IV-1) the power-flattening radiator is shown in the primary loop on the outlet side of the heat source. NaK will leave the converter at a temperature higher than the desired converter inlet temperature. The power-flattening radiator will reject the difference between the power generated by the heat source and that required by the converter and, in the process, reduce the NaK temperature to the specified converter inlet temperature. An alternate location for the power-flattening radiator is in the primary loop on the inlet side of the heat source. This requires the power-flattening radiator to operate at a lower average temperature and, hence, increases its area; it has the advantage, however, of limiting the temperature of NaK at the heat source exit to that desired in the converter. Since there is little data on the compatibility of NaK and stainless steel at temperatures above 1500°F, the power-flattening radiator for the RCA system will be located on the heat source inlet side, limiting the maximum NaK temperature in the system to 1500°F. For the lower temperature Westinghouse system, the power-flattening radiator is located as indicated in the schematic.

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On the basis of the results of the pump evaluation study conducted under the Reactor-Compact Converter System Study and because of the relatively large ΔT available in isotope systems, across-the-line dc conduction pumps, using PbTe thermoelectric material, have been selected for these systems. The pump will be located as indicated in the schematic. In the RCA systems a thermal impedance will be established between the NaK line and the pump thermoelectric hot junction to limit the hot junction temperature of the PbTe to 1000°F.

Expansion compensators are located in both NaK loops to maintain the NaK pressure and to accommodate the change in volume of the NaK with system temperature changes.

The reference system designs use single secondary loops as indicated. The advantages and disadvantages of multiple secondary loops are discussed in the reliability sections.

As indicated in the schematic, shielding of the Po^{210} heat sources is required to obtain acceptable radiation dose levels in the reference manned applications.

2. Component Description and Performance

This section contains a detailed discussion of the Po^{210} system components including component performance, operating parameters, and weight.

a. Heat Source Concepts

The heat source provides the functions of fuel encapsulation, reentry protection and heat transfer. Geometrical shape of fuel encapsulation components is largely dependent on the reentry protection concept. The reentry protection concept, in turn, affects the heat source size and shape. The various reentry concepts which have been investigated can be divided into four categories, as follows:

- 1) Reentry of the fuel in separate capsules.
- 2) Reentry of the fuel enclosed in a lightweight sheet which oscillates like a falling leaf and lands softly.
- 3) Reentry of the fuel enclosed in a lenticular lifting body aerodynamically designed to seek a stable attitude and glide to a soft landing.

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4) Reentry of the complete heat source assembly in a package that is equipped with devices for controlled reentry and recovery.

These four concepts are discussed below. Table IV-1 gives typical characteristics of each conceptual configuration.

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TABLE IV-1
SUMMARY OF REENTRY BODY CONCEPTS

Concept	1 Individual Capsules		2 Lightweight Sheet	3 Gliding Body	4 Recoverable Package	
	Po	Pu	Po	Po	Po	Pu
Isotope fuel	Po	Pu	Po	Po	Po	Pu
Ballistic coefficient, W/C_{DA} (lb/ft ²)	30	110	10	26	-	145
Lift/drag ratio (subsonic)	0	0	0	2	0	0
Terminal velocity (ft/sec)	160	305	92	30	10	10*
Probability of burial at impact	high	high	moderate	low	low	low
Peak aerodynamic rate, (Btu/ft ² -sec)	200	400	50	80	-	125
Heat-protection material						
Broad faces:						
Type	ZnO + Mo	AlF ₃ + Mo	ceramic	ceramic		phenolic refrasil
Thickness (in.)	0.21	1.05	0.10	0.10		2.0
Edges:						
Type	same	same	ZnO + Mo	ZnO + Mo		-
Thickness (in.)	0.4	1.3	1.0	1.0		-
Specific weights (lb/kwt)						
Fuel and reentry protection	5.0	43.2	1.0	1.2	38.6	76.8
Heat exchanger and structure	5.4	5.4	5.4	5.4	10.0	10.0
Unshielded	10.4	48.6	6.4	6.6	48.6	86.8
Shield	8.8	10.0	6.0	6.5	17.6	33.7
Shielded	19.2	58.6	12.4	13.1	66.2	120.5

*with parachute

(1) Individual Capsule Reentry

An attractive method of providing reentry protection, from the point of view of simplicity and reliability, is to provide individual aerodynamic heating protection for each fuel capsule. If the capsules are designed to spin and tumble during the period of intense aerodynamic heating, the heat input rates are distributed over the outer surfaces of the capsules. It has been found that this minimizes the amount of heat-protection material required, as compared with the amount needed for reentry in a stable attitude.

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A typical polonium-fueled capsule with individual reentry protection material is shown in Figure IV-2. The outer surface of the capsule is coated with approximately 0.21 in. of zinc oxide, held in a matrix of molybdenum wire. Zinc oxide sublimates at a temperature of approximately 2800°F, and the endothermic heat of sublimation limits the temperature of the capsule wall to about this same value during reentry.

The capsule in Figure IV-2 is shown with external fins which will insure that the capsule spins during reentry. It is expected that these fins will sublime fairly early during the reentry heat pulse, but the angular momentum which they impart to the capsule will remain. A circular cylinder of this type has a natural trim position with its major axis at a right angle with respect to the relative wind, but its degree of stability is very low. Therefore, the initial spin rate will be practically undamped during the reentry period.

Figure IV-2. Reentry Clad
Polonium Isotope Capsule

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Figure IV-3 shows terminal velocities of nonlifting bodies as a function of ballistic coefficient, $W/C_D A$. Curves are given for atmospheric densities corresponding to standard sea level. The terminal velocity of the polonium-fueled capsule will be 160 ft/sec at sea level. (Impact velocities are very nearly equal to terminal velocities for bodies having ballistic coefficients less than about 300 lb/ft².)

The capsule is designed to survive the shock of impact at terminal velocity and/or earth burial without release of the isotope fuel.

The plutonium-fueled capsule, discussed in Section V, is larger than the polonium-fueled capsule for a given thermal power output. Its ballistic coefficient is higher, as shown in Table IV-1. This increases the intensity of the aerodynamic heating pulse. Consequently, more reentry protection material is required. Because the relative void volume allowed for containment of helium evolved during decay is less for the plutonium-fueled capsule, it is deemed preferable to limit the maximum temperature during reentry to a lower value than with polonium. Thus a material such as aluminum trifluoride, which sublimes at about 2100°F, is used for the plutonium capsule.

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Figure IV-3. Reentry Body Terminal Velocity at Sea Level

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(2) Reentry of Lightweight Sheets

Another approach to the problem of insuring intact reentry of cylindrical fuel capsules is to enclose an array of slender capsules in a body having a large surface area-to-mass ratio. Such a design is shown in Figure IV-4. Curving the block by about 30° of arc will tend to insure a preferential orientation during reentry with its convex face forward. This curvature will not completely suppress oscillation and tumbling of the sheet, and the edges will require application of a rim of heat-protective material.

An alternate design would be to curve the sheet in the shape of a segment of a sphere. This would give added stability in the face-forward attitude, but would require that the heat exchanger be less compact than would be possible with singly-curved sheets.

Preliminary studies indicate that the mean ballistic coefficient of a singly-curved sheet or block can be made as low as 10 lb/ft^2 , for sheets having about 3 ft^2 of surface area (each side). With polonium fuel, the sheets can be fueled to a mean heat source power of $10 \text{ to } 15 \text{ kw/ft}^2$, dissipating half from each side.

Figure IV-4. Light-Weight Sheet

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The greater part of the volume of the lightweight sheet shown in Figure IV-4 consists of a honeycomb or foamed structure, made of a superalloy. The outer surfaces of the sheet are also of a superalloy. The fuel is enclosed in slender tubes of tantalum alloy, with a platinum oxidation barrier.

Terminal velocity for an oscillating sheet of this type could be as low as 92 ft/sec at sea level. The honeycomb and outer structure would absorb much of the shock on impact, and the fuel tubes are designed not to rupture. Burial would not occur upon impact with most surface soils.

The maximum aerodynamic heating rate at the center of a curved sheet of approximately 2-ft diameter is estimated to be 50 Btu/ft²-sec. This figure is based on the calculated trajectory for a nonlifting body having a $W/C_D A = 10 \text{ lb/ft}^2$ with a near-zero initial angle of orbital decay. The equilibrium surface temperature corresponding to this heating rate is approximately 3100°F. Therefore, it is expected that some heat protective material which sublimates at a temperature of 2800°F, ZnO or glass, is required on the forward face of the sheet. Greater thicknesses will be required on the edges of the sheet.

(3) Reentry of Lenticular Lifting Body

A lighter landing can be accomplished if the body is shaped so that it has some aerodynamic lift in the subsonic flight regime just prior to impact. A design incorporating this concept is shown in Figure IV-5. The underside of this body has a large spherical radius which shifts the CG down and stabilizes the body with this side down in the hypersonic flight regime during which maximum heating occurs.

After the body has slowed to subsonic velocities, it loses its tendency to stabilize face-forward, and tends to oscillate over wider limits. The center of mass can be offset horizontally, and stabilizing fins provided will tend to make the body fall on a gliding path. The fins will be on the lee side of the body during the period of high heating, and thus will not melt away.

The predicted specific weight, in pounds per kilowatt thermal of this lifting body is very nearly the same as that of the lightweight curved plate. The additional weight of the stabilizing fins is partially offset by the possibility of saving some weight of protective material due to the flight attitude being more closely controlled.

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Figure IV-5. Lenticular Lifting Body
(Concept 3)

A novel feature shown in Figure IV-5 is the enclosure of the fuel in a flat sheet, rather than in separate tubes. Thus the reentry body has the form of a sandwich, with Haynes-25 honeycomb as the main structure. Heat transfer from the inner surface, surrounding the fuel, to the outer surface is by thermal radiation and conduction through the cells of the honeycomb. It is estimated that a temperature difference of about 100°F will exist between the inner and outer plates when the outer plate is at 1800°F. This design puts a crushable cushion between the fuel container and the point of impact, which helps to absorb the impact energy. This same concept could also be used in the lightweight sheet design, but is not practical for Pu^{238} sources.

The major advantage of this body is the high nonburial probability that its stable and low-velocity landing mode provides.

(4) Controlled Reentry of Complete Heat Source

A controlled reentry and recovery of the heat source assembly is highly desirable if the fuel is valuable enough to offset the resultant high cost in

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equipment weight. One concept for recovery is shown in Figure IV-6. The point of reentry is controlled by firing a retrorocket at a selected point in the orbit.

The reentry package is shaped to be stable in one particular attitude, like a manned reentry capsule. Heat protective material is used on the forward face. At the end of the heating period, a parachute is deployed, reducing the sink rate to a few feet per second. The capsule can then be recovered in the air, or it can be allowed to reach the earth where it can be picked up. Floatation gear would be used for recovery in water.

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The concept of controlled reentry has a disadvantage with respect to the weight of the equipment required for a given thermal power, when it is compared with the other concepts discussed previously. Its use may be mandatory for plutonium fuel, which has a long half-life, giving a greater incentive for recovery. For polonium-fueled capsules, the other concepts are preferable.

(5) Effect of Reentry Mode on Heat Source Design

The major effect that the reentry mode has on heat source design is on the specific weight, as can be seen from an inspection of Table IV-1. For polonium, the fuel and reentry protection weights vary from 1.0 lb/kwt for a lightweight sheet and 5.0 lb/kwt for individual capsules to almost 40 lb/kwt for a reentry body. Heat exchanger and structural specific weights are the same order of magnitude as the encapsulated fuel weights, so the unshielded heat source specific weights vary the same as do the fuel weights. It is readily seen that a recoverable package suffers a substantial weight penalty and its use must be justified on the basis of economics. It is more likely to be used with Pu^{238} than Po^{210} systems.

Integration of either of the source block concepts into a kilowatt thermal heat source will require more than one block per heat source. For large manned systems, the area required for a single source block design is impractical from the shielding and vehicle integration standpoint, but a group of 2 to 5 blocks can be integrated into a compact, cubical array. As an example, six source blocks roughly 17 by 17 by 1 in. would provide the equivalent of 80.6 kwt.

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Figure IV -6. 45-kwt Reentry Package Heat Source, Pu²³⁸ Fueled

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Finally, heat sources comprised of source blocks can be made more compact than with capsules. Because of their compact design, the source block heat source shielded areas are less than those for capsules, and both the shield weights and shielded heat source weights are lower. Thus a lightweight-sheet heat source offers a 35% weight saving over individual capsule designs. However, it presents a probability of burial which must be considered. The stabilized gliding body on the other hand offers a slightly lower weight savings, 32%, but has a lower probability of burial. Because of this, it is a very promising approach.

b. Reference Heat Source Design

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A requirement of the present contract was that the reference heat source was to be one of those designed as part of the Large Radioisotope Heat Source Study reported in AI-65-221. All six of these designs used individual capsule reentry protection. Consequently, none of the other reentry approaches was considered further in this study. Out of the six LRHSS designs, the Universal Modular Heat Source concept was selected because of its adaptability to both polonium and plutonium fuels and its design flexibility. With it, heat sources of varying power levels can be readily designed to match the varying power levels of the parametric studies.

The primary heat source component is the encapsulated fuel. In addition to providing fuel containment during normal operation, a safety and hazards analysis results in additional design criteria. Basically, these imply that all capsules must contain the helium pressure buildup resulting from alpha decay throughout a normal mission, and also provide protection against burnup resulting from abnormal reentry. In addition, the polonium capsule must provide containment on exposure to a launch fire, in the event of earth impact, and under conditions of earth burial or ocean submergence for the effective (~3 to 5 yr) life of the fuel.

The reference Po^{210} fuel capsule is shown in Figure IV-7. The capsule contains a tantalum-dysprosium polonide cermet within a refractory metal structural container. No separate fuel liner is provided in this design since the refractory alloy itself is compatible with the fuel form. A secondary cladding surrounds the primary structural container. This cladding not only acts as

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Figure IV-7. Polonium Isotope Capsule
(Isometric)

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oxidation protection for the refractory metal, but also provides the contamination-free double containment found necessary from past capsule fueling experience. A barrier is employed between the two claddings to prevent intermetallic diffusion. Surrounding the oxidation cladding is an outer layer of reentry protection material. As shown in Figure IV-2, sufficient material is provided to limit the capsule temperature during abnormal reentry of the capsules from orbit or launch abort. This ablative coating is in turn coated with a material (such as alumina) which limits the amount of sublimation which can occur during normal orbital operation.

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In the temperature range of interest, only the refractory metals possess the strength properties required for helium containment. The tantalum alloy, T-222, was selected as the best commercially available container material based on both long-term creep rupture, impact strength-to-weight ratio, and compatibility with the fuel form. Platinum was selected as the most desirable oxidation cladding on the basis of its high melting point in addition to its excellent oxidation and sea-water-corrosion resistance. The high melting point is extremely important in setting the power level for the polonium capsule design, which is limited by the temperature rise of a buried capsule.

A high-temperature alumina-baria-silica glass was selected as the barrier material to prevent interdiffusion between the T-222 primary container and the platinum cladding. This type of glass, which can be crystallized to give an even more stable structure, has been used very successfully in the SNAP reactor fuel elements. The rare earth polonides were selected as the most stable polonium compounds and DyPo was selected for its high dissociation temperature.

The heat source, when optimizations of capsule diameter are performed, decreases in weight as the polonium capsule size decreases; however, the number of capsules required increases rapidly. From the burial standpoint, the most desirable design would be a small capsule with an L/D of one, i. e., one that approaches a spherical geometry. A cost effectiveness evaluation considering launch weight cost vs manufacturing cost indicated that the optimum diameter can vary anywhere from 1/4 to 3/4 in., depending on the launch cost-per-pound assumed and the type of mission. A 1/2-in. diameter capsule was selected in the NYOO study as a compromise, and an L/D of 4 was used to reduce the number of capsules for a given heat source. These same results are used in this study.

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Figure IV-8. Modular NaK Heat Source Panel

The allowable capsule power loading was set by limiting the capsule surface temperature to 2800°F under earth burial conditions. This provides about 400°F of margin to the oxidation cladding melting point. Compatibility of the Ta matrix fuel form with the T-222 is not expected to be a problem at this temperature for short times, and, because of the diffusion barrier, no problems should result with the other claddings.

The polonium capsule can be allowed to reach a temperature as high as 2800°F during the reentry transient because of the large internal void volume and the resultant low helium pressure present. The evaluation of a number of protection approaches for this capsule indicated that composites made up of a moly-wire structural support with ZnO as an ablator is the preferred approach. Use of the high-temperature ablating ZnO results in a relatively thin coating because of increased radiant heat losses to space that is not obtained with low-temperature ablators. The coating thicknesses required for the capsules are 0.21 in.

The second basic component of the heat source is the modular NaK heat exchanger panel which is shown in Figure IV-8. The polonium panel is 17.75 x 0.65 x 10.0 in., machined from Type 316 stainless steel, and consists of 20 machined channels in a 0.65-in. -thick plate. NaK flows through the inlet transition into the inlet manifold, then through these channels to the outlet manifold and transition section. Each channel is 0.368 in. wide by 0.610 in. high. These channel dimensions avoid NaK plugging problems as well as providing a low pressure drop path.

Using these moduels as building blocks, heat sources of differing power levels and temperatures can be synthesized. Each panel can accommodate 17 rows of 4-high stacks of polonium fuel capsules, making a total of 68 capsules. The beginning- and end-of-life powers (90-day mission) are 6.80 and 4.35 kw per panel, respectively. An almost continuous power spectrum of heat sources can be made from filled and partially filled panels.

There is every indication that these panels will not exhibit a corrosion problem during a 90-day mission at the maximum converter inlet temperature used in the temperature parametrics, 1600°F, even though compatibility data for NaK/316 stainless steel is scant above 1450°F. If there is a small amount of corrosion at the higher temperatures, panel walls can be thickened to prevent corrosion puncture. Proper sizing of the flow channels will prevent corrosion

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REFERENCE SYSTEM (2 kwe)	D	W	H
Po-RCA	19.0	28.7	28.0
Po-W	15.5	19.1	20.8
Pu-RCA	23.2	43.61	47.7
Pu-W	22.6	37.9	46.8

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Figure IV-9. Modular Assembly Heat Exchanger

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product deposition and plugging problems resulting from any mass transport. Development testing will be required to determine the magnitude of the problems involved.

The alternatives to the 316 stainless steel-NaK materials combination are available, but they are less attractive. If it is determined that NaK corrosion is a problem in the 1500 to 1600°F range, the first approach to a solution would be to restrict operating temperatures to the 1400 to 1500°F range, where data exist and corrosion is not severe. However, an off-design performance penalty will be incurred as described in Section VI-E.

A second alternative is to use a panel material which is less susceptible to NaK corrosion. At high temperatures, the materials which have substantially greater NaK corrosion resistance than 316 stainless steel are:

- 1) Pure iron,
- 2) Columbium and molybdenum, and
- 3) Tungsten and tantalum (in increasing order of corrosion resistance).

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Pure iron is weak, however, and the other four are refractory metals which rapidly oxidize at temperatures greater than 600°F in contact with air. The latter would require oxidation protection during ground checkout either by maintaining an inert atmosphere in the heat sources or by protective cladding. Either method complicates heat source operation and/or fabrication.

A third alternative is to retain 316 stainless steel and use potassium as the coolant. Potassium is much less corrosive than NaK and has been used for many thousands of hours in the MPRE at Oak Ridge National Laboratory without any noticeable corrosion effects. However, it freezes at 154°F, creating system startup problems which are discussed in a later section.

A heat source assembly is comprised of a number of heat exchanger panels interconnected both mechanically and hydraulically. An isometric drawing of a representative heat source is shown in Figure IV-9. The panels are mechanically fastened together at the protruding lugs. The external flow header can be arranged to provide differing series-parallel flow path combinations. The Po²¹⁰ capsules are loosely held between the panels by triangular supports welded to the panels. They are held loosely so that differential thermal expansion will not bind them, compromising ejection capability.

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Safety analyses have shown the necessity for emergency heat source cooling. With individual capsules, capsule ejection is one method of providing the cooling. In the heat source under discussion, capsule ejection was provided by Rene 41 springs located at the inboard end of the heat source. Each spring forces a stack of capsules against the spring-loaded ejectable door. The door is held in place by a fusible link. If heat source interior temperature exceeds a safe level — in this case 2200°F — the link melts and releases the door. The door is ejected by its springs, and the capsules are ejected by their springs. The capsules are designed to survive any event subsequent to ejection, be it the space environment, atmospheric reentry, earth burial and/or impact, or ocean submergence.

Pertinent parametric characteristics of the heat source are shown in Figures IV-10 and IV-11. In the first figure, the pressure drop as a function of flowrate is shown for a varying number of series-connected panels. It is readily seen that the heat source pressure drop can be made quite low by the proper hydraulic interconnection. The dominant pressure loss is the panel entrance and exit losses. In the second figure, the unshielded heat source weight

Figure IV-10. Po^{210} and Pu^{238} Heat Source Exchanger Pressure Drop (Universal Type)

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Figure IV-11. Unshielded Heat Source Weight - Po²¹⁰ Capsules

is shown as a function of thermal power. In actuality, this weight varies in a stepwise manner because power is always added in discrete weight packages, i. e., fuel capsules and modular panels. However, the difference between this stepwise variation and the faired linear variation shown is slight.

This modular heat source design was used in the parametric system optimization, and two such sources were designed for the reference systems. The modular approach provided a variable power level which was readily related to weight and volume. This design can be used for all temperature levels used in this study. Finally, but most important, it provides the safety features required to survive all credible accidents without polonium fuel release.

c. Thermoelectric Converter

The converter designs used in this study were established by RCA and Westinghouse and are described in their final Phase I reports.*† The converters are

*NYO 3582-12, "Final Phase I Report for Compact Thermoelectric Program," Radio Corporation of America

†WANL-PR (CC) 006, "Final Progress Report Compact Thermoelectric Converter," Westinghouse Astronuclear Laboratory

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Figure IV-12. RCA Module Fabricated from Four Submodules

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assembled from converter modules. Each module consists of four submodules which are the basic building blocks. The description of the two module designs follows.

(1) Converter Descriptions

(a) RCA Converter Module

The RCA converter module is shown in Figure IV-12. It consists of four submodules, each of which is a complete power conversion unit. The submodules are interconnected in series hydraulically and can be connected in series or parallel electrically. Two types of submodules are used, a right- and left-hand unit, differing only in the direction of bend of the electrical and hydraulic connections.

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The submodule (see Figures IV-13 and IV-14) consists of: (1) a single, central hot heat exchanger plate; (2) two banks of SiGe thermocouples with hot and cold insulator stacks at the terminations to provide electrical isolation from the NaK loops; (3) flexible waffle copper connectors; and (4) two outside cold heat exchanger plates. Hot and cold NaK is pumped through internal channels in the heat exchanger plates, and heat is passed from these plates through the SiGe thermoelements by direct thermal conduction. To ensure that the maximum possible temperature differential is maintained across the thermoelements and to ensure that a continuous path is maintained for heat flow, the SiGe elements are metallurgically bonded to the hot heat exchanger plate for high thermal conductance, and are thermally connected to the cold heat exchanger plates by flexible, multi-laminate copper connectors which are brazed at both ends. Each thermocouple assembly thus consists of an electrical insulator (BeO), a tungsten hot strap that electrically interconnects the thermoelements, the thermoelements with shoes, and bimetallic bending moment compensation members (flexible connector) which absorb thermal expansion stresses. Each submodule consists of a 12- by 3-in. array of thermocouples bonded to each side of the hot heat exchanger plate. Use of both sides of the hot heat exchanger plate results in minimum heat loss and eliminates any net tendency toward warping.

Protection against open-circuit electrical failure is ensured through the use of series-parallel circuitry which provides current path redundancy. Three rows of thermoelements are electrically paralleled at the cold-junction end of the thermocouples by copper connectors brazed between insulator stacks.

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Figure IV-13. Partial Side View of RCA Submodule

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Figure IV-14. RCA Submodule Materials

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Figure IV-13 shows the details of the electrical and hydraulic connections. The electrical output from the module is brought out by an expansion-joint connector to an insulator stack terminal on the cold plate. To reduce volume, the heat exchanger plates are made quite thin (0.20 in.). The joint between the liquid-metal tubing and the heat exchanger plates is made on the flat surfaces of the heat exchanger plates where the required seal area is available. The spacing between the hot and cold heat exchanger plates provides adequate clearance for the pipe curvature without special tube-forming requirements.

The heat exchanger plates are fabricated in two halves by milling the coolant channels into two rectangular sheets of Hastelloy-X for the hot plate and type 316L stainless steel for the cold plates. The curved coolant inlet and outlet tubes are then welded into each heat exchanger plate half section and an electron beam weld is employed to join the two half sections together.

The materials used in the thermoelement stackup between the hot and cold plates are shown in Figure IV-14 along with the pertinent dimensions.

The converter module is made up of four submodules. In this assembly, the submodules are connected in parallel hydraulically. Electrically, they are connected either in parallel or series. The converter is then assembled from the modules.

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(b) Westinghouse Converter Module

The Pb-Te converter module designed by Westinghouse also consist of four identical units called a thermoelectric module (submodule). Figure IV-15 shows the Westinghouse submodule. This submodule consists of: (1) the inner clad, (2) the outer clad, (3) the thermoelectric material, (4) electrical insulation, (5) conductor rings, and (6) miscellaneous end-fitting components.

The inner clad forms the flow channel and heat transfer surface for the hot NaK. It is made of Inconel-X750. The outer clad forms the heat transfer surface for the cold NaK and encloses the submodule. It is fabricated from type 316 stainless steel.

The thermoelectric material consists of rings of types N- and P-doped Pb-Te. The P elements are doped with sodium and the N elements are doped with iodine. The powdered material is pressed into washers which are assembled between the inner and outer clad materials.

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Figure IV-15. Westinghouse Converter Submodule

Figure IV-16. Westinghouse Compact Converter Module

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The electrical insulation between adjacent N and P elements is provided by five-mil mica washers. Boron nitride tubes, with a wall thickness of 20 mils, electrically insulate the thermoelectric rings from the inner and outer clad.

The electrical path through the submodule is closed by rings of Armco iron used both on the OD and ID of the thermoelectric rings. This assembly procedure connects all of the thermocouples in a submodule in series. Iron pins connected to the end iron rings project through the end retainers to complete the electrical path.

The end-fitting components consist of the required electrical insulation (Alsimag-222) and end closures.

After the above items are assembled and the outer clad has been welded to the end closures, the entire submodule is degassed using a hydrogen-inert gas-vacuum system. Following degassing, each submodule is swaged to eliminate radial interface clearances and to partially densify the Pb-Te washers. The complete densification of the Pb-Te occurs during the final operation, gas pressure sintering. This process reduces the submodule diameter until densification is complete and all internal voids are eliminated, and develops high contact pressures at the interfaces among the various layers of internal components so that good thermal and electrical conduction across these interfaces are achieved. The gas pressure sintering takes place at 750°C and 10,000 psi for 2 hr using helium as the working fluid.

Four completed submodules are assembled to make a converter module. This assembly is shown in Figure IV-16. In this module assembly, the NaK channels are parallel and the four submodules are connected in series or parallel electrically. These assemblies are then stacked to yield the required electrical output.

(2) Converter Performance

(a) Power Output

The submodule, matched load power output is shown in Figure IV-17 for RCA and Figure IV-18 for Westinghouse. For equal Carnot efficiency, the Westinghouse submodule produces more power than the RCA and has a higher efficiency. However, the RCA submodule has a higher specific power (watts/lb).

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Figure IV-17. RCA Submodule Power vs Radiator Temperature

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Figure IV-18. Westinghouse Submodule Power vs Radiator Temperature

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The data shown here and for the other performance characteristics are based on stable properties established after a suitable burn-in period. Therefore, the data are considered beginning-of-life (BOL) data and appropriate factors must be taken from the degradation curves to obtain end-of-life (EOL) data for the particular heat source (mission life) under consideration.

The effect of element length on power is shown in Figure IV-19 for the RCA submodule and in Figure IV-20 for the Westinghouse submodule. Decreasing the thermoelectric element length results in an increase in submodule power. The data shown are for a NaK ΔT of 100°F for the Westinghouse submodule and 200°F for the RCA submodule.

(b) Efficiency

The efficiency of the RCA submodule is shown in Figure IV-21 and that of the Westinghouse submodule in Figure IV-22. The efficiency of the submodules as a function of thermoelectric length is shown in Figures IV-23 and IV-24. The data shown are for a NaK ΔT of 100°F for the Westinghouse submodule and 200°F for the RCA submodule. As shown in the figures, the module efficiency

Figure IV-19. RCA Submodule Power vs Element Length

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Figure IV-20. Westinghouse Submodule Power vs Element Length

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Figure IV-21. RCA Submodule Efficiency vs Radiator Temperature

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Figure IV-22. Westinghouse Submodule Efficiency vs Radiator Temperature

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Figure IV-23. RCA Submodule Efficiency vs Element Length

Figure IV-24. Westinghouse Submodule Efficiency vs Element Length

decreases with decreasing element length. Therefore, while a reduction in converter weight would occur with decreasing element length, a weight increase would occur in the heat source and radiator.

The efficiencies shown here are the efficiencies occurring at matched load. The maximum efficiency occurs at a somewhat lower current (or higher voltage) than the matched load or maximum power condition. However, the difference is small and the matched load efficiencies have been used in this study.

(c) Weight

Figures IV-25 and IV-26 show the submodule weight as a function of thermoelectric element length. The RCA submodule weight is 3.0 lb at the reference element length of 0.4 in. The Westinghouse submodule weight is 13.95 lb at the reference OD of 1.75 in. These weights include the NaK contained in the submodules.

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Figure IV-25. RCA Submodule Weight
(Includes NaK)

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Figure IV-26. Westinghouse
Submodule Weight
(Includes NaK)

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(d) Voltage

The matched load voltage for the RCA submodule is shown in Figure IV-27, and in Figure IV-28 the matched load voltage for the Westinghouse submodule is shown. In general, the voltage output of the RCA submodule is lower than that of the Westinghouse submodule. This results in somewhat greater flexibility in arranging the RCA submodules in an electrical array which provides matched load power at the require voltage.

(e) Volume

The volume required to house the submodules is shown in Figures IV-29 and IV-30. The RCA design volume is 45 in.³ while the Westinghouse design volume is 41 in.³

(f) Degradation

The power degradation of the RCA submodule is shown in Figure IV-31. The first 1000 hr of operation is discounted as the predelivery burn-in period to provide property stabilization. After the burn-in period, the power degrades 5% in 10,000 hr.

Figure IV-27. RCA Submodule Voltage

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Figure IV-28. Westinghouse Submodule Voltage

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Figure IV-29. Westinghouse Submodule
Envelope Volume
(ID = 0.5 in.)

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Figure IV-30. RCA Submodule Envelope Volume

Figure IV-31. RCA Submodule Power Degradation

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The degradation has no significant dependence on average primary NaK temperatures between 1000 and 1500°F.

Figure IV-32 shows the power degradation for the Westinghouse submodule. The degradation is somewhat dependent on the average primary NaK temperature as shown. For this module, a 500-hr burn-in period is allowed for property stabilization. The degradation shown is for a constant average hot-junction temperature. These numbers were used in the Po^{210} system designs where the power flattener controls hot-junction temperature. The converter degradation for constant power input (T_H increases over lifetime) is about half that shown in the curve. The lower degradation was used in the Pu^{238} system designs where power is essentially constant over lifetime.

(g) Pressure Drop

The hydraulic pressure drop through the RCA module is shown in Figure IV-33. The pressure drop for the flow through both the primary NaK channels and the secondary NaK channels is shown. As the four submodules making up the RCA module are connected in series, a pressure drop considerably higher than that for the Westinghouse design occurs.

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Figure IV-32. Westinghouse
Submodule Power
Degradation

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Figure IV-33. RCA
Module Pressure
Drop

Figure IV-34 shows the Westinghouse submodule pressure drop. For the same flow rate through the modules, the RCA module pressure drop is about 17 times that of the Westinghouse module in the respective reference designs.

d. Heat Transfer Loop and Pumping

(1) Coolant Selection

NaK-78 was selected as the coolant for both heat transfer loops based on a study which compared the prime alkali metals, i. e., sodium, potassium, lithium, and eutectic NaK. The following parameters were investigated in this evaluation:

- 1) Coolant physical properties,
- 2) Effects of coolant selection on system reliability, and
- 3) Effects of coolant selection on system design and integration.

NaK was selected for the reference design for all systems. Size, weight, and reliability were found to vary greatly between coolants. A discussion of the above parameters and their effects on the system follows.

Figure IV-34. Westinghouse Submodule Pressure Drop

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(a) Coolant Physical Properties

Table IV-2 is a compilation of the critical physical properties of the candidate coolants at 1000°F. The primary advantages sodium and lithium offer are the higher heat transfer coefficients and lower required flow rates. However, these advantages are offset by their high freezing point. This is also true of potassium. Use of these coolants would require auxiliary coolant heating and special equipment to insure that freezing would not occur during ground handling. NaK-78 freezes at 12°F and can be maintained in the liquid state without auxiliary equipment throughout all phases of assembly, ground testing, and launch.

Considering the properties affecting coolant mass flow rate, i.e., density and specific heat, lithium requires the lowest flow rate, followed by sodium, NaK-78, and potassium. The corrosiveness of lithium at temperatures in the 1000 to 1500°F range is such that oxidation-susceptible refractory metals would have to be used. For this reason and that of the freezing point, lithium was eliminated from consideration.

TABLE IV-2
COOLANT PHYSICAL PROPERTIES AT 1000°F

Coolant	Density (lb/ft ³)	Specific Heat (Btu/lb-°F)	Volumetric Expansion (per °F)	Freezing Point (°F)	Vapor Pressure (psia)	Thermal Conductivity (Btu/hr-ft° F)
Sodium	50.9	0.301	1.49×10^{-4}	210	5×10^{-7}	37.6
NaK-78	46.4	0.209	1.64×10^{-4}	12	1.5×10^{-4}	15.1
Lithium	29.8	0.996	8.1×10^{-5}	357	$<10^{-8}$	17.6
Potassium	44.4	0.182	1.51×10^{-4}	146	1.1	21.1

Potassium requires a higher pumping power (~20% over NaK-78) and has a high freezing point, but presents the advantage of lower corrosiveness. Although low pumping power and higher heat transfer coefficients are obtainable with sodium, these advantages over potassium are more than offset by its relatively corrosive nature and its relatively high freezing point.

The remainder of the physical properties are such that their influence does not greatly alter the affected system parameters. These properties are electrical resistivity, vapor pressure, volumetric expansion, and viscosity.

(b) Loop Reliability

Loop reliability must be considered when selecting the coolant. The important factors to be considered here affecting reliability in a heat transfer loop are corrosion, weld length, and component life in the design environment. Much data on space components (EM pumps, volume compensators, etc.) for similar systems have been generated in NaK systems. The data tends to favor NaK from the reliability standpoint. Typical component data in 1000 to 1200°F NaK is that for dc pumps. Here, over 200,000 hr of pump operation was obtained without a pump failure. The more stringent weld and material requirements for systems operating in a lithium environment would tend to reduce that system's reliability. In attempting to find reliability data or large amounts of component test data in sodium, lithium, and potassium environments, there was no success. Hence, to maintain the degree of confidence in the designs selected, the highest reliability could be assured with the utilization of NaK.

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(c) System Design Characteristics and Integration

No detailed designs employing all of the considered coolants were done; however, consideration as to specific integration problems of each were studied. The integration factors considered were:

- 1) Variation of stress levels,
- 2) Component location, and
- 3) Variation in assembly and loading techniques.

Again, the experience with NaK systems and the problems created by new materials and handling techniques dictated the selection of NaK.

(d) Primary Alternate Coolant

NaK, at the temperatures being considered in this study, does present one possible problem in that its compatibility with the piping and heat source material, type 316 stainless steel, is not well known at 1500°F and above. If it presents a corrosion problem, the preferred solution would be to reduce the temperature to the 1400 to 1450°F range where NaK corrosion is not a problem. If it is desired to operate at the higher temperatures and corrosion has been determined to be a problem, the more desirable solution is to provide an alternate for the NaK coolant rather than to provide an alternate for the stainless steel, as was discussed in the Heat Source section. The best alternate coolant for avoiding a corrosion problem is potassium. Experience with type 316 stainless steel-potassium systems has demonstrated compatibility at 1600°F for thousands of hours.

The major system problem with potassium is its high freezing point, 156°F. Even though the radioisotope fuel continuously provides heat which will keep the potassium molten, the coolant would be loaded into the system before the fuel so that there would be an unheated period. Many solutions for this freezing problem are available, such as continuously heating the system with battery power, substantially preheating the system to keep the potassium molten while the system cools during a carefully controlled delay period, and loading the potassium as a liquid and letting it freeze in the lines. The latter is the simplest solution, but heating of the lines to 154°F on the launch pad to melt the potassium before fuel loading will be required, and the effect of freezing on

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certain components, particularly the expansion compensator, has not been investigated in detail. To avoid these problems, NaK is evidently the preferred coolant; but if corrosion consideration dictates the need for potassium, it is reasonably certain that the system problems can be readily solved.

(2) Loop Design Considerations

The piping for both loops of the RCA and Westinghouse systems contains the NaK and hydraulically transfers it from the heat source to the associated heat sink. The design requirements of the piping system for each loop are tabulated below.

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Material —	Corrosion resistant steel
Weight —	Minimum
Volume —	Minimum
Pressure drop —	0.5 psi maximum for each loop

The configuration of the piping must be such that it integrates readily into the service module. The piping must also provide the primary means for mounting the thermoelectric pump and NaK coolant loading taps. These loading taps are to include internally mounted nozzles to direct the coolant and maintain proper coolant flow balance during the loading procedure. In all cases, standard tube sizes should be used to minimize costs and fabrication lead times.

All joints are to be inert gas welds, using the parent material as filler. Full penetration welds will be required, conforming to high-temperature NaK specifications. These welds are to be inspected by means of x-ray and die-penetrant techniques. Entire piping subassemblies are required to be helium leak checked such that leak rates more than 10^{-7} cm³/sec are a basis for rejection. The inside tube weld areas are to be clear of weld drop-through so as to eliminate pressure losses due to this constriction.

(a) Design of Loop

The configuration of the coolant system and piping was primarily dictated by integration criteria. The only variables of the piping system that remain to be determined are pipe diameter, length, volume, and thickness. Since the volume requirements are such that they are to be minimum, the design resolves to the selection of the minimum pipe diameter to ensure meeting of the pressure drop

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requirements. Also, by minimizing pipe lengths and the number of bends, the pressure drop can be greatly reduced.

The pressure drop (psi) due to friction in a pipe is expressed by the well known Fanning equation,

$$\Delta P = \frac{2fLV^2\rho}{gD_e}$$

where

f = the Fanning friction factor,

L = pipe length (ft),

V = velocity (ft/sec),

ρ = coolant density (lb/ft³),

g = gravitational constant, and

D_e = equivalent hydraulic diameter (ft).

This equation reduces to:

$$\frac{\Delta P}{L} = 3.58 \times 10^{-7} \frac{\mu^{0.2}}{\rho} \frac{W^{1.8}}{D_e^{4.8}},$$

where

μ = absolute viscosity (lb/hr), and

W = flow rate (lb/hr).

Figure IV-35 is a plot of this equation. Note the slight dependence on this function of temperature (fluid properties in the form of $\mu^{0.2}/\rho$).

Various piping layouts were analyzed using this expression and varying the pipe diameter over the flow ranges were considered. The pipe lengths and the number and angle of the bends were all converted to equivalent lengths and the pressure drops were calculated. The minimum pressure drop system does not exist as long as pipe diameter can be increased. The physical integration scheme

Figure IV-35. Fluid Frictional Resistance

limited the tube size to a maximum of 1.25 in. From this criteria, the piping lengths were calculated and the pressure drops were determined. Table IV-3 gives the piping system parameters for the RCA and Westinghouse systems.

TABLE IV-3
PIPING SYSTEM CHARACTERISTICS

	RCA		Westinghouse	
	Primary	Secondary	Primary	Secondary
Pipe diameter (in.)	1.25	1.25	1.25	1.25
Wall thickness (in.)	0.035	0.035	0.035	0.035
Pipe length (ft)	14.6	47.6	8.75	24.2
ΔP at design flow (psi)	0.25	0.52	0.35	0.47
Material	SS 316	SS 316	SS 316	SS 316

(3) Expansion Compensation

(a) Design Requirements

The NaK system must be provided with a method of providing for volume changes to prevent system overpressure and subsequent rupture of the coolant containment. In addition, the coolant system pressure must be regulated to

prevent pump cavitation and void formation resulting in hot spots. The primary design requirement of the expansion compensator for each loop are tabulated below.

	RCA		Westinghouse	
	Primary	Secondary	Primary	Secondary
Design volume (in. ³)	1150	1250	1260	1300
Operating average NaK Temperature (°F)	1400	525	1050	340
ΔV (design volume/in. ³)	310	110	230	65
Operating pressure (psia)	10	10	10	10

These design volumes could be substantially reduced if the system were allowed to have some void volume while below operating temperatures. For example, the RCA system operated only between the limits of 1500 and 900°F compact converter inlet temperature, and the Westinghouse system operated between 1100 and 900°F. If the expansion compensators are designed to take the volume change only over these ranges, they would be much smaller. System penalties would be imposed for the initial void space and the problem of accurately filling the system, but these might be made to be relatively small.

Welded bellows configurations similar to that employed on the SNAP 10A system will be used. Their selection was based on well known operation and reliability characteristics. Each of these compensators must also contain a secondary volume in the event of a bellows failure. The secondary containment must also provide at least 5 psia to the system. The size of the compensator must be such that it can be easily integrated into the system at the highest point. If the integration limits this requirement, the feed line to the compensator must come off the highest point in the system. This alleviates an added requirement for a hold-down device during launch as additional pressure is created by the static height of NaK above the bellows.

(b) Compensator Design

Two bellows designs were formulated on the basis of the requirements: one design to accommodate the large primary loop volume changes and another for the secondary. The differences in exact volumes would be compensated for by

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changing the convolution number and auxiliary spring requirements. Figure IV-36 is a photograph of a typical bellows configuration depicting both primary and secondary containment.

The stresses were computed by elastic beam theory according to

$$t = \frac{3E\delta t}{L^2} + \frac{PL^2}{2t^2},$$

where

E = modulus of elasticity (lb/in.²),

t = diaphragm thickness (in.).

L = beam length $\frac{OD-ID}{2}$ (in.).

δ = diaphragm deflection (in.), and

P = pressure difference across bellows (psi).

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Figure IV-36. Contained Expansion Compensator

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It has been found experimentally that the stresses as computed from the above equation will be at most 0.7 of that value. A preload of 0.5 psi is provided to insure no voids during ground handling and checkout. This preload is provided by heat treating the secondary bellows in an extended position prior to installation into the compensator. This results in a pressure-loaded top plate prior to loading of the NaK. The primary bellows is heat treated in the stacked or collapsed position. Thus, the primary bellows works in tension and the secondary bellows operates in compression.

Table IV-4 lists the characteristics of the bellows designs as formulated for each of the four loops analyzed. Their component weights were found to be within 10% of weight equation formulated for the design optimization studies. These weights are represented by

$$W_{ECU} = 10 + 0.083 \Delta V ,$$

where

W_{ECU} = expansion compensator weight (lb) and

V = system volume change (in.³).

TABLE IV-4
EXPANSION COMPENSATOR CHARACTERISTICS

	RCA		Westinghouse	
	Primary	Secondary	Primary	Secondary
Material	Inconel-718	AM350, SCT 1000	Inconel-718	AM350, SCT 1000
Design primary volume capacity (in. ³)	320	110	240	65
Outside diameter (in.)	12.5	8.2	12.5	8.2
Diaphragm span (in.)	1.0	0.8	1.0	0.8
Diaphragm thickness (in.)	0.010	0.010	0.010	0.010
Diaphragm area (in. ²)	104	40.6	104	40.6
Number of convolutions	32	18	24	10
Weight (lb)	35	20	30	16

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Figure IV-37. Across-the-Line DC Pump Schematic

(4) Pumps

The pump study performed for the SNAP 8-Compact Converter Program* established that dc electromagnetic pumps integrated into thermoelectric systems offered the lightest weight and highest reliability. Based on integration criteria, a direct-radiating dc pump similar to that employed on SNAP 10A was eliminated. This pump would have to view space directly to establish the ΔT across the integral thermoelectric elements and could not stand large amounts of heat being transferred to it from adjacent components. A separate source dc pump (i. e., a unit powered from a separate power source and connected by large bus bars) could not be economically produced with the Westinghouse converter because its output voltage exceeds the voltage requirement of the pump. Also, a separate source pump for these applications was also found to weigh more and cause greater integration problems than self-contained units. For these reasons, the integral-powered, across-the-line dc pump was selected for use with both thermoelectric systems. The pump design represents a scale-up of both the SNAP 2 and 10A designs on which over 200,000 hr of operating data were logged. A schematic depicting the operation and configuration of this pump is shown in Figure IV-37. Note that with this design, both loops are pumped from a common integral thermoelectric source.

With the design concept selected, a number of ground rules were established based on test experience. Typically, these were:

- 1) The integral thermoelectric elements are to be PbTe and PbSnTe as was used on SNAP 10A. The upper temperature limit of these elements is set at 1100°F.
- 2) The magnet material is to be of high-density Columax (energy product = 7.5×10^6 gauss-oersteds). High-permeability Hyperco is to be used for the remainder of the magnetic circuit.
- 3) A common design is to be used for both thermoelectric systems. Pressure-flow variations will be obtained by varying pump length and magnetic field.

*Atoms International Technical Staff, "Design Study of SNAP 8 Compact Converter," NAA-SR-11984 (CRD), June 30, 1966

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4) Copper is to be used for the connecting bus bars such that braze joints previously developed are employed.

5) Pump fabrication scheme is to be based on state-of-the-art technology.

Within the constraints of these ground rules, many pump designs were conceived to establish power and weight requirements. The results of these designs are represented in Figures IV-38 and IV-39, which depict pump power and weight as a function of flow rate. These curves were used for the optimization studies to select the reference design flow rates.

The optimization studies established typical pump requirements. These are tabulated below.

	RCA		Westinghouse	
	Primary	Secondary	Primary	Secondary
Flow rate (lb/hr)	3550	3550	5180	5180
ΔP (psi)	2.7	2.3	1.5	2.1
Pump power (watts)	11.7	10.0	9.1	12.75

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Figure IV-38. Across-the-Line DC Pump Weight Parametrics

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Figure IV-39. DC Pump Thermal Power Parametrics

The design first established an optimum throat cross-section for both requirements. With this established and the thermoelectric ΔT fixed by system and pump constraints, the optimum magnetic field was calculated to insure a minimum weight configuration. It was found that both the RCA and Westinghouse requirements had magnetic fields in the order of 15,000 lines/in.²; hence, this was fixed at this value, since the magnetic field-power characteristic is relatively flat in this region. The remainder of the design was then completed in accordance with previously established equations and procedures. The results of these pump designs follow. A drawing of this design is shown in Figure IV-40.

e. Radiator Design

Cycle waste heat is rejected to space by the main radiator. It is mounted on and supported from the exterior of the AAP vehicle skin; moreover, radiator area availability on the AAP vehicle is one of the integration limits, along with system weight and volume. Integrating radiators within the established limits necessitated two panel shapes for this study (1) a longitudinal section of a cylinder, running the full cylinder height and a fraction of the cylinder circumference

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Pump Characteristics	RCA		Westinghouse	
	Primary	Secondary	Primary	Secondary
Channel height (in.)	0.8	0.8	0.8	0.8
Channel width (in.)	0.8	0.4	0.8	0.4
Active throat length (in.)	9.0	9.0	9.0	9.0
Overall pump length (in.)	13.0	13.0	13.0	13.0
Pressure rise, $\delta P/\delta L$ (psi/in.)	0.31	0.26	0.17	0.25
Overall pump width (in.)	5.0		5.0	
Overall pump height (in.)	6.0		6.0	
Pump weight (lb)	65		65

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Figure IV-40. Thermoelectromagnetic Liquid Metal Pump

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and (2) a circumferential section of a cone frustrum, running a fraction of the cone height and completely around the circumference. The mechanical design for both shapes is discussed in this section following a discussion of the thermal analysis and design.

(1) Thermal Analysis

Using the reference system conditions, radiator areas were calculated by the method of Coombs and Stone by means of the following equation:

$$A = \frac{60 \dot{w} C_P}{\sigma \epsilon \eta T_s^3} \left\{ \left[\frac{1}{4} \ln \left(\frac{\frac{1}{\theta_2} + 1}{\frac{1}{\theta_2} - 1} \right) + \frac{1}{2} \tan^{-1} \left(\frac{1}{\theta_2} \right) \right] \right. \\ \left. - \left[\frac{1}{4} \ln \left(\frac{\frac{1}{\theta_1} + 1}{\frac{1}{\theta_1} - 1} \right) + \frac{1}{2} \tan^{-1} \left(\frac{1}{\theta_1} \right) \right] \right\} \dots (IV-1)$$

The corresponding radiator weight is equal to the sum of the weights of the fin, tubes, meteoroid armor, NaK filling the tubes, and structural material. For each set of thermal conditions, the tube spacing was varied until a minimum total weight was found. Since the curve, weight = f (area), showed a flat minimum, the data reported here represent weights that are 10% above the minimum and the areas correspond to these weights. This approach enabled an appreciable saving of area to be effected with only a small weight penalty. The fin is 0.018 in. of Al-1100. The armor is also Al-1100 and its thickness was computed by the modified NASA Lewis equation,

$$t_a = \left(\frac{a}{2.54} \right) \gamma \left(\frac{6}{\pi} \right)^{1/3} \left(\frac{62.4 \rho_p}{\rho_T} \right)^{1/2} \left(\frac{V}{C} \right)^{2/3} \\ \cdot \left(\frac{\alpha A \tau}{-\ln P(o)} \right)^{1/3\beta} \left(\frac{1}{\beta + 1} \right)^{1/3\beta}, \dots (IV-2)$$

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where:

a = damage thickness factor in armor equation (recommended value = 1.5),

A = radiator area (ft^2),

c = velocity of sound in target material (16,650 fps in Al),

C_p = fluid specific heat (Btu/lb-°F),

$P(o)$ = probability of zero punctures during mission life,

t_a = armor thickness (in.),

T_1 = fluid inlet temperature (°R),

T_2 = fluid outlet temperature (°R),

T_s = space temperature (°R),

V = particle effective velocity in armor equation = 65,500 ft/sec,

W = fluid flow rate (lb/min),

α = first Whipple constant = 5.3×10^{-11} ,

β = tube spacing (in.); second Whipple constant in armor equation = 1.34,

γ = cone half-angle; material correlation coefficient in armor equation = about 2 for A,

ϵ = radiator emissivity,

η = fin effectiveness,

$\theta_1 = T_s / T_1$,

$\theta_2 = T_s / T_2$,

ρ_p = meteoroid particle density = 0.2 g/cm^3 ,

ρ_T = target material density (lb/ft^3),

σ = Stefan-Boltzmann constant, $12.02 \times 10^{-12} \text{ Btu/hr-}^\circ\text{R}^4\text{-in.}^2$, and

τ = time of exposure (days).

Credit was taken for the protection afforded by the fin and the tube wall in calculating the net armor thickness required. The tubes were of steel, with a wall thickness of 0.030 in., and ID of 0.25 in. The fluid was NaK-78. The

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structural weight was determined to be proportional to area and a function of cone angle and shield weight.

Equation IV-1 and IV-2, plus the standard fluid flow-pressure drop relationships, were computerized and sets of parametric curves were produced. Each set was calculated for constant values of meteoroid nonpuncture probability, radiator structural specific weight (lb/ft^2), and inlet-to-outlet temperature difference of the NaK. Sample parametrics for representative values of these constants are presented in Figures IV-41, -42, -43, and -44. For any power level-radiator temperature combination, these curves can be used to determine: (1) radiator area, (2) radiator weight, and (3) tube spacing. Finally, knowing the tube length from vehicle integration constraints and the system flow rate set by compact converter considerations, the pressure drop can be determined. Parametric radiator curves typified by those in the figures were used for radiator design in the parametric system studies.

(2) Mechanical Design

The radiator consists of a fin-tube arrangement as shown in AI Drawing No. N68810009, Figure IV-45. The fins are made of a Chem-Etch 6061-aluminum extrusion to which 316-corrosion-resistant-steel tubings are inserted and diffusion bonded. In the service module panel radiator, the tubes are parallel with the longitudinal axis of the vehicle; in the SLA skirt panel radiator, the tubes are perpendicular to the vehicle longitudinal axis. Both radiators are identical except for the panel configuration.

This radiator concept has been extensively developed by the SNAP 2 Program and can be used as a primary load-carrying member of the spacecraft or be attached to the spacecraft structure. The radiator rejects the waste energy to space from one side. The back of the radiator is insulated with two layers of low-emittance gold on Molyfoil. All headers are located to minimize the number of welds in the radiator or piping system. The radiator tubes terminate in inlet and exit manifolds which, in turn, are connected to the compact converter heat exchanger.

(a) Service Module Panel Radiator

The service module panel radiator is supported by an integral structure which consists of the tubes, the 2014-aluminum stringers, and the two 6061

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Figure IV-41. Radiator Area Parametrics

Figure IV-42. Radiator Weight Parametrics

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Figure IV-43. Radiator Tube Spacing Parametrics

Figure IV-44. Radiator Pressure Drop

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Figure IV-45. Radiator — Large Radioisotope Compact Converter

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extrusion beams. This radiator section has a split inlet and outlet manifold at one end and an intermediate manifold at the other end, both of which are inboard of the radiator surface. The radiator tubes are both load-carrying and coolant distribution lines. Final size and cross-section of the stringers and beams are determined by the structural requirements.

(b) SLA Skirt Panel Radiator

The SLA skirt radiator is supported by an integral structure which consists of 2014-aluminum-stiffener rings at the top and bottom and intermediate vertical 2014-aluminum stringers. Radiator tubes terminate in inlet and exit manifolds which, in turn, are connected to the compact converter heat exchanger. The upper stiffener ring is attached to the service module lower ring. Multi-foil insulation, laminated with fiberglass, is inserted between the upper stiffener ring and the service module at attachment points.

For both radiator configurations, the aluminum fins are seam-welded to form a "flat plate" radiator. In the case of the service module panel radiator section, the flat fins are longitudinally seam-welded to conform to the service module curvature. In the SLA skirt panel radiator, the flat fins are longitudinally seam-welded after each radiator tube section is rolled and welded to the inlet and outlet manifolds.

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(3) Radiator Fins

The primary radiator fin material, 6061 aluminum, has been chosen for its weldability, strength-to-weight ratio, and its good thermal conductivity. The radiator support structure is made of 2014 aluminum. It was selected as the load-carrying material because of its high strength characteristics in a non-welded application. For example, at room temperature, 2014 has a yield strength of 60,000 psi. The radiator tubes and manifold are fabricated of 316 stainless steel, which has excellent NaK corrosion resistance, adequate strength, and excellent weldability. No braze materials are placed between the 316 stainless steel and aluminum. This joint is diffusion-bonded and has demonstrated excellent thermal conductivity.

(4) Radiator Piping

The piping consists of Type-316 corrosion-resistant-steel tubing. The radiator fin tubes are 1/4 in. OD with a 0.030-in. wall thickness. All manifolds are

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1.25 in. in diameter with a 0.030-in. wall thickness. The design of the piping system was based on minimizing pipe length and NaK volume. All welds in the piping system conform to high-temperature NaK welding specifications and are full-penetration, inert gas welds. Both x-ray and dye-penetrant techniques are utilized for local weld inspection. When the entire piping system is assembled, leak detection will be utilized to insure joint and system soundness. NaK loading is accomplished through inlet and exit loading nozzles located on the radiator manifold.

(5) Radiator Fabrication

(a) Service Module Panel

Fabrication and assembly of the service module radiator section subassembly is as follows: Prior to start of initial assembly, a simulated vehicle rack is built from master tooling, which has been verified for SM simulation accuracy by the spacecraft vehicle contractor to assure a matching interface. The radiator tubes are mounted on the assembly fixture. The NaK inlet and outlet manifolds are prefitted to the tube assemblies, trimmed, and faced. Then, radiator fins are trimmed and the manifolds are welded to the tube assemblies. Finally, the radiator fins are seam-welded and inspected.

Upon completion of welding of the radiator, cross-frames and beams are installed on the radiator assembly, trimmed, and riveted in place. With the installation of frames and beams to the radiator tubes, mechanical assembly of the radiator has been completed. The radiator assembly is removed from the assembly fixture, and gold-coated molybdenum foil is tack-welded to the underside of the radiator assembly.

(b) SLA Skirt Panel

Fabrication and assembly of the radiator subassembly for the SLA section is as follows: Prior to start of initial assembly, the radiator structure assembly fixture simulated SLA is built. The NaK inlet and outlet manifolds are prefitted to the tube assemblies, trimmed, and faced. The radiator fins are trimmed and the manifold is welded to the tube assembly, and the radiator fins are seam-welded and inspected. Upon completion of welding, the radiator frames and stringers are installed on the radiator assembly, trimmed, and riveted in place.

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The radiator assembly is removed from the assembly fixture. Gold foil is tack-welded to the underside of the radiator assembly and the unit is delivered to the final assembly area for integration with the service module panel radiator. Dimensions and support details of the radiators are presented in the reference design section.

f. Shielding Design and Analysis

Nuclear shield weight required to protect personnel from the isotope source radiation is a major consideration with radioisotope heat sources. The shield is comprised of two parts, a gamma ray shield and a lithium-hydride neutron shield. The weight of this shield will depend on:

- 1) Isotope source characteristics,
- 2) Isotope form (i.e., oxide, nitride, etc.),
- 3) Impurities associated with the isotopes,
- 4) Heat source geometry,
- 5) Vehicle geometry,
- 6) Mission operational constraints, and
- 7) Allowable dose rates.

This section presents shield design philosophy and discusses the calculational methods used.

(1) Vehicle Geometry and Dose Criteria

In the present study, the nuclear radiation shield was designed to limit the total dose to the crew in the command module to 10 rem/90 days. The isotope heat source was located in the bottom of the service module resulting in an effective separation distance of 16 ft as shown in Figure IV-46. Thus, all shields are designed to 10 rem/90 days or 4.62 mrem/hr at a separation distance of 16 ft.

The 10-rem/90 day mission was selected using MORL exposure criteria. Table IV-5 presents the allowable radiation exposures for MORL crewmen.*

*"Model Specification, Preliminary Design of a Pu-238 Isotope Brayton Cycle Power System for MORL," SM-48833, Volume II (September 1965) (Confidential) pp 3-39.

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Figure IV-46. Po^{210} Shield Design

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TABLE IV-5
ALLOWABLE RADIATION EXPOSURES FOR MORL CREWMEN

Critical Organ or Area	Maximum 3-month Exposure (rem)	Maximum 6-month Exposure (rem)	Maximum 12-month Exposure (rem)	Maximum Single Exposure (rem)	Maximum Emergency Single Exposure (rem)	Acceptable Integrated Exposure, Lifetime (rem)
Skin of Whole Body	300	350	400	100	400	1000
Skin of Extremities	650	750	900	250	600	1200
Lens of Eye	215	250	270	100	200	600
Bone Marrow	50	80	100	25	150	700

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The critical value is the 50 rem to bone marrow in a 90-day mission period. This 50 rem will necessarily be apportioned between the two sources of radiation, natural space radiation and the radioisotope heat source. Of the allowable 50-rem/90-day mission, it is felt that 10 rem, or 20% of the allowable total dose, from the radioisotope heat source is a reasonable value.

(2) Shielding Analysis

The first item in radioisotope shielding analysis is the determination of fuel capsule self-shielding. The Po^{210} capsules were those used in the Large Radioisotope Heat Source Study for NYOO-AEC.* Self-shielding calculations were performed for these capsules with the QAD code to determine dose rate as a function of angle from capsule axis. Figure IV-47 presents the ratio of the clad

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Figure IV-47. Ratio of Clad to Unclad Gamma Ray Dose Rate for Po^{210} Capsules

*"Large Radioisotope Heat Source Study Final Report to New York Operations Office of the Atomic Energy Commission," AI-65-221, Volume II (December 17, 1965) (Confidential)

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to unclad gamma ray dose rate as a function of this angle. It may be noted that the capsule self-shielding is greatest in the direction parallel to the capsule axis. Neutron self-shielding in the heat source is insignificant. In the heat exchangers, capsule ejection capability required the non-optimum orientation of the capsule perpendicular to the direction of the dose plane.

The results of the capsule self-shielding analysis, along with intercapsule shielded, unshielded neutron and gamma ray dose rates for the entire heat sources, were determined. For this calculation, the gamma ray and neutron source strengths were required; these are given below.

RADIATION CHARACTERISTICS OF Po^{210}

Gamma Ray Source Strength (0.8 Mev photons) (Mev/sec-watt)	1.16×10^7
Neutron Source Strength (n/sec-watt)	2.1×10^3
Neutron Source Strength (n/sec-curie)	~ 70
Neutron Attenuation Coefficient in LiH (cm^{-1})	0.176

Shield weight optimization was performed by assuming that the shields are in a form of a slab. The optimization was carried out using the following expressions:

$$D = N e^{-\Sigma T_L} + G e^{-\mu T_U}, \quad \dots (\text{IV-3})$$

$$W = A(\rho_L T_L + \rho_U T_U), \quad \dots (\text{IV-4})$$

where:

D = allowable dose rate (mrem/hr),

N = unshielded neutron dose rate (mrem/hr),

G = unshielded gamma ray dose rate (mrem/hr),

Σ = neutron attenuation coefficient (cm^{-1}),

μ = gamma ray attenuation coefficient (cm^{-1}),

T_L = thickness of lithium hydride (cm),

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T_U = thickness of uranium (cm),

W = weight of shield (gm),

A = area of shield (cm^2),

ρ_L = density of lithium hydride (gm/cc), and

ρ_U = density of uranium (gm/cc).

Equation IV-3 may be rewritten by introducing the quantity, "F," which is the fraction of dose rate at the dose plane from gamma rays:

$$FD = Ge^{-\mu T_U} \quad \dots (\text{IV-5})$$

$$(1 - F)D = Ne^{-\Sigma T_L} \quad \dots (\text{IV-6})$$

Using Equations IV-4, -5, and -6, an optimized shield may be determined, and an optimum "F" is given by the following expression:

$$F = 1 / \left(1 + \frac{\mu/\rho_U}{\Sigma/\rho_L} \right) \quad \dots (\text{IV-7})$$

A minimum weight shield can thus be achieved by determining "F." For Po^{210} , using uranium for the gamma ray shield and lithium hydride for the neutron shield, F was calculated to be equal to 0.723.

It should be noted that in the above method of optimization, it is assumed that the uranium is not attenuating neutrons and the lithium hydride is not attenuating gamma rays. It is felt that this is a good approximation since the uranium thickness is approximately 1/2 to 1 in. only and this would not greatly affect the neutron attenuation. In addition, since LiH is a very poor gamma ray shield, approximately 6 in. of LiH should not greatly affect the optimizations.

Referring to Figure IV-46, it is seen that the uranium shield is the internal shield and the LiH is the external shield about the heat source. Space between the heat source and the shield was provided for both plumbing and thermal

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insulation. The shield thicknesses that were obtained from the shield thickness optimization analysis, Equations IV-3 through IV-7 were used on the top shield. A unique analysis was used to calculate the back and side shield thicknesses. The theory was that the minimum shield thickness along a line of sight between the heat source and the dose plane would be equal to the thickness of the top shield. Again referring to Figure IV-46, it can be readily seen that the side and back shield thicknesses are equal the top shield thicknesses multiplied by $\cos \varphi$ and $\cos \alpha$, respectively.

Both the gamma shield and neutron shield are only attenuating by a factor of about 25 or less, and the cosine of angles φ and α are 0.33 or greater, the result of which is that the shield thicknesses at the sides and back of the heat source are slightly nonconservative. However, the angles φ and α are for the edges of the dose plane; and, actually, the astronauts will be closer to the center of the dose plane; and the net result is that the shields are slightly conservative.

Since both the gamma and neutron shields are attenuating by a factor of only 25 or less, the dose rate from wall scattering will be negligible. The dose rate from neutron capture gamma rays is also negligible since the neutron fluxes are relatively very small.

(3) Parametric Shielding

Shielding calculations were performed to determine the shield weight as a function of power. Figure IV-48 shows the result of this analysis, a curve of shield weight as a function of beginning-of-life (BOL) power. The dose rate was

Figure IV-48. Po^{210} Shield Weight vs Beginning-of-Life Power

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set at 10 rem/90 days at a separation distance of 16 ft. The shielding geometry was that presented in Figure IV-46. In the shielding calculations, the power was time-integrated, averaged over the 90-day mission. Thus, each capsule which has a BOL power of 100 watts had an average power, in the shielding calculations, of 80.6 watts.

g. Power-Flattening Subsystem

(1) Functional Design Description

The polonium systems considered require close control of the converter inlet temperature. This is accomplished by dumping the excess BOL power with a power-flattening device (see Figure IV-49). This device is made up of: (1) a stainless-steel radiator with NaK flowing in stainless-steel tubes; (2) louvers which vary the amount of heat which is dumped by changing the radiation view factor to space; (3) a louver actuator control mechanism; and (4) a sensing device located at the primary compact converter inlet, which provides the signal to the actuator.

The radiator mechanical design is the same as the main radiator, with the substitution of 316 stainless steel for the 1100 aluminum because of the higher temperature requirements. The design of the louvers and sensor is described in this section.

The heart of the power flattener is the louver actuator control mechanism which is thermomechanical and/or electromechanical. At AI, the electromechanical approach has been used for control of the SNAP 2, 8, and 10 reactor systems. It has successfully met the sophisticated control requirements in space. However, a thermomechanical control approach provides an exceedingly simple reliable primary control system. This concept does not require extraneous power for control or actuation purposes. It draws upon the power system's abundant thermal energy rather than upon the systems electrical output for its control and actuation power.

The launch configuration of the louvers is "closed," since the polonium system is cooled to a temperature level considerably below the design point prior to hydrogen fuel loading. A positive locking feature assures maintenance of this louver position until completion of launch. At that time, a pyro-pin will be

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Figure IV-49. Power Flattening Arrangement

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actuated, but the louvers will remain closed until the lower operating temperature is reached. At that temperature, the thermomechanical actuator(s) becomes activated and effect(s) control motion of the louvers in the "open" direction. The nominal louver position is approximately 50% open.

The louver control system is designed to effect a louver response from "full closed" to "full open" over a temperature range of 20°F.

The actuator control motion stems from volumetric variations within it caused by expansion of NaK in the sensor bulb. The sensor bulb is located at the inlet hot line of the converter and its volumetric output signal is directly proportional to temperature change. A set of torsion bars provides positive return force thereby assuring bi-directional control response of the louver system.

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(2) Thermal Design

Power-flattening radiator (PFR) thermal design was performed, using a set of parametric curves similar to that for the main radiator. For the PFR, however, a 316-stainless-steel fin was substituted for the 1100-aluminum fin because the temperatures are too high for aluminum. Because of the similarity in the calculational methods, the analysis will not be presented here, but reference is made to the Radiator section of this document.

(3) Component Descriptions

(a) Structure

The power-flattening device is supported from the service module skin with bracketry similar to that for the main radiator. The louvers and actuating mechanism is independently supported from the SM skin.

(b) Louvers

The basic geometrical configuration for the individual shutter louvers is shown in Figure IV-49. Each louver assembly weighs about 5 lb and is of box-type construction. Structural integrity of a louver is achieved by sizing its cross-sectional stiffness to efficiently carry the predicted launch and operating loads. The skin material of the louver is thin-gage (0.020-in. approximately), stainless-steel sheets with low emissivity coating. The box interior will be

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Figure IV-50(a). Thermomechanical Actuator with Electromechanical Override/Calibration

filled with a granular or fibrous light-weight insulating fill material, MIN-K, The end faces of the louver consist of a web with integral shaft socket allowing the insertion of the combination bearing/crankshaft as indicated in the figure. After putting the crank pin of the shaft in the appropriate relation with the louver assembly section, it is securely dowelled into place.

(c) Bearings

The bearings near the actuator accept both radial and thrust loads. The other bearings allow for thermal expansion of the louver assemblies and accept radial loads only.

The bearings shown in Figure IV-49 are identical in design and material selection to the bearings developed for the SNAP 8 reactor control system. The primary bearing materials are:

Outer race	Inco 718
Ball	Carbon graphite, Type P5N
Shaft	Inco-718, aluminum-oxide-coated using the gun vapor-blasting technique

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The above combination of materials and coating process have demonstrated a lack of any tendency to self-weld or adhere for any conceivable operating environment.

(d) Acuator

Figure IV-50(a) depicts the actuator assembly indicated in Figure IV-49. The thermomechanical actuator configuration consists of the actuator bellows assembly, the calibration/override bellow assembly, and the actuator shaft, all packaged into an actuator housing. It has no bearing or other sliding components.

The reference thermomechanical actuator uses as its physical principle of operation the high rate of volumetric thermal expansion or contraction characteristic of liquid metals. The actuator, in design similar to a hydraulic cylinder, responds to increasing temperature by a displacement of its output shaft. This motion is transferred to a crank link, in turn acting upon the crank arms thereby effecting positional control of the louver array. Increasing control temperature will result in opening the louvers.

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The design concept shown allows adequate transverse displacement of the output shaft attachment bore to follow the curvilinear motion of the crank pins. The larger bellows assembly sets the desired actuator position after filling the actuator with NaK and during calibration of the actuator at operating temperature. Fine positioning of the actuator is accomplished by appropriately adjusting the calibration/override screw shown in Figure IV-50(a).

The bellows material is a 300-series stainless steel. Formed bellows are preferred. They will experience a maximum stress level of about 20,000 psi. The stress is based on the following bellows data:

Actuator stroke (in.)	0.800
NaK volume (in. ³)	100
Maximum NaK volumetric change (in. ³) (over a 20° temperature change)	0.350
Bellows free length (in.)	4.000
Bellows OD (in.)	0.875
Bellows span (in.)	0.125
Free pitch (in.)	0.100
Nominal wall thickness (in.)	0.005
Deflection (in.)	±0.400
Maximum pressure (external) (psi)	60
Approximate life cycle (full)(hr)	10,000

Comparative bellows tests have been conducted at AI with bellows made from Inco-718 filled with liquid metal at a temperature of about 900°F over approximately 4000 hr and with internal pressure ranging from 10 to 30 psi. Post-test inspection of these bellows revealed no effects of deterioration or degradation of performance. Any adjustment motion of the electrically driven adjustment screw results in a volume change within the calibration/override bellows. As a result, there is a change in the position of the actuation shaft. These interactions may not only be used for initial calibration of the actuator and louver system but offer a practical approach to recalibrating or otherwise change the nominal temperature setpoint during operation in orbit.

To obtain highest combined operation performance reliability plus the ability to calibrate and shim the louver position, the thermomechanical actuator is

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augmented with an electromechanical (EM) override provision. This allows recalibration of the power-flattening system while in space. This will allow for correction of unavoidable minor deficiencies when simulating the thermal-radioactive orbital environment during ground calibration. In a manned mission, onboard personnel may exercise the option to recalibrate or change the power output level within a wide range.

The electromechanical drive unit consists of a high-speed dc motor with integral planetary reducer. Its output shaft (85 rpm) is coupled with a standard harmonic drive reducer. The EM drive unit is a standard component similar to the several-hundred harmonic drive units which have established a record of high reliability. The entire electrical override system including the adjustment screw are in a completely sealed environment. These considerations together with the extreme simplicity of the thermomechanical actuator suggest a level of reliability unachievable with an equivalent all electrical control system. The mode of control for the EM system shown consists of simple On-Off pulses of predetermined duration to the dc motor. To provide an additional feature of redundancy, two identical, but completely separate, actuator systems are provided.

(e) Sensor Bulb

The sensor bulb is a dead-ended, NaK-filled bulb in intimate contact with the flowing NaK stream. The hydro-mechanical energy required to operate the thermomechanical actuator is supplied by the NaK volumetric thermal expansion volume in the sensor bulb due to increasing temperature. Conversely, the sensor system's return spring will exert a return force upon the actuator adequate to replenish any volume reduction in the sensor bulb due to decreasing temperature. A conceptual design layout for the sensor bulb is shown in Figure IV-50(b). Each actuator requires a separate sensor bulb.

For highest control accuracy, the sensor bulb is located at the inlet point of the thermoelectric converter.

This power-flattening radiator assembly is used in all the Pu^{210} fueled systems. Its envelope dimensions vary from system to system; but, in the power range of interest, these variations do not necessitate any basic design changes.

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Figure IV-50(b). Sensor Bulb Thermomechanical Control System

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h. Electrical Regulation

The output of the thermoelectric converter will be held at a constant voltage by an upper limit shunt regulator. The regulator circuit selected has a zener and divider circuit that determines the voltage limit. Solid-state components are used exclusively in the regulator circuits. The circuits are dc only and do not contain any on-off switching devices.

The advantages of the shunt regulator are as follows:

- 1) When the load requires full output power, the regulator circuits are biased off. The only power drawn by the regulator is leakage current through the various transistors and zener and divider circuits in the input circuit. This power is very small and, for comparison to the generator output, it may be assumed to be zero.
- 2) There are no switching circuits to cause electromagnetic interference.
- 3) The regulator has fast response, excellent regulation, and essentially no ripple.
- 4) The shunt-type regulator presents a fixed load to the thermoelectric generator.

The power program selected to determine the size and capabilities of the shunt regulator was: (1) prior to power demand from the vehicle, the regulating system must consume 100% of the thermoelectric output; and (2) after the vehicle demand for power is given, the shunt regulator must consume 0 to 25% of the thermoelectric output while the vehicle load consumes 75 to 100%. The surplus power will be ejected through resistors (heaters) mounted on the primary radiator.

The resistors (heaters) will be sized for 100% dissipation of the thermoelectric generator electrical output. These resistors will be shunted directly across the generator output prior to the astronauts switching from launch-phase power to mission-phase power. Upon power demand from the vehicle, the resistors will be switched into the shunt regulating circuit and the shunt regulator will be placed across the line parallel with the load. The resistors will continue to dissipate the surplus power through the radiator. The consumption of power by the shunt regulator is smooth and continuous with slight changes in voltage.

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The power output of the thermoelectric generator with a shunt regulator requires no further power conditioning for dc power delivery.

B. REFERENCE DESIGN POINT SELECTION

The selection of the reference system design points is based primarily on a weight and area evaluation as influenced by the proposed integration of the systems into the Apollo service module for the AAP applications. This section includes the design point constraints, both those established by the USAEC for this study and those resulting from the proposed application. The system performance parameters of weight, area, and overall efficiency are presented as they vary with Carnot efficiency (radiator temperature) and flow rate, and the reference design point selection is made on the basis of optimum performance within the design and integration constraints.

1. System Requirements

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The system requirements and constraints discussed here are those which affect the tradeoff studies for selection of the operating points (i. e., temperatures, areas, efficiencies) of the reference Po^{210} system designs. The integration, reliability, and operational and safety considerations which affect the detailed system designs for the selected operating conditions are discussed in subsequent sections.

As indicated previously, the temperature limits specified for the compact converters in the reference 2-kwe designs are 1500°F inlet for the RCA converter and 1100°F inlet for the Westinghouse converter. The average hot-junction temperature for the converters is a variable, depending on the flow rate or NaK loop ΔT selected. The thermal and hydraulic performance of the compact converters for the reference system designs has been specified as that presented in the RCA and Westinghouse compact converter reports. Effects on the systems of changes in converter parameters, such as pressure drop, element length and efficiency, are discussed in Section VI.

The reliability of the Po^{210} systems is discussed in detail in Section IV-E. There are two results of the reliability evaluation which affect the tradeoff studies for design point selections. First, though the reliability specification is for 0.95 full power and 0.98 partial power, it has been determined that the

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Po²¹⁰ systems can be designed for a full power reliability of 0.98 with no significant weight penalty. The systems do not require multiple secondary loops for full power redundancy or to aid in obtaining increased partial power reliability, and the tradeoff studies are, therefore, performed on the basis of single secondary loops. The second reliability input to the tradeoff studies is the meteoroid nonpuncture probability required for the radiator. This is 0.985 for 90-day systems using the RCA and Westinghouse converters. This number affects the radiator optimization and the radiator weights used in the system tradeoff studies.

The power specified for the reference system designs is 2 kwe net. To provide a design contingency and an allowance for power distribution losses in the using vehicle, all system designs are based on 2.1 kwe net. The mission lifetime for the Po²¹⁰ system is 90 days plus 14 days pad hold time.

Several integration considerations affect the system tradeoff studies. First, the shield weight is a strong function of the integration geometry. The shield weights used in the system optimizations are those described in Section IV-A for the Apollo SM location. The selection of an external location for the radiators dictates the use of a radiator structure, in addition to the radiator proper and the meteoroid protection, in order to withstand aerodynamic loading during launch.

System integration considerations also provide the major criteria for design point selection. In evaluating the Apollo Applications program, it has become clear that minimum weight is not a compelling justification for the selection of a system design point and that it is necessary to establish some method of evaluating the relative importance of other system parameters, such as efficiency and area. It is obvious that high system efficiency is desirable from the standpoint of reducing the isotope inventory and, hence, cost. However, the evaluation of this parameter against weight and area requires a detailed mission specification and a cost effectiveness tradeoff which, while feasible, is beyond the scope of this study. It is, however, possible to examine the SM and rank the desirability of various area requirements. This evaluation has been accomplished and the results are shown in Table IV-6. The ranking in this table is based on availability, ease of integration, and lack of interference with existing

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TABLE IV-6
AREA AVAILABLE ON APOLLO SERVICE MODULE
(in order of desirability)

Location	Approximate Total Area (ft ²)
1. Sector IV SM	70
2. Sector IV + Sector I SM	140
3. Sector IV + ~4 ft of SLA	250
4. Sector IV + Sector I + ~4 ft of SLA	320
5. Deployable Radiators	Large

systems requirements. This ranking of area availability has been used as the primary criterion for the selection of reference systems design points.

The Po²¹⁰ system requirements are summarized in Table IV-7. These requirements provide the basis for the parametric system performance shown in the next sections.

2. System Tradeoffs and Design Point Selection

Based on the Po²¹⁰ system requirements summarized in Table IV-7 and on the component parametric data presented in Section IV-A-2, the weight, area, and efficiency of Po²¹⁰ compact converter systems were calculated as a function of Carnot efficiency. The system thermal requirements are based on the requirements of the thermoelectric converter and the pump at the specified Carnot efficiency and include a 7% allowance for miscellaneous system losses. The system pressure drops are based on the heat source, converter, and radiator hydraulic characteristics presented in Section IV-A and on a piping arrangement consistent with the Apollo SM location. The weights for each system include the heat source, shield, thermoelectric converter, radiator and radiator structure, power-flattening subsystem, piping, expansion compensator, pump, NaK inventory, converter and heat source support structure, electrical control equipment, and instrumentation. The weights which are dependent on vehicle integration (e.g., shield, piping, structure, etc.) are based on the reference Apollo service module integration scheme.

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TABLE IV-7
SUMMARY OF 2-kwe Po²¹⁰ SYSTEM REQUIREMENTS

	RCA Compact Converter Systems	Westinghouse Compact Converter Systems
System Net Power (kwe)	2.1	2.1
Mission Life	90 days + 14-day pad hold	90 day + 14-day pad hold
Full Power Reliability	0.98	0.98
Number of Secondary Loops	1	1
Meteoroid Nonpuncture Probability Required to Meet System Reliability	0.985	0.985
Converter Performance	From RCA compact converter report	From Westinghouse compact converter report
Converter Inlet Temper- ature (°F)	1500	1100
Integration Scheme	Apollo SM	Apollo SM
Radiator	Must withstand launch aerodynamic loads	Must withstand launch aerodynamic loads
Radiator Area Constraints	See Table IV-6	See Table IV-6

The weight, area, and efficiency for 2.1-kwe Po²¹⁰ systems using the RCA compact converter are shown in Figure IV-51. The efficiency shown is the overall system efficiency at the end-of-life. As indicated, the system efficiency increases with increasing Carnot efficiency (decreasing radiator temperature). The system radiator area increases exponentially with increasing Carnot efficiency due to the decreasing radiator temperature and the T^4 relationship for heat rejection from the radiator.

Both unshielded and total system weights are shown in the figure. The weights decrease, pass through a minimum, and then increase with increasing Carnot efficiency. The initial weight decrease is due primarily to decreases in the source and shield weight as the system efficiency increases. As the Carnot efficiency continues to increase, the radiator weight begins to dominate and turns the total weight curve up. For the systems using the RCA converter,

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Figure IV-51. Po^{210} RCA System Performance vs Carnot Efficiency

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Figure IV-52. Po^{210} RCA System Performance vs NaK Loop ΔT

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the minimum system weight of 1610 lb occurs at 52% Carnot efficiency. However, it should be noted that the weight curve is relatively flat, varying only 10% over a range of 42 to 60% Carnot efficiency.

The data in Figure IV-51 are for a NaK loop ΔT of 200°F. Previous optimization studies have shown that maximum system performance is obtained when the ΔT 's in the primary and secondary loops are equal. Therefore, equal loop ΔT 's have been used in this study. The NaK loop ΔT determines the loop flow rates as a function of the heat source thermal power. The selection of a 200°F ΔT for systems using the reference RCA converter is based on the system tradeoff shown in Figure IV-52. The figure shows system weight, area, and efficiency as a function of NaK loop ΔT , or flow rate, for a 2.1-kwe system operating at a fixed converter inlet temperature of 1500°F and a Carnot efficiency of 50%. As the NaK loop ΔT decreases, the NaK flow rates increase. The increasing flow rates cause higher system pressure drops and, hence, higher pumping power requirements and higher pump and heat source weights. However, as the NaK loop ΔT decreases, the average radiator temperature increases and the radiator area decreases. In going from 250°F ΔT to 200°F ΔT , the increase in pumping power and pump weight is small and the decreasing weight of the radiator is controlling, causing the total system weight to decrease. As the ΔT is reduced below 200°F the increased pumping power and pump weight become controlling and cause a more rapid decrease in system efficiency and an increase in total system weight. On the basis of these results, a 200°F NaK loop ΔT was selected as the reference for systems using the RCA converter. It should be noted that the controlling pressure drop in these systems is the pressure drop of the converter itself. The pressure drop used for the converter is that specified in the RCA report. It appears that the pressure drop in the RCA converter might be substantially reduced without significantly affecting the converter weight. The system performance benefits associated with a reduction in converter pressure drop are discussed in Section VI.

Figure IV-53 shows the system weight as a function of radiator area for a 2.1-kwe Po²¹⁰ system using the RCA converter. This is a cross-plot of the information in Figure IV-51 to show directly the relationship of system weight and area. It is this information which was used in the selection of the reference design point for the Po²¹⁰-RCA system. Referring back to Table IV-6, it is

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Figure IV-53. Po^{210} RCA System
Weight vs Radiator Area

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Figure IV-54. Po^{210} Westinghouse System
Performance vs Carnot Efficiency

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seen that, in the range of interest, the area limits for integration into the service module, in order of desirability, are 70 and 140 ft². Allowing 10 to 15 ft² for the power-flattening radiator and access door, the 70-ft² limit results in about 55 ft² available for the system radiator. Selection of this design point would result in a system weight of approximately 2100 lb or 30% over the minimum possible system weight. It was, therefore, determined to use the 140-ft² integration limit. An allowance of 20 ft² was made for the power-flattening radiator and access doors and a radiator area of 120 ft² was picked for the reference Po²¹⁰-RCA system design for this study. This point is marked on Figures IV-51 and IV-53. It should be noted that the selection of this design point is based on the judgment that the use of both Sectors IV and I rather than the Sector IV alone is generally more desirable than incurring a weight penalty of approximately 500 lb. If for any particular mission this were not true, then, of course, the design point selection would change.

Figure IV-54 shows the weight, area, and efficiency for 2.1-kwe Po²¹⁰ systems using the Westinghouse compact converter. The trends of weight, area, and efficiency as a function of Carnot efficiency are the same as discussed for systems using the RCA converter. The radiator areas for the Westinghouse systems are greater than for the RCA systems, approximately 40% greater for the minimum weight systems, because of the lower temperature of the PbTe systems. The system weight curves are again relatively flat, varying 10% over the range of 40 to 50% Carnot efficiency. The total system weights are about the same for the Westinghouse and RCA Po²¹⁰ systems, the Westinghouse system showing a slight advantage. The system efficiencies of the Westinghouse systems, however, are substantially higher than those of the RCA, approximately 25% higher for the minimum weight systems.

The data in Figure IV-54 are for a NaK loop ΔT of 100°F. The ΔT is selected on the basis of the system tradeoff shown in Figure IV-55. Again, the system performance is shown as a function of NaK loop ΔT or flow rate. For Po²¹⁰ systems using the Westinghouse converter, the optimum performance is obtained in the range of 100°F ΔT . The Westinghouse systems optimize at a lower ΔT than the RCA systems because of the lower pressure drop of the reference Westinghouse converter modules. For ΔT 's less than 100°F, the

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Figure IV-55. Po^{210} Westinghouse System Performance vs NaK Loop ΔT

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Figure IV-56. Po^{210} Westinghouse System Weight vs Area

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system pressure drop is beginning to be controlled by the radiator and piping pressure drops. The piping and NaK weight increases required to reduce these pressure drops is greater than the associated savings in pump weight and the weight associated with radiator area reductions and heat source weight. Therefore, it is concluded that the reference Westinghouse converter is designed with the proper pressure drop for isotope system applications and no significant systems savings could be achieved by further reducing the converter ΔP .

Figure IV-56 shows the plot of systems weight as a function of radiator area for the Po^{210} -Westinghouse systems. Again referring to Table IV-6, it is seen that the applicable integration area limits are 140 and 250 ft². As discussed previously, the allowance for power flattening and access reduce the 140 ft² to 120 ft² available for radiator area. To design the Po^{210} -Westinghouse system for 120 ft² would involve a weight penalty of about 20% and an efficiency penalty of about 25% over the minimum weight design. This penalty appears undesirable and it was decided to use the integration approach involving Sector IV and the SLA. The reference design point for the 2.1-kwe Po^{210} system using the Westinghouse converter was, therefore, selected at a radiator area of 200 ft², corresponding closely to the minimum system weight point.

The reference design points selected for the Po^{210} systems are summarized in Table IV-8.

TABLE IV-8
REFERENCE Po^{210} SYSTEM DESIGN POINTS

	RCA Compact Converter	Westinghouse Compact Converter
Net Power (kwe)	2.1	2.1
Converter Inlet Temperature (°F)	1500	1100
NaK Loop ΔT (°F)	200	100
Average Converter Hot-Junction Temperature (°F)	1400	1050
Carnot Efficiency (%)	48	47
Radiator Temperature (°F)	505	340
Radiator Area (ft ²)	120	200
EOL System Efficiency (%) [*]	4.5	5.95
Thermal Power (EOL) (kwt) [*]	46.7	33.8
Thermal Power (BOL) (kwt) [*]	78.7	59.6
Total System Weight (lb) [*]	1640	1580

^{*}Approximate performance from parametric studies. See Section IV-C for detailed design and performance of reference systems.

C. REFERENCE DESIGN DESCRIPTION AND SPACECRAFT INTEGRATION

This section presents a summary of the Po²¹⁰ RCA and Westinghouse reference systems, and details of system design and Apollo spacecraft integration. Section 1 presents the critical Apollo spacecraft environments, Section 2 presents the reference system performance summaries, including system schematics and a brief system description, and Section 3 presents the system design and integration details.

1. Apollo Spacecraft Environments

a. Thermal Constraints

The following thermal constraints were used as guidelines in the integration of the power system with the Apollo spacecraft:

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- 1) Maximum heat load to CM = 200 Btu/hr.
 - 2) Maximum temperature rise of aft CM heat shield due to power system equals 100°F at the bond line.
 - 3) Thermal insulation required between power system sector and adjacent bays.
 - 4) SM structure shall never exceed 250°F.
 - 5) All exposed surfaces of the power system shall be limited to less than 932°F from the time of S-IVB propellant fueling until liftoff.

b. Shock and Vibration

(1) Shock

Mechanical shock transients of varying severity may occur during the mission. These transients are caused by launch vehicle release, engine ignition and cutoff, staging, pyrotechnics, docking and reentry loading impact. Except for impact, the effects of shock transients will be localized and will be attenuated rapidly with distance from the source.

During the vehicle boost sequence, the power system will be subjected to a maximum shock loading of 20 g longitudinal and 10 g lateral. These values are based on a half-sine wave of six-millisecond duration.

Equipment subject to earth impact of the command module must be capable of withstanding a 78-g terminal peak shock pulse with a local duration of 10 to 15 msec including a decay time of 10% of total duration. Non-operational equipment must maintain structural integrity and remain attached to its respective support.

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(2) Acceleration

The boost load factor-time history for Saturn V and Saturn I-B is shown in Figure IV-57. For design purposes, the maximum longitudinal acceleration was taken as 7.5 g and the maximum lateral acceleration as ± 1 g. Components installed in the command and service modules and critical for steady-state launch accelerations may be designed to a limit launch load factor envelope of 4.9 g axial aft, 2.0 g axial forward, and 0.9 g lateral. For integration of components, the launch load factors are more critical than spaceflight maneuver load factors.

The maximum deceleration for design of the spacecraft and on-board equipment during atmospheric entry is 20 g (limit).

(3) Vibration

During atmospheric flight, noise on the exterior of the spacecraft excites vibration throughout the structure. Figure IV-58 presents a typical vibration intensity profile experienced during atmospheric flight.

Vibration intensity and spectral shape varies with location in the spacecraft. Data are presented in Figure IV-59 and IV-60, showing expected mission vibration.

Specific values of launch vibration used in system design were taken as follows:

Longitudinal	1/2-in. DA	5 to 12 cps
	3.5 g	12 to 400 cps
	7.5 g	400 to 3000 cps
Lateral and Normal	1/2-in. DA	5 to 10 cps
	5.0 g	10 to 400 cps
	7.5 g	400 to 3000 cps

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Figure IV-57. Boost Load Factor Time History

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Figure IV-58. Vibration Time History - Atmospheric Flight

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Figure IV-59. Vibration - Command Module
Atmospheric and Space Flight

(4) Acoustics

The acoustic noise level varies with the location of the components in the spacecraft. Acoustic design criteria are presented in Figures IV-61 and IV-62.

2. Reference Systems Performance Summary

a. Po²¹⁰ RCA System

The schematic diagram of the reference Po²¹⁰ RCA system during normal operation is presented in Figure IV-63. After flowing past the compact converter hot junction, the primary NaK flows past the conduction TE pump hot junction, through the power-flattening radiator (PFR), and then through the heat source. Location of the power-flattening radiator on the inlet side of the heat source was predicted on minimizing NaK-316 stainless steel corrosion problems. For example, the temperature rise across the heat source at the

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Figure IV-60. Vibration - Service Module
Atmospheric and Space Flight

Figure IV-61. Acoustics - Command Module
Atmospheric Flight

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Figure IV-62. Acoustics - Service Module
Atmospheric Flight

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Figure IV-63. Po^{210} RCA System Schematic – Normal Operation

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Figure IV-64. Po^{210} RCA System Schematic – Ground Subcooling Operation

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end of life is 200°F, but at the beginning of life it is 334°F. The excess 134°F must be removed in the power flattener either by overheating the heat source outlet NaK to 1634°F, or by subcooling the heat source inlet NaK to 1166°F. With the lack of NaK-316 stainless steel compatibility data at these elevated temperatures, it was judged advisable to locate the PFR on the heat source inlet side and to pay the small system penalties of an additional 5 ft² PFR area and increased PFR control complexity. Location of the other primary loop components was straightforward, with both the pump and expansion compensator at the relatively cool portion of the loop.

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Secondary NaK flow is past the TE pump cold junction, past the compact converter cold junction and parallel flow through the Bay IV and Bay I sections of the main radiator. Selection of these two radiator sections is described in Section IV-B. Twenty square feet of area exterior to Bay IV is taken up by the power-flattening radiator, the heat source ejection door, and an access door, leaving 50 ft² for the Bay IV radiator. Since such exclusion areas are presented in Bay I, the full 70 ft² is used. By proper orificing, the NaK flow is divided in proportion to the radiator areas to maintain similar NaK temperature profiles and the same 505°F mean temperature in each. As in the primary loop, the expansion compensator and pump are located in the cold side of the loop.

The NaK flowrate is the same in both loops, 3550 lb/hr, or 10.1 gpm, and 8.4 gpm at mean pump conditions for the primary and secondary loops respectively.

The compact converter produces 2.15 kw of electrical power, and 2.1 kwe of 28 volts dc power is provided at the voltage regulator terminals.

Prior to hydrogen fueling of the S-IVB stage (see mission profile description Section III), all exposed surfaces of the power systems must be cooled to less than 932°F to eliminate the hydrogen explosion hazard. The system is subcooled by a water boiloff system. During the subcooled period a temperature difference exists across the system, and it will operate in a degraded manner at reduced temperatures, as shown in the ground subcooled schematic for the RCA system, Figure IV-64. To provide an additional safety design margin, the maximum system exposed hot point is limited to 900°F. The maximum Po²¹⁰ heat source thermal power for the RCA system on the launch pad is 80.6 in the case of a launch relatively early in the hold period. A portion of this power, 1.21 kw is converted into electrical energy by the 516°F temperature difference across the

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compact converter and can be dissipated as heat in the voltage regulator. A second portion of this power, 23.2 kwt, is rejected by radiation and convection from the main radiator. No heat is rejected from the power-flattening radiator because its shutters will be held closed by the actuator. The remainder of the power, 56.2 kwt, is removed by the water boiler.

The water boiler is a 3/8-in. -diameter, 316 stainless steel tube coiled around a portion of the heat source inlet piping and joined to it with a generous (large fillet) braze. Controlling heat transfer resistance is on the NaK side; 1.04 ft of NaK pipe is required to provide sufficient heat transfer area. A water flowrate of 0.37 gpm nominal at 100°F is provided from an umbilical connection to the boiler where it is boiled and slightly superheated so that the steam dumped overboard will be dry. Ground control will be required to assure dry steam ejection with variation in atmospheric conditions. At launch the umbilical water connection is guillotined.

Table IV-9 presents a summary of the Po²¹⁰ RCA reference system design conditions.

b. Po²¹⁰ - Westinghouse System

A schematic for the Westinghouse system is presented in Figure IV-65. Because of the less stringent corrosion conditions, and larger PFR area for this lower temperature primary loop, the PFR is located upstream of the heat source. As a result, the heat source outlet NaK is overheated to a maximum of 1167°F at the beginning of life and is cooled to the 1100°F compact converter inlet temperature in the PFR. The primary pump and expansion compensator are located in the relatively cool portion of the loop.

The secondary flow is divided between the 55-ft² Bay IV radiator and the 145-ft² SLA radiator. It is divided, by proper orificing in proportion to each radiator area, to maintain the same 340°F mean radiator temperature in each. The expansion compensator and pump are in the cool part of the loop.

Primary and secondary NaK flowrates are both 5180 lb/hr, or 13.8 gpm and 12.2 gpm, respectively, at pump mean conditions.

Two kilowatts electrical power at 28 volts dc is provided at the system terminals.

	Po ²¹⁰ RCA		Po ²¹⁰ RCA		Po ²¹⁰ -RCA		Po ²¹⁰ -RCA
Spacecraft Integration		System Temperatures (*F)		Converter Summary		Reliability (Continued)	
Vehicle hardware	AAP	Maximum capsule clad temperature	<1700	Carnot efficiency (%)	48	Secondary coolant system	
Heat source and TE converter location		Primary coolant loop (BOL)		Converter efficiency - EOL (%)	4.83	Piping	0.9999
Launch and normal operation	Bay IV of SM	Converter inlet	1500	Number of submodules	22	ECU	0.99998
Reentry	Bay IV of SM	Converter exit	1300	Voltage/submodule - matched load (volts)	1.52	Radiator	
Radiator location and area (ft ²)		Heat source inlet	1166	Voltage/submodule - design (volts)	1.27	Performance	0.9995
Main		Heat source exit	1500	Element length (in.)	0.4	Meteoroid requirements	0.985
Bay I	70	Power flattening inlet	1300	Element diameter (in.)	-	Capsule safety eject	0.99977
Bay IV	50	Power flattening exit	1166	Power degradation (%)	2.5	Across-the-line pump	0.9994
SLA	-	ΔT across converter	200	Pump Summary		Performance Reliability	0.995
Total	120	Secondary coolant loop (BOL)		Type	Across-the-line, dc conduction	Total reliability	0.98
Power-flattening		Converter inlet	405			Materials	
Bay IV	15	Converter exit	605	Primary loop		Heat source	
Grew dose	10 rem/90 days	Mean radiator	505	Flow rate (lb/hr)	3550	Fuel	Ta-DyPo ²¹⁰
Mission Definition		ΔT across converter	200	ΔP (lb/in ²)	2.7	Clad	T-222
Type	200-n.m. earth orbit	Maximum expansion compensator temperature	<600	Hydraulic power (watts)	11.7	Oxidation coating	Pt
Lifetime (yr)	0.25	System Pressure Drops (lb/in. ²)		Thermal power (watts)	500	Diffusion barrier	Glass
End-of-life power (kwe)	2.1	Primary loop		Secondary loop		Ablator	ZnO-Mo
Launch date	1972	NaK flow rate (lb/hr)	3550	Flow rate (lb/hr)	3550	Insulation	Ta-multifoil
Overall System Performance		Heat source	0.003	ΔP (lb/in ²)	2.3	TE converter	
Specific weight (lb/kwe)	792	Converter	2.68	Hydraulic power (watts)	10.0	Hot plate	Hastelloy X
Specific power [w(e)/lb]	1.26	Piping	0.05	Thermal power (watts)	460	Submodule stack	See Figure IV-14
Specific area (w/ft ²)	17.5	Total	2.73	Shield Summary		Cold plate	316L SS
Total energy (kwe-hr)	4,536	Secondary loop		Type	Shaped shadow	Coolant loops	
Specific energy (kwe-hr/lb)	2.73	NaK flow rate (lb/hr)	3550	Dose plane separation (ft)	16	Coolant	NaK-78
Full-power reliability	0.98	Converter	2.0	Pu ²³⁶ full concentration	-	Piping	316 SS
Number of primary coolant loops	1	Radiator	0.05	Pu ²³⁸ age at start of mission (yr)	-	ECU (primary and secondary)	Inconel 718, AM 350, SCT 1000
Number of secondary coolant loops	1	Piping	0.25	k _{eff}	-		
Overall system efficiency	4.5	Total	2.30	Fraction of dose from gamma rays	0.723	Pump	
Weight Summary (lb)		Heat Source Summary		Lithium hydride thickness (in.)		Flow channel	316 SS
Heat source	496	Thermal power - BOL (kwt)	78.7	Top	N/A	Electrical conductor	Cu
Shielding	574	Thermal power - EOL (kwt)	46.7	Sides	N/A	Magnet	Columax
Pump	65	Number of capsules	787	Back	N/A	Power-flattening Radiator	
TE converter	66	Capsule power - BOL (watts)	100	Uranium hydride thickness (in.)	N/A	Fin	316 SS
NaK	35	Basic capsule outer diameter (in.)	0.50	Reliability		Tube	316 SS
Expansion compensator	54	Clad wall thickness (in.)	0.030	Heat source		Prime radiator	
Radiator and piping	240	Oxidation clad thickness (in.)	0.020	Isotope capsules	0.998	Support	2014 Al
Power flattener	19	Diffusion barrier thickness (in.)	0.005	Heat exchanger	0.9997	Tubes	316 SS
Structure	45	Ablator thickness (in.)	0.21	Shield	0.99999	Fins	0061 Al
Instrumentation and control	70	Overall capsule diameter (in.)	0.92	Converter electrical	0.99973	Water boiler	
Total	1664	Overall capsule length (in.)	2.42	Primary coolant system		Tubing	316 SS
Power Balance - EOL (kw)		Capsule weight (lb)	0.314	Piping	0.9999	Structure	Ti (6 Al-4V) 300 series stainless 7075 T6 Al 7178 T6 Al
Net electrical power	2.1	Number of panels	13	ECU	0.99998		
Main radiator power and thermal losses	41.4	Panel dimensions (in.)		Power-flattening system		Shield	
Converter thermal power	43.5	Height	10.0	Radiator	0.9999	Neutron shield	LiH
Pumping power	1.0	Length	17.75	Shutters and mechanism	0.99992	Gamma shield	Depleted U
Thermal losses	2.2	Thickness	0.65	Control	0.9996	Can	316 SS
Heat source power	46.7						
Thermal dump - BOL	32.0						
Heat source power - BOL	78.7						

-N/A = Not Applicable

Table IV-9. Summary of Po²¹⁰ RCA Reference System Design Conditions

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Figure IV-65. Po²¹⁰ Westinghouse System Schematic — Normal Operation

A water boiloff subcooler, similar to the RCA subcooler, will be required for the Westinghouse system. The smaller thermal power, 59.6 kw, and the proximity to the design point of the Westinghouse system when subcooled to 900°F, results in a smaller boiler power requirement. Boiloff thermal load is 26 kw and the mean radiator temperature is 280°F.

Table IV-10 presents a summary of the Po^{210} Westinghouse reference system design conditions.

3. System Design and Vehicle Integration Details

a. Po^{210} - RCA System

(1) Structural Design

Figures IV-66(a), (b), and (c) show the system integration layout drawings for the Po^{210} RCA power system. The heat source and TE converter components are located adjacent to the aft bulkhead in Bay IV of the service module. The radiator is located external to Bays I and IV.

The primary structural support system for the power system components is comprised of a lightweight airframe structure attached to the vertical members of the service module bay. Two deep beams cross the bay just above the heat source. The lower flanges of the two beams are connected by a web to provide an inboard-outboard load path. These beams attach to the vertical beams which enclose the bays in the service module. Vertical stiffeners are chem-milled into these vertical beams in order to support the added cross beams. Likewise, a horizontal beam member is added to the service module vertical beam to pick up loads from the web of the cross beam. The stiffeners added to the service module structure extend as far as required to insure an adequate load path from the heat source assembly installation to the service module. The heat source also attaches to a fitting off the face of the aft bulkhead so as to have additional torsional stability. Most of the other system components are supported or stabilized by the heat source assembly.

The support structure material is titanium. Structural shapes are such as to tend to reduce conductive heat transfer between the heat source support structure and the service module structure.

	Po ²¹⁰ Westinghouse		Po ²¹⁰ Westinghouse		Po ²¹⁰ Westinghouse		Po ²¹⁰ Westinghouse
Spacecraft Integration		System Temperatures (°F)		Converter Summary		Reliability (Continued)	
Vehicle hardware	AAP	Maximum capsule clad temperature		Carnot efficiency (%)	47	Secondary coolant system	
Heat source and TF converter location		Primary coolant loop (BOL)		Converter efficiency - EOL (%)	6.57	Piping	0.9999
Launch and normal operation	Bay IV of SM	Converter inlet	1100	Number of submodules	12	ECU	0.99998
Reentry	Bay IV of SM	Converter exit	1000	Voltage/submodule - matched load (volts)	2.08	Radiator	
Radiator location and area (ft ²)		Heat source inlet	1000	Voltage/submodule - design (volts)	2.33	Performance	0.99938
Main		Heat source exit	1167	Element length (in.)	-	Meteoroid requirements	0.985
Bay I	-	Power flattening inlet	1167	Element diameter (in.)	1.75	Capsule safety eject	0.99977
Bay IV	55	Power flattening exit	1100	Power degradation (%)	5*	Across-the-line pump	0.9994
SLA	145	ΔT across converter	100	Pump Summary		Performance Reliability	0.995
Total	200	Secondary coolant loop (BOL)		Type	Across-the-line, dc conduction	Total reliability	0.98
Power flattening		Converter inlet	290	Primary loop		Materials	
Bay IV	12.5	Converter exit	390	Flow rate (lb/hr)	5180	Heat source	
Crew dose	10 rem/90 days	Mean radiator	340	ΔP (lb/in ²)	1.5	Fuel	Ta-DyPo ²¹⁰
Mission Definition		ΔT across converter	100	Hydraulic power (watts)	9.1	Clad	T-222
Type	200-n. mi. earth orbit	Maximum expansion compensator temperature	<600	Thermal power (watts)	440	Oxidation coating	Pt
Lifetime (yr)	0.25	System Pressure Drops (lb/in. ²)		Secondary loop		Diffusion barrier	Glass
End-of-life power (kwe)	2	Primary loop		Flow rate (lb/hr)	5180	Ablator	ZnO-Mo
Launch date	1972	NaK flow rate (lb/hr)	5180	ΔP (lb/in ²)	2.1	Insulation	Ta-multifoil
Overall System Performance		Heat source	0.002	Hydraulic power (watts)	12.75	TE converter	
Specific weight (lb/kwe)	809	Converter	0.73	Thermal power (watts)	620	Hot plate	Inconel X-750
Specific power [w(e)/lb]	1.23	Piping	0.75	Shield Summary		Submodule stack	See Figure IV-15
Specific area (w/ft ²)	10.0	Total	1.48	Type	Shaped shadow	Cold plate	316 SS
Total energy (kwe-hr)	4,536	Secondary loop		Dose plane separation (ft)	16	Coolant loops	
Specific energy (kwe-hr/lb)	2.80	NaK flow rate (lb/hr)	5180	Pu ²³⁶ full concentration	-	Coolant	NaK-78
Full-power reliability	0.98	Converter	0.72	Pu ²³⁸ age at start of mission (yr)	-	Piping	316 SS
Number of primary coolant loops	1	Radiator	0.1	k _{eff}	-	ECU (primary and secondary)	Inconel 718, AM 350, SCT 1000
Number of secondary coolant loops	1	Piping	1.3	Fraction of dose from gamma rays	0.723	Pump	
Overall system efficiency	5.95	Total	2.12	Lithium hydride thickness (in.)		Flow channel	316 SS
Weight Summary (lb)		Heat Source Summary		Top	N/A†	Electrical conductor	Cu
Heat source	367	Thermal power - BOL (kwt)	59.6	Sides	N/A	Magnet	Columax
Shielding	440	Thermal power - EOL (kwt)	33.8	Back	N/A	Power-flattening Radiator	
Pump	65	Number of capsules	596	Uranium hydride thickness (in.)	N/A	Fin	316 SS
TE converter	165	Capsule power - BOL (watts)	100	Reliability		Tube	316 SS
NaK	35	Basic capsule outer diameter (in.)	0.50	Heat source		Prime radiator	
Expansion compensator	31	Clad wall thickness (in.)	0.030	Isotope capsules	0.9985	Support	2014 Al
Radiator and piping	375	Oxidation clad thickness (in.)	0.020	Heat exchanger	0.9997	Tubes	316 SS
Power flattener	30	Diffusion barrier thickness (in.)	0.005	Shield	0.99999	Fins	6061 Al
Structure	40	Ablator thickness (in.)	0.21	Converter electrical	0.9994	Water boiler	
Instrumentation and control	70	Overall capsule diameter (in.)	0.92	Primary coolant system		Tubing	316 SS
Total	1618	Overall capsule length (in.)	2.42	Piping	0.9999	Structure	Ti (6 Al - 4V) 300 series stainless 7075 T6 Al 7178 T6 Al
Power Balance - EOL (kw)		Capsule weight (lb)	0.314	ECU	0.99998	Shield	
Net electrical power	2.0	Number of panels	10	Power-flattening system		Neutron shield	LiH
Main radiator power and thermal losses	28.8	Panel dimensions (in.)		Radiator	0.9999	Gamma shield	Depleted U
Converter thermal power	30.8	Height	10.0	Shutters and mechanism	0.99992	Can	316 SS
Pumping power	1.1	Length	17.75	Control	0.9996		
Thermal losses	1.9	Thickness	0.65				
Heat source power	33.8						
Thermal dump - BOL	25.8						
Heat source power - BOL	59.6						

Constant temperature operation
†Not applicable

Table IV-10. Summary of Po²¹⁰
Westinghouse Reference System
Design Conditions

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Figure IV-66(a). Design Integration — Large Radioisotope Po²¹⁰ RCA Compact Converter

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Figure IV-66(b). System Installation Large Radioisotope Po^{210}
RCA Compact Converter

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Figure IV-66(c). Design Integration - Large Radioisotope Po^{210}
RCA Compact Converter
(Heat Source Detail)

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The outer skin of the heat source assembly forms the support structure for the fuel capsules, the insulation, and the shielding. Internal stiffeners provide for the load path from the inner unit to the outer surface skin. The heat source assembly is mounted such that the bottom surface is 3 in. above the face of the aft bulkhead so as to minimize heat transfer. External stiffeners on the inboard and side faces of the heat source assembly provide attachment points for other components of the system. Piping connections to the heat source are on the bottom of the unit to simplify the shielding requirements.

Fuel capsules in the heat source are positioned to face outward to facilitate both installation and removal, as well as ejection. External access is obtained via a removable door in the Apollo service module skin.

The compact converter is located alongside the heat source assembly and is supported from the two structural cross beams. Rotational (or sway) stability is obtained by attaching the lower (or aft) end of the converter to support stiffeners on the heat source assembly. By locating the converter within close proximity to both the vehicle skin and the heat source, piping lengths are held to a minimum. Support bracketry and fittings attach from the upper edges of the converter to inboard-outboard oriented stiffeners that run between the two main (cross) support beams noted above. This structure provides excellent load path integrity while offering a minimum of conductive heat transfer.

The main radiators for the system are externally mounted over Bays I and IV of the service module (see Figure IV-67 for mounting details). Radiator configurations with respect to the heat source and the power-flattening (thermal control) assembly are based on the most effective use of skin area in conjunction with piping manifold requirements. For the RCA system, 50 square feet of radiator area is located in Bay IV and 70 square feet of radiator area is located in Bay I. Supports for these external radiators are off of the module skin, with the load path being through 2-in.-deep stiffeners. Insulation on the underside of the radiator protects the module skin from excessive temperature.

The thermoelectromagnetic pump (Figure IV-68) is mounted off the side of the heat source and is positioned below the converter. Structural support for the pump comes from the vertical stiffeners on the side of the heat source. This location was chosen in order to keep the piping systems as short and free of bends as possible. The pump is located on the cool side of both NaK loops (primary and secondary) in order to prevent elevated temperature problems.

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Figure IV-67. Radiator — Large Radioisotope Compact Converter

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Figure IV-68. Thermoelectromagnetic Liquid Metal Pump

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The NaK piping has been laid out so as to minimize lengths, bends, and skin or structure penetrations. A general loop configuration or form has been followed in order to control thermal expansion stresses. Piping support fittings are designed to minimize heat transfer to the supporting structure.

The expansion compensator units (ECU's) — both primary and secondary — are mounted atop the two main cross beams. They are readily supported by these beams as well as being accessible to lines from the top of the radiators. The primary ECU is connected to a dead end line in the thermal control radiator. The secondary ECU is connected to a dead end line in the main radiator. This then causes the ECU's to feel only the volume of NaK in one small line during launching load. Freezeup is eliminated by having the lines in the radiators where they can absorb heat directly through the fins.

The power-flattening radiator and shutter assembly is located above the heat source and adjacent to the vehicle skin line (see Figure IV-66). Consistent with the overall design integration philosophy, the specific location was selected to minimize the required piping lengths, bends, and welds. The power-flattening assembly is supported directly from the service module rather than off of the cross beams described earlier in this section. Stiffeners are added at the skin line to support the shutter assembly as well as the cover door required for same. Weights and corresponding load levels are such that no difficulty is encountered with this approach.

The power-flattening shutters are arranged in a vertical array with the actuator mechanisms positioned along the top of the assembly. A protective door covers the shutter assembly during launch sequence and is subsequently blown off to activate the power flattening cycle. The shutter actuation system is a thermomechanical unit.

The water boiler is located vertically adjacent to the skin and the heat source assembly. Structural support is provided by the heat source assembly outer shell and stiffeners. This tube and shell boiler uses ground-supplied water and converts it to steam to effect ground cooling in the launch tower. At launch, the cooling water line is guillotined and water in the system boils off to give the required protection until the radiators become effective.

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(2) System Installation

The design principle followed was one that would allow preassembly of all the components (except power flattener and radiators) prior to installation on the Apollo service module. This will allow most piping welds to be accomplished with automatic equipment and controlled environments, and will greatly facilitate the overall assembly operation as well.

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The power system will be bench-assembled and supported by the two main structural cross beams. All components except for the power flattener and the radiators will be assembled by the manufacturer and shipped as a unit to the integration area. Most internal pipe installation, welding, and electrical wiring will have been completed and tested prior to delivery. Handling, testing, as well as basic assembly will use ground support equipment which will hold the power assembly via the cross beam and will also supply the needed torsional stability.

Vehicle installation equipment will support the power assembly from the structural cross beams and position the unit in the service module. Attachment to the vehicle will be between fittings off the cross beam to the vertical stiffeners in the module vertical beams. The radiators will require handling gear to effect installation on the service module but this operation will present no problem. With the structural attachment complete, the piping will be welded together, thus allowing for NaK loading and final testing. For installation of the power system into the service module, the skin panel will be removed, or an access panel will be provided adjacent to the service module propulsion system access panel.

Special ground handling equipment will be developed for all phases of capsule handling. Installation of capsules into the heat source (at the launch tower) will be performed as a semiremote type of operation using a man-integrated machine. This concept will assure a rapid, precise, and fully controlled operation and still maintain the ability of the operator to be in full command of the sequence. This specialty gear will be developed making use of the AI experience gained in nuclear and launch tower operations.

(3) Thermal Design

(a) Capsule Surface Temperature

The temperature of the surface (interface of capsule and reentry material) of the Po^{210} capsule, plotted as a function of surface emissivity, is shown in

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Figure IV-69. The emissivities of the outer surface of the reentry material, the surface of the capsule guide-fins, and the heat exchanger surface were all assumed equal — this is the emissivity referred to in Figure IV-69. The basic capsule was 0.50 in. in diameter and 2.0 in. long enclosed in a reentry material of 0.50-in. thickness. The analyses were for a NaK temperature of 1550°F maximum, fin-guides of 0.010 and 0.020 in. thickness, and a fin effectiveness parameter of 0 to 0.4. The curves show that for emissivities greater than 0.800, the temperature of the capsule surface will be below the allowable 1800°F.

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Figure IV-69. Po^{210} Capsule Surface Temperature

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(b) Expansion Compensator Temperature

The temperature of the expansion compensators of systems using either the RCA or Westinghouse compact converters is calculated to be approximately 600°F. This is well below the allowable temperature of 750°F. The analysis is based on all hot lines in the area of the compensators having foil wrap with an emissivity of 0.05 and the pump and expansion compensator surface having an emissivity of approximately 0.2. The surrounding surfaces other than NaK lines and pump were assumed to be at a temperature below 200°F. The area of the largest compensator, approximately 4.58 ft², was used in the calculation as more surface is exposed to radiating heat from the high-temperature lines.

(c) Line and Pump Heat Losses

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The heat loss from the NaK lines in the SM bay was calculated to be 0.75 kw. This is based on 12 ft of 1-1/4-in. line at 1300°F, 12 ft at 450°F, an emissivity of 0.05, and radiation to a temperature of 100°F.

The heat loss from the pump, which will have a surface temperature of approximately 600°F, a surface area of approximately 2.8 ft², and an emissivity of 0.2, will be less than 400 watts.

(4) Electrical Design

The system optimization analysis disregarded the fact that an integral number of modules would be used in the final design. Once the optimization was completed, the problem of assembling submodules to produce the design power at matched loads and at 28 vdc was investigated.

Each submodule's power output varies with the load resistance for fixed thermal conditions. The power reaches a maximum when the load resistance is at a certain value called the matched load resistance. The resulting load voltage is called matched load voltage. Figure IV-70 shows the shape of a typical submodule power output as a function of load voltage. Though the maximum module power occurs at matched load it is significant to note that voltage variations of 10 to 15% around matched load voltage results in only small power losses. For design purposes the matched load voltage can be considered to be one-half of the open-circuit voltage of the submodule.

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Figure IV-70. Submodule Power Output vs Load Voltage

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Once the converter ΔT has been set by the system design point selection, the converter power output per module and voltage output per module is fixed. In order to produce a given total power at a given voltage it is generally necessary to operate at other than the matched load condition. As long as the variation from matched load voltage is small, the associated power loss is small. With the reference designs the approach was to use an electrical arrangement of an integral number of submodules which would give the output power nearest the required value of 2.0 kw at 28 vdc with minimum deviation from matched load conditions.

Table IV-11 shows the calculated number of submodules required to produce 2.1 kw at matched load conditions and shows the integral numbers of submodules and electrical arrangement of these submodules which would produce output power near the required level at an output voltage of 28 volts. The power output at 28 volts can be compared to the matched load power. Also shown is the matched load voltage for each case.

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TABLE IV-11
ELECTRICAL LOAD MATCHING - Po^{210} RCA REFERENCE DESIGN

Calculated Number of Submodules	Number of Parallel Circuits	Number of Submodules in Each Parallel Circuit	Power Output at 28 volts (watts)	Power at Matched Load (watts)	Matched Load Voltage (watts)
21.6	2	10	1934	1947	30.3
	4	5	546	1990	15.2
	2	11	2095	2150	33.4
	3	7	1835	2045	21.2

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Two parallel circuits of eleven submodules in series was chosen for the reference design. The power at 28 volts is very close to the matched load power of 2150 watts.

The discussion above is based on the premise that the smallest electrical unit which must be maintained as presented by the converter designers is the submodule. With the submodule as this basic unit, the RCA converter appears to have sufficient flexibility for design of the lower power system. As total system power increases the problem of matching converter load decreases and the matching might be accomplished on a converter (four-pack) basis.

b. Po^{210} Westinghouse System

Figures IV-71(a), (b), and (c) show the system integration layout drawings for the Po^{210} Westinghouse power system. The heat source and TE converter components are located adjacent to the aft bulkhead in Bay IV of the service module. The radiator consists of 55 square feet located external to Bay IV of the service module, and 145 square feet exterior to the SLA skirt.

Structural support for the entire system is identical to that specified for the RCA system and will utilize two deep beams which cross the bay above the heat source. These beams in turn attach to the vertical beams of the service module.

Location of components in comparison with the RCA system is identical in that both the heat source and the compact converter are located on the underside of the two parallel cross beams and adjacent to each other. Also, both the

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Figure IV-71(a). Design Integration — Large Radioisotope, Westinghouse Compact Converter

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Figure IV-71(b). System Installation Large Radioisotope Po^{210} Westinghouse Compact Converter

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Figure IV-71(c). Design Integration - Large Radioisotope Po^{210} Compact Westinghouse Converter (Heat Source Detail)

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primary and secondary expansion compensator are located above and attached to the two parallel beams. The thermoelectric pump is located inboard of the compact converter and is supported off of the adjacent vertical beam of the service module. Component sizes differ slightly due to the differences in operating temperature between the two systems. The coolant radiators differ only in location. The RCA system utilizes Bay I and Bay IV, while the Westinghouse system utilizes Bay IV and the SLA skirt panel. Both piping systems are identical with the exception that piping for the heat source runs directly to the coolant rather than to the power-flattening radiator in the case of the Westinghouse system.

Details of the radiator mounting to the SM and SLA panels are shown in Figure IV-67.

The problem of assembling TE submodules to produce the design power at matched loads, at 28 vdc, was investigated. Table IV-12 shows the calculated number of submodules required to produce 2.1 kw at matched load conditions and shows integral numbers of submodules and electrical arrangement of these submodules which would produce output power near the required level at an output voltage of 28 volts. The power output at 28 volts can be compared to the matched load power. Also shown is the matched load voltage for each case.

TABLE IV-12
ELECTRICAL LOAD MATCHING - P_{o210} WESTINGHOUSE
REFERENCE DESIGN

Calculated Number of Submodules	Number of Parallel Circuits	Number of Submodules in Each Parallel Circuit	Power Output at 28 volts (watts)	Power at Matched Load (watts)	Matched Load Voltage (watts)
12.4	2	6	1890	2020	37.5
	3	4	1990	2020	25.0
	4	3	1530	2010	18.8
	1	13	1248	2180	81.3
	2	7	2050	2360	43.8
	3	5	2500	2530	31.3

In the case of the P_{o210} Westinghouse system, three parallel circuits of four submodules in series was chosen as the reference design. Though the output power here is somewhat below the desired 2100 watts, utilizing the next best arrangement of two parallel circuits, with seven submodules in series would result in an efficiency and system weight penalty of about 16%.

D. SAFETY

1. Introduction

The use of Po^{210} systems in the AAP has been analyzed to define the safety criteria which this system design must meet. The safety criteria derived in this analysis are directly related to the possibilities of: (1) radiation exposure of personnel during all phases of the mission, and (2) uncontrolled release of radioactive or other hazardous materials to the environment. Although the operational sequence and safety requirements involving the AAP with two radioisotope fuel materials are identical in most aspects, some basic differences do occur. In this section the primary emphasis is on the polonium radioisotope. In Section V-D, the ramifications of the plutonium radioisotope fuel are discussed.

The most hazardous environment which could be created in using a radioisotope fuel is the volatilization and dispersal of the fuel material into the atmosphere at tropospheric levels where rapid and direct transfer to humans through inhalation could occur. Ocean contamination, soil contamination, and high-altitude dispersion generally represent lesser hazards in the order given, since the dispersal and ecological chain processes are less direct to man. In addition, considerable radioactive decay of polonium during its movement through the human environment will decrease its potential hazards.

The safety analysis is accomplished by thoroughly defining potential loss of fuel containment accident modes and assessing the mode occurrence probabilities. Since most of the detailed characteristics of the movement of polonium through or to various human environments are unknown or subject to question, release of the polonium is considered hazardous in all cases. This conservative approach results in the requirement of high containment reliabilities, which, in some cases, may actually be higher than is necessary to achieve adequate levels of safety.

In the course of describing the safety analysis, a typical mission sequence is presented, including: (1) shipment and ground handling of the fuel capsules, (2) launch site operations, (3) launch through orbit injection, (4) orbital operations and reentry, and (5) post-reentry. For each phase, the normal operational procedure is summarized, followed by a discussion of the potential accidents associated with the phase.

2. Operational Sequence

In this section a typical mission is presented, in which the various mission sequences are identified along with the potential accidents associated with the particular phase. The radiological hazard analysis for these accidents will be deferred until the next section. The typical mission has been divided into the following sequences: (1) shipment and ground handling of the fuel capsules, (2) launch site operations, (3) launch through orbit injection, (4) orbital operations and reentry, and (5) post-reentry.

a. Shipment and Ground Handling

(1) Normal Operation

Fueling, final assembly, and acceptance testing of the fuel capsules will be performed at the facility of the isotope supplier. The fuel capsules, either individually or in a source block configuration, will be loaded into shipping casks. Because of the short half-life (138 days) of the material air shipment is recommended for Po^{210} . For plutonium, the schedule is more relaxed because of its long half-life (86.4 years) and either truck, rail, or air shipment is feasible. A minimum number of shipments is desirable from the accident viewpoint. The shipping cask design for the isotopes also includes consideration for use as storage containers at the launch site, thus eliminating costly storage facilities.

(2) Potential Accidents

Potential accidents during shipment can be divided into two categories: insufficient natural convection cooling and transportation vehicle accidents. Loss of cooling during transportation by surface methods, could only occur following a transportation vehicle accident. However, loss of aircraft pressurization, during air shipment, could lead to elevated capsule temperatures through the reduction of free convective cooling. Transporting vehicle accidents, which include single or multivehicle surface collisions, or an aircraft crash, produce impact forces and thermal environments which would be partially transferred to the shipping cask and possibly to the fuel capsules.

(3) Design and Procedural Safeguards

The shipping casks are to be designed in conformance with ICC Specifications. A typical cask configuration and the technical approach for the shipment of quantities of fuel required in the AAP program has been shown in LRHSS reports.*

The shipment of the radioisotope fuel material in flight-qualified capsule form is, in itself, a major contribution towards safety. The capsules themselves are designed to withstand severe thermal and mechanical shock environments such as those associated with potential accidents from launch pad aborts, aerodynamic reentry forces, and terminal velocity impact onto granite.

b. Launch Site Operations

(1) Normal Operational Sequence

Launch activities are defined here in a broad sense to include the sequence of events which encompasses the arrival of the fuel capsules at the launch site to the time of terminal launch countdown. A typical sequence of these events would include:

- (a) Arrival and temporary storage of the fuel capsules at launch site facilities.
- (b) Power systems checkout and vehicle integration prior to fuel capsule loading.
- (c) Transfer of the fuel capsules or the source block to a fuel loading device.
- (d) Transporting the loading device to the gantry and raising it into a position for loading.
- (e) Loading the fuel capsules or source block.
- (f) Power systems performance checkout.
- (g) System chilldown prior to hydrogen propellant loading.
- (h) Launch vehicle fueling phase following gantry withdrawal.
- (i) Terminal countdown and launch.

While the actual listing of the event sequences would be much more lengthy and detailed, the intent of the above listing was to show the various phases of

*Large Radioisotope Heat Source Study - Final Report to New York Operations Office of the Atomic Energy Commission, Vol II, AI-65-221, Vol. II (CRD) December 17, 1965

launch activities, in order to permit identification of potential accidents in the operational sequence.

(2) Potential Accidents

Analysis of the prelaunch activity sequences indicates that the following conditions, either individually or in some instances, in combination, categorize the major potential accident modes:

- (a) Loss of fuel-capsule cooling, which could result in capsule meltdown and release of dangerous amounts of fuel material to the atmosphere.
- (b) Inadvertent mishandling which could result in dropping the fuel capsules either individually or as a group. The height of such a fall could range from few inches to several hundred feet, as would result from a fall from the gantry onto the pad.
- (c) The possibility of binding and pinching the fuel capsules (during the fuel capsule or source block loading sequence at the launch pad), thus subjecting them to abnormal mechanical forces. Such a binding action could also cause a rupture of the NaK cooling lines in the power unit and cause a NaK fire.
- (d) The possibility of a launch pad abort fire involving the heat source — this possibility exists from the time propellant tanking commences.
- (e) The possibility, throughout the prelaunch phase, of radiation exposures from direct gamma radiation and also neutrons if inadequate shielding is provided and/or overly long exposure periods result from ground handling equipment malfunctions or improper procedures.

(3) Design and Procedural Safeguards

Loss of capsule cooling is prevented by the design of the storage facilities and the ground handling equipment. Secondary cooling capability is provided in the event of the primary loss of coolant capability.

The fuel capsules are designed to withstand terminal velocity impacts onto granite during reentry. Therefore, inadvertent mishandling and dropping the capsules or source block, even from the gantry, would not result in a loss of fuel capsule integrity.

Mechanical forces such as those which could result from the binding or pinching of a fuel capsule or source block in the loading are precluded by the loading device design and procedural safeguards for its operation. The procedural safeguards also would include provisions for fighting NaK fires in the event of a rupture of any NaK cooling lines.

Direct radiation overexposures are minimized by providing adequate localized shielding and limiting exposure periods. The exact procedural safeguards to be employed would depend upon the actual mission itself. Therefore, establishment of the procedural safeguards would require a detailed analysis of the programmatic sequences during this phase of the prelaunch activities. Once this has been accomplished, procedures of the type shown below can be instituted to minimize potential accident modes and provide an emergency plan in the event of an accident.

- (a) Controlled access areas;
- (b) Limited periods of exposure to unshielded capsules;
- (c) Procedural requirements in primary and auxiliary equipment operation;
- (d) Training of personnel in the required programmatic procedures;
- (e) Provision of film badges and monitoring services by radiological safety unit;
- (f) Emergency plans providing for personnel evacuation, fire, protection, decontamination, etc.

Following fuel capsule or source block integration with the SM, the probability of a loss-of-cooling accident is very small. A highly reliable water boiling type coolant loop provides cooling for the heat source when it is not being checked out. In the event of failure of this system, the backup capability exists for either fuel capsule or source ejection via hardline umbilical eject command signal.

c. Launch Through Orbit Injection

(1) Normal Operation

The Apollo spacecraft will be launched over the Eastern Test Range by the Saturn IB vehicle. The final countdown is normally initiated about 10 hours prior to scheduled time of launch, during which time flight readiness verification of both power system and launch vehicle is accomplished. Checks of

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telemetry links including the launch vehicle destruct and fuel capsule or source block ejection channels are made to assure maximum confidence in the system performance. Propellant tanking for the launch vehicle is commenced during the latter stages of the countdown when strict launch area access controls are in effect. At launch, the AAP in the service module will be lifted by the Saturn IB vehicle. Following a vertical-ascent phase, a pitch program is initiated which starts the missile on a preselected pitch rate and results in a transition from vertical to downrange flight which crosses the shoreline about 1/2 to 3/4 of a mile from the pad. Actual orbit injection will occur just prior to the impact point reaching the African Continent.

(2) Potential Accidents

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From the time of launch vehicle fueling through the major portion of the vertical ascent, the possibility of missile fallback or launch pad aborts must be considered as to their resultant effects on the fuel capsules. Severe thermal shocks, overpressure of several thousand psi, impact on a concrete surface, exposure to a sustained (30-minute) fire of 2000°F, vehicle debris entrapment, and soil burial are all potential environments to which the fuel capsules, either individually or in a source block configuration, could be exposed.

As the launch vehicle proceeds downrange, the potential abort environment that could be experienced by the AAP is significantly reduced as the missile fuel is expended. However, any resultant fall to the earth's surface will ultimately attain terminal velocity. The extent of any aerothermodynamic reentry effects on the SM during this phase of the mission will depend upon the time of vehicle failure. Since land impact (of any significant probability) is limited to the launch area, the probability of vehicle debris entrapment or fuel capsule burial either individually or in a source block configuration following a missile failure is significant only during the first minute or so of flight. Failures later in the flight would result in an ocean impact with potential capsule rupture from sea water corrosion.

(3) Safeguards

The fuel capsules will survive the potential thermal shock, overpressure, and concrete surface impact forces of a launch pad abort because of the generally more restrictive design considerations imposed on system design by the reentry

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environment. For water impact of the fuel capsules resulting from later missile failures, the capsules are designed both to survive the thermal shock and to provide sufficient corrosion resistance to prevent capsule rupture until the Po²¹⁰ fuel material will have undergone sufficient radioactive decay to present a negligible contamination hazard.

d. Orbital Operations and Reentry

(1) Normal Operations

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Once orbit has been attained, a variety of maneuvers can be performed depending upon the particular mission. This could entail further boost into an interplanetary or translunar transfer orbit, or simply a circularization of the command and service module orbit for an earth-orbital mission.

The reentry phase at mission termination would begin with the orientation of the command and service module and ignition of the deboost engine in the service module. The two modules begin the reentry maneuver as a single unit and a separation would occur at a programmed interval; the service module could either eject the fuel capsules or source block at the aerodynamic heating zone or the fuel capsules could remain in the service module until ocean impact occurs, with subsequent deep ocean burial of the fuel. The command module, after separation would simultaneously reenter to its designated recovery point.

(2) Potential Accidents

During orbital operation of the power supply, loss-of-coolant accidents could cause excessive fuel capsule temperatures with a resultant loss or damage of the ablative coating to the fuel capsules or the source block. Rupture of the capsule structural material could then occur during reentry or subsequent to earth burial. Potential causes of this excessive fuel capsule temperature accident include NaK pump failure, expansion compensator rupture, and meteorite puncture of coolant piping.

A heating pulse sufficient to cause capsule rupture could potentially occur during reentry and would result in the dispersal of the fuel in the upper atmosphere.

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(3) Safeguards

A temperature sensing device will be provided to eject the fuel capsules should the fuel capsule temperatures become excessive and the astronauts be unable to control the temperature rise.

If the capsules, either individually or in a source block, should be ejected, the design provides adequate protection against fuel capsule rupture from aerothermodynamic heating. The capsule is also designed to survive soil burial resulting from an accidental land impact either from a successful deboost or random reentry mode.

e. Post-Reentry

(1) Normal Operation

Successful deboost will assure deep ocean impact where the fuel capsules will sink to the ocean floor. Although containment upon deep ocean impact is not required, the capsules are designed for long-term integrity under the sea water environment as a protection against accidental coastal water impact. If they remain in the service module, they will be cooled when the vehicle is submerged in the ocean.

(2) Potential Accidents

The potential accidents of significance involve an isotope release to the ocean as a result of a coastal water impact and an early rupture of the fuel capsule containment.

A gross error in the separation between the command and service module could possibly lead to land impacts, where subsequent fuel capsule or source block rupture or ruptures as the result of complete soil burial, must be prevented.

(3) Design Safeguards

As previously mentioned, the fuel capsules have been designed to withstand long-term sea water environments and also to withstand fuel capsule or source block burial.

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3. Radiological Hazard Analysis

The objective of this subsection is a brief presentation of the potential magnitude of radiological consequences resulting from a loss of fuel capsule containment. The detailed analytical techniques and discussion of the assumptions are given in the LRHSS. To avoid repetition in the discussion for plutonium fuels, the consequences for both fuel forms will be shown here.

Atmospheric contamination can be caused by two general types of accident modes: (1) containment loss resulting from the atmospheric forces encountered during reentry, and (2) containment loss resulting from forces encountered at the earth's surface.

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a. Atmospheric Release During Reentry

Upper atmospheric release of the isotope fuel material can result from fuel capsule integrity violation, reentry burnup, and dispersal well above the earth's surface. Any particles formed which fall out rapidly would be too large to be respirable and do not readily enter the ecological food chain. Since polonium and plutonium are predominately alpha emitters they are essentially harmless unless taken into the body; possible fallout hazards are therefore dominated by the small, respirable particles. The small particles of interest are brought to ground level primarily by atmospheric processes. Table IV-13 shows the reentry burnup quantities of the two isotopes which can produce maximum permissible concentration - airborne - (MPC_a) if released in the lower polar stratosphere. Such a release point results in higher fallout concentrations of the fuel in the human environment due to the more rapid injection of the fuel material at the tropopause than would occur at lower latitudes. Because of its shorter half-life and higher MPC_a , a relatively large amount of Po^{210} may be dispersed without reaching MPC_a in the lower atmosphere.

As is shown in Table IV-13, to utilize Pu^{238} systems at any significant power level a design safeguard must be provided to assure adequate reentry protection for the fuel material. It should be emphasized that while the atmospheric contamination is not nearly so critical for the Po^{210} systems with single-mission reentry burnup, multimission burnup of Po^{210} could result in a rise in the air concentrations to undesirable levels.

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TABLE IV-13
REENTRY BURNUP QUANTITIES WHICH WILL
PRODUCE MPC_a FOR A LOWER
POLAR STRATOSPHERE
RELEASE

Nuclide	Particle Form (chemical)	MPC _a * (c/m ³)	Maximum Release	
			kwt	curies
Po ²¹⁰	Soluble	6 x 10 ⁻¹²	1100	3.3 x 10 ⁷
	Insoluble	2 x 10 ⁻¹²	367	1.1 x 10 ⁷
Pu ²³⁸	Soluble	2 x 10 ⁻¹⁴	1.6	5.7 x 10 ⁴
	Insoluble	3 x 10 ⁻¹³	24.1	8.6 x 10 ⁵

*For large population groups.

b. Ground Level Release

The accident modes which could possibly lead to a capsule rupture and release of the isotope fuel material at ground level are:

- a) Loss of coolant accident,
- b) Fuel capsule reentry burnup,
- c) Launch pad abort environment,
- d) High-velocity earth impacts,
- e) Fuel capsule soil burial.

The quantity or rate of release of the isotope fuel material into the atmosphere is highly dependent upon the temperature of the fuel material following rupture. Table IV-14 shows the amount of fuel material released from a ruptured capsule as a result of shallow earth burial, and a launch pad abort environment. The shallow earth burial assumes a capsule temperature of 2400°F with the end cap removed and the fuel material in the capsule exposed to the atmosphere. The launch abort environment is characterized by a 2000°F fire for 30 minutes with all the capsules ruptured.

The data in Table IV-14 indicates that Po²¹⁰, because of its high vapor pressure and consequent high fuel release rate, requires a fuel containment with

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TABLE IV-14
GROUND LEVEL RELEASE OF FUEL MATERIAL

	Fuel	
	Po ²¹⁰	Pu ²³⁸
Launch Pad Fire (6000°F for 0.1 sec, 3500°F for 1.0 sec, 2000°F for 30 min)		
Reference Heat Source Power (kwt)	80.6	47.8
Total Material Released During Fire (kwt)	80.6	2×10^{-6}
Integrated Inhalation Dose at Max- imum Air Concentration (rem)	$\sim 10^8$	6.8×10^{-3}
Distance Downwind to 1.5 rem dose* (meters)	$>10^6$	-
Shallow Earth Burial - Single Fuel Capsule		
Capsule Power at Burial (kwt)	0.1	0.9
Material Released in One Year (kwt)	0.1 (instantaneous release)	4×10^{-6}
Integrated Inhalation Dose at Max- imum Air Concentration (rem)	$\sim 10^5$	Average 1.5 rem at 100 meters
Distance Downwind to 1.5 rem Dose* (meters)	$\sim 2 \times 10^5$	100

*Permissible critical organ dose for an uncontrolled population is 1.5 rem.

a high degree of reliability until sufficient radioactive decay of the fuel material has occurred to minimize any release to the atmosphere. Pu²³⁸ on the other hand, with its low vapor pressure, enables a fuel capsule with proper loading to rupture at high temperatures and the exposure is limited to 1.5 rem/year at 100 feet for half-time occupancy. (See LRHSS for the detailed exposure model.)

c. Ocean Releases

If a radioisotope release should occur following capsule rupture in deep ocean waters, the thermocline acts as a diffusion barrier and prevents significant contamination of the surface water where the marine life important to human food

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consumption normally resides. However, in continental shelf areas or other ocean bottom areas above the thermocline (100 to 200 meters deep) radioisotope release could result in significant contamination of waters where seafood is harvested.

Table IV-15 shows the distance from the release point which would be contaminated above maximum permissible concentration — sea water (MPC_s) from the rupture of all of the fuel capsules in the heat source. It is assumed in the analyses that all the fuel capsules have ruptured instantaneously on water impact from an early launch abort. The data shown is for a release in coastal waters, 100 meters in depth and with a diffusion rate of 0.01 m/sec. The Po^{210} fuel material will hydrolyze in sea water to PoO_2 , which is fairly soluble in sea water; hence, its release is practically instantaneous. The Pu^{238} is highly insoluble which is the major reason for the smaller MPC_s radius.

TABLE IV-15
DISTANCE FROM RELEASE POINT ABOVE MPC_s FOR
COASTAL WATER IMPACT AND RUPTURE
OF THE AAP FUEL CAPSULES

Nuclide	MPC_s ($\mu c/cc$)	Thermal Power (kwt)	Distance From Point of Release Above MPC_s (meters)
Po^{210}	2×10^{-11}	80.6	2.8×10^6
Pu^{238}	3×10^{-10}	47.3	2.5×10^5

The limiting exposure case arising from sea water contaminated with radioisotope is the exposure to persons whose protein diet consists entirely of seafood. Such an exposure model was developed in the LRHSS. It is based on a "fish domain" concept.

The fish domain is defined as the linear distance about a point in which a fish spends its lifetime. The exposure model conservatively assumes a person will consume seafood caught only within this domain. This consumption period is

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the 70-year lifespan of the person for Pu^{238} , and one year in the case of Po^{210} . Any ingested isotope is assumed to decay within his body for his lifetime. The model takes into account the movement of fish, the diffusion and decay rates of the radionuclide, and the time it takes a fish to come into chemical equilibrium with its radioactive environment.

The consequences of the release of AAP fuel material are shown in Table IV-16. Shown first is the allowable integrated dose for each isotope; shown next are the limiting fish domain radii within which these doses will be exceeded. Thus, for Pu^{238} only the fish which remain within 500 meters of the heat source constitute a hazard. This domain is so small that Pu^{238} ocean release does not produce significant contamination.

TABLE IV-16

SEVENTY-YEAR INTEGRATED CRITICAL ORGAN DOSE FROM
SEAFOOD CONSUMPTION BY RELEASE OF AAP FUEL
MATERIAL INTO COASTAL WATERS
(100-meter depth)

Nuclide	Heat Source Power (kwt)	Critical Organ	Allowable Integrated Dose (rem)	Fish Domain-Radial Distance to Receive Specific Dose (meters)	
				140 rem	90 rem
Pu^{238}	43.7	Bone	140	500	850
Po^{210*}	80.6	Spleen	90	1,100	1,400
Po^{210}	Instantaneous Release			112,000	140,000

*5-year containment assumed prior to release.

For Po^{210} the fish domain becomes 112,000 meters (~67 miles) for an instantaneous release of 80 kwt of fuel. The consumption of seafood caught from such an area becomes highly likely due to its large area extent. An example is also shown for Po^{210} with a 5-yr decay period before capsule rupture and demonstrates the advantage gained by fuel containment for that period.

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Figure IV-72. Operational Accident Mode Evaluation - Launch Phase
(Individual capsule ejection system - manned and unmanned missions)

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4. Accident Probability Evaluation

Having defined the possible accidents and their potential consequences, it is necessary to evaluate the probability of their occurrence. Since the potential accidents involved in the mission phase are manifold and, in some cases, complex, it is useful to present the major phases schematically, both for clarity and to help assure that all significant accident or failure modes have been included. When probability or reliability values are assigned to the potential events in these schematics, the technique is often referred to as "fault-tree" analysis. Usually the probability values assigned will fall into one of three general levels of confidence: (1) very high, as where certain features of the earth are involved (e.g. land-ocean fractions); (2) fairly high, where the values have considerable basis in prior experience or analysis of a similar nature; and (3) fairly low, where new concepts are involved with little applicable previous experience or data.

Because of the complexity of the mission sequence and potential accident modes, it is convenient to divide the fault-tree diagrams into several subsections, each of which encompasses a portion of the mission. It should be noted that these diagrams include the design safeguards for the mission.

Figure IV-72 shows the fault-tree analysis for the launch phase of the mission. It can be readily seen that the possibility of fuel capsule rupture as a result of direct exposure to a launch pad abort environment or after impact in coastal waters represents the greatest potential hazard. However, other potential accident modes of capsule rupture, such as vehicle debris entrapment and excessive temperatures from the resultant insulation effects, are also significant. The term "fuel capsule," as used on the fault-tree schematics, is an all-inclusive term denoting either the fuel capsules individually or capsules contained in the source block configuration.

Figure IV-73 shows the reentry phase for the polonium fuel capsules where no recovery is planned but deep ocean disposal is made. This is the planned reentry mode for the polonium capsules. However, if fuel recovery is not deemed desirable for the plutonium, it would follow a similar reentry mode. The use of an effective capsule design has reduced the probability of accidental earth impact with subsequent burial or coastal water impact causing a

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Figure IV-73. Operational Accident Mode Evaluation – Reentry Phase [Individual Fuel Capsule Reentry, No Recovery Planned; Deep Ocean Disposal (Manned and Unmanned Missions)]

hazard to the world's population as a whole to a relatively insignificant level.

Figure IV-74 shows the reentry phase for the plutonium capsules where recovery of the fuel is planned and reentry is in the command module. Both isotopes have been included on this reentry schematic in the event it is decided to also recover the polonium fuel.

As a tentative guideline in the analysis, the acceptable total mission probability of accidents which result in radiological consequences of major proportions was assumed to be in the order of 10^{-5} to 10^{-6} per mission. The basic radiological guidelines used are:

a) Permissible radiation exposures to launch site operating personnel during fuel handling, shipment to launch site, and ground handling phases will be limited to that prescribed by appropriate AEC manuals. In general these limits are: 3.0 rem/13 weeks and not more than 5 rem/yr.

b) The contamination concentrations listed below serve as maximum permissible values for uncontrolled areas (i.e., of general public occupancy or access) where long-term exposures are possible. Where short-term exposures are possible, the permissible concentrations will be limited to that which will result in an integrated dose 0.5 rem/yr to the critical organ.

Contamination Guidelines
($\mu\text{c/cc}$)*

Isotope	Atmosphere† (tropospheric)		Water† (potable)		Ocean§ (coastal waters) ($\mu\text{c/cc}$)
	Soluble ($\mu\text{c/cc}$)	Insoluble ($\mu\text{c/cc}$)	Soluble ($\mu\text{c/cc}$)	Insoluble ($\mu\text{c/cc}$)	
Po ²¹⁰	6×10^{-12}	2×10^{-12}	2×10^{-7}	1×10^{-5}	2×10^{-11}
Pu ²³⁸	2×10^{-14}	3×10^{-13}	2×10^{-6}	1×10^{-5}	3×10^{-10}

*These values are for large population groups.

†Recommendations of International Commission on Radiological Protection (ICRP) 1959.

§Calculated values based on a conservative evaluation of contamination levels which could result in injection doses, similar to ICRP recommended limits for air and water consumption.

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Figure IV-74. Operational Accident Mode Evaluation-Reentry Phase
(Command module reentry recovery planned; fuel capsules located
in command module — manned mission)

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c) Permissible radiation exposures to the astronauts from the power unit during a 90-day mission are limited to 10 rem and for a 2-year mission are limited to 10 rem/90 days. If recovery of fuel is required in the mission sequence, the additional radiation exposure from this mission phase shall be limited to 10 rem.

5. Reference AAP System Requirements

The objectives of this section have been to (1) identify potential hazards during all phases of the operational sequence; (2) quantitatively evaluate these hazards to ascertain their contamination level relative to permissible levels; (3) quantitatively evaluate the occurrence probability of these hazards. As a result, certain conditions have been identified as credible accidents which result in an unacceptable hazard.

For these conditions safeguards requirements for the AAP mission are compiled in Table IV-17.

6. Conclusions

Since the potential radiological hazards posed by the fuel materials can be large if the fuel is dispersed into the human environment under the most adverse or pessimistic conditions, every reasonable effort has been made to assure safe disposal or recovery at the end of a mission. Realizing that this cannot be accomplished under all circumstances, 100 percent of the time, design safeguards have been instituted which either completely contain the fuel material until sufficient radioactive decay of all the material has occurred (Po^{210}) to present a minimal hazard; or the fuel form and capsule design (Pu^{238}) limit the release rate of the radioactive material to the human environment whereby acceptable exposure levels could occur. These safeguards and/or recovery and disposal methods limit the probability of an accident of major consequence occurring to 10^{-5} to 10^{-6} .

E. Po^{210} SYSTEM RELIABILITY

The reliability objective for the Po^{210} source power systems is to provide the required electrical power for a period of 90 days with 0.95 probability of success. A partial power objective of 0.98 probability for 25% of full power is also required.

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TABLE IV-17
SUMMARY OF REFERENCE AAP SYSTEM
SAFEGUARD REQUIREMENTS

1. Individual fuel capsule containment survival either separately or in a source block configuration under launch pad abort environments, including the potential effects of:
 - a. Explosive overpressures
 - b. Launch vehicle fuel fires
 - c. Concrete impact
 - d. Vehicle debris insulation
 - e. Possible complete earth burial. For the polonium fuels, this must be accomplished with a high degree of reliability because of the high vapor pressure of temperatures characteristic of such an environment. For the plutonium fuel, the reliability requirements are somewhat less stringent due to the fuel form and low vapor pressure at these temperatures.
2. Individual fuel capsule containment survival either separately or in a source block configuration under preorbital launch abort environments, including the potential effects of:
 - a. Terminal velocity impacts on soil, rock, or water
 - b. Thermal shock of water impacts
 - c. Atmospheric heating
 - d. Long-term ocean submersion
 - e. Possible complete earth burial
3. Protection against fuel capsule containment damage as a result of operational loss-of-cooling accidents
4. Individual fuel capsule containment survival either separately or in a source block configuration under potential effects of atmospheric reentry heating and ablation forces
5. Individual fuel capsule containment survival either separately or in a source block configuration under all post-reentry environments, including the potential effects of:
 - a. Terminal velocity impacts on soil, rock, or water
 - b. Long-term ocean submersion
 - c. Possible complete earth burial. In the case of plutonium fuel capsules the containment cannot be assured for periods approaching the half life (89.4) years; therefore the capsule is designed to limit the rate of release of the fuel material to MPC at 100 ft from shallow soil burial, and an insoluble fuel form is used to limit ocean exposure contamination.
6. Fuel capsule or source block ejection subsystem which provides protection against accidental land impacts and meltdown of integral heat sources including:
 - a. Launch aborts where land impacts may occur
 - b. Erroneous orbital deboosts (or complete failure) where land impacts may occur

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1. Component Reliability

The reliability estimates for the components and systems are based on available failure rate information for similar equipment, reliability margin estimates, and the established reliability objectives for the converter modules. The adjustment of system reliability to meet the objectives is accomplished by combinations of redundancy and/or meteoroid nonpuncture protection.

a. Heat Source

The failure rate for the heat source is based on the weld failure rate for the capsules. ORNL experience has shown approximately 10^9 reactor element weld hours without a failure. For this study each isotope fuel capsule is estimated to have a failure rate of 1×10^{-9} failures per hour.

b. Heat Exchanger

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The heat exchanger design is estimated to be equivalent to 12 weld areas. ORNL experience has not been able to show piping weld failure rates less than 1×10^{-8} failures per weld hour. The heat exchanger is thus estimated to have a failure rate of 1.2×10^{-7} failures per hour.

c. Shield

The radiation shield is basically a structural item for which a failure rate of 0.4×10^{-8} failures per hour is estimated. This assumes a high structural margin of at least five standard deviations of the margin distribution.

d. Power-Flattening Radiator

The power-flattening radiator is considered equivalent to four piping welds and is assigned a failure rate of 4×10^{-8} failures per hour.

e. Piping

The piping for either the primary coolant system or the heat rejection system is considered to include the converter manifold. This portion of the system is considered equivalent to four piping welds and assigned a failure rate of 4×10^{-8} failures per hour.

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f. Expansion Compensator Unit

The Expansion Compensator Unit (ECU) is considered as two functional bellows assemblies in parallel. Each bellows is estimated to have a failure rate of 1.8×10^{-7} failures per hour and a non-time-dependent success probability of 0.997 due to basic structural considerations. These bellows reliabilities are based on a study of strength-affecting variables. The total ECU reliability is then calculated:

$$R = 1 - \left\{ 1 - \left[e^{-(1.8 \times 10^{-7})t} \right] (0.997) \right\}^2$$

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g. Converter Electrical

The electrical reliability values for the converter assembly are based on the manufacturer's goal of 0.9999 per module for 10,000 hr for either a short or an open fault-free condition. This is equivalent to a failure rate of 2×10^{-8} failures per hour for each module for both failure modes.

h. Radiator

The complexity of the radiator assembly varies directly with square root of the radiator area. A previous detailed study showed a 60-ft² radiator to be equivalent to 14 piping welds for a failure rate of 14×10^{-8} failures per hour. All radiators for this study are estimated to have failure rates equal to:

$$\lambda = (0.18 \sqrt{A}) \times 10^{-7}$$

where A is the area of the radiator in square feet. The meteoroid protection of the radiator vulnerable area is considered a variable which is established to meet system objectives.

i. Power-Flattening Mechanism

The power-flattening mechanism consists of two actuator and shutter assemblies in parallel redundancy. A failure of one shutter and mechanism at any time during the mission can be offset by continued operation of the remaining

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set. The reliability of this portion of the system is estimated to be 0.99992 for 90 days.

The control system reliability for the power-flattening system is based on two alternative channels for initiation of control and a channel select switch. The failure rates for the channels are estimated based on state-of-the-art failure rates for similar electronic equipment. A redundancy math model is used to calculate the total success probability which is 0.9996 for 90 days.

j. Capsule Safety Eject System

The capsule safety eject system affects the system operation reliability considerations because of an inadvertent operation possibility. A similar system for the Po RTG study was evaluated for the various failure paths which could result in inadvertent capsule ejection; this study resulted in a failure rate of 0.92×10^{-7} failures per hour based on state-of-the-art failure mode "Therblig" failure rates for similar electronic equipment.

k. Across-the-Line Thermoelectric Pump

The pump failure rate is based on an estimate of the critical areas and their respective failure rates. Including thermoelectric bonds, throat assembly, flow dividers, and electrical bus bonds, the pump is estimated to have a failure rate of 2.4×10^{-7} failures per hour.

2. System Reliability

The difference in reliability between the system using RCA converters and the system using Westinghouse converters is caused by a difference in converter efficiency resulting in isotope inventory differences, and the level of converter module power to which the reliability objective applies. Table IV-18 shows the system reliability breakdown. From this table it can be seen that the Westinghouse converter system requires 595 isotope fuel capsules compared to 806 capsules for the RCA system, which accounts for a difference in total failure rates for the heat source. The RCA system requires 5-1/2 converter modules each having a failure rate of 2×10^{-8} compared to the Westinghouse system which requires 3 converter modules. The objective failure rate for the Westinghouse converter, however, applies to the submodule level of which there are 12 required (4 per module). This makes the Westinghouse converter assembly failure rate more than twice that of the RCA converter assembly.

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Another slight difference in system reliability is caused by the greater radiator area required for the Westinghouse system.

Both systems have a resulting performance reliability in excess of the 0.98 partial power reliability objective. By adjusting the radiator meteoroid protection the total system reliability can be met at 0.98 for full power using either Westinghouse or RCA converters. This exceeds the system objectives for full power and meets the partial power objective.

TABLE IV-18
RELIABILITY BREAKDOWN FOR Po^{210} 2-kw, 90-DAY SYSTEM

Subsystem or Component	RCA		Westinghouse	
	$\lambda \times 10^7$	Reliability	$\lambda \times 10^7$	Reliability
Heat Source				
Isotope capsules	8.1	0.998	6.0	0.9985
Heat exchanger	1.2	0.9997	1.2	0.9997
Shield	0.04	0.99999	0.04	0.99999
Primary Coolant System				
Power-flattening radiator	0.4	0.9999	0.4	0.9999
Piping	0.4	0.9999	0.4	0.9999
ECU		0.99998		0.99998
Converter Electrical	1.1	0.99973	2.4	0.9994
Heat Rejection System				
Piping	0.4	0.9999	0.4	0.9999
ECU		0.99998		0.99998
Radiator				
Performance	2.0	0.9995	2.5	0.99938
Meteoroid requirements		0.985		0.985
Power-Flattening System				
Shutters and mechanism		0.99992		0.99992
Control		0.9996		0.9996
Capsule Safety Eject	0.92	0.99977	0.92	0.99977
Across-the-Line Pump	2.4	0.9994	2.4	0.9994
Performance Reliability		0.995		0.995
Total Reliability		0.98		0.98

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SECTION V.
Pu²³⁸ COMPACT CONVERTER REFERENCE
SYSTEM DESIGN

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V. Pu²³⁸ COMPACT CONVERTER REFERENCE SYSTEM DESIGN

The design and optimization of the reference 2-kwe Pu²³⁸ systems using the RCA and Westinghouse compact converters was accomplished using the same general approach as that described for the Po²¹⁰ systems. The results of the system tradeoff analyses and a detailed description of the reference Pu²³⁸ systems are presented in the following sections.

A. COMPONENT AND SYSTEM DEFINITION

The general configuration of Pu²³⁸ compact converter systems is discussed in this section to establish a framework for the system performance tradeoff studies. Descriptions and parametric performance for the Pu²³⁸ heat sources and for the Pu²³⁸ radiation shielding are presented. The thermoelectric converters, heat transfer loops, radiators, structure and electrical subsystems are common to systems using either Pu²³⁸ or Po²¹⁰ (though the operating points may differ) and reference should be made to Section IV for the appropriate component parametric data.

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1. Systems Configuration

The heat source for the Pu²³⁸ systems in this study has been specified as the compact heat exchanger type discussed in the Atomics International Large Radioisotope Heat Source Study. The general configurations for the Pu²³⁸ compact converter systems with this type of heat source is essentially identical to the configuration discussed for the Po²¹⁰ systems. A schematic for the Pu²³⁸ system is shown in Figure V-1(a).

The major system components are the heat source, the compact converter (either RCA or Westinghouse) and the radiator. These components are thermally connected by primary and secondary NaK coolant loops. The reference system temperature limits on the compact converters are 1500°F inlet on the RCA converter and 1100°F inlet on the Westinghouse converter.

Since the half-life of Pu²³⁸ is 89 years, the power of the Pu²³⁸ heat source decays only 1-1/2% over the 2-year mission lifetime and power flattening is not required. Across-the-line dc conduction pumps with PbTe thermoelectric elements will be used in the Pu²³⁸ systems. The placement of the pumps is indicated in the schematic and again, each of the NaK loops includes an expansion compensator.

Figure V-1(a). Pu²³⁸ System Schematic

The reference Pu²³⁸ systems use a single secondary NaK loop. (Multiple loops are discussed in the Reliability section.) As indicated in the schematic, shielding will be required to reduce the radiation doses to acceptable levels in the reference manned application.

2. Component Description and Performance

The system components for the Pu²³⁸ system are of the same general design as the Po²¹⁰ system. There are two components which are significantly different in dimensions, but not in concept — the heat source, and the shield. These designs are discussed in this section.

a. Heat Source

The Pu²³⁸ heat source basic concept is the same Universal Modular Heat Source design as was used with Po²¹⁰. However, because of the lower fuel power density and longer mission lifetimes for Pu²³⁸, the capsule and panel sizes for Pu²³⁸ are significantly larger.

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The Pu^{238} fuel form utilized is that of $\text{Pu}^{238}\text{O}_2$ flame-hardened microspheres. The microspheres were selected because of their nonrespirable size, their low solubility in water, and their chemical inertness.

Plutonium capsule materials, Figure V-1(b), are the same as for the polonium capsule, i.e., T-222 structural container protected from oxidation by a platinum cladding with a glass diffusion barrier separating the two. The plutonium capsules are completely filled with microsphere fuel, and, as a result, the controlling design criteria for the plutonium capsule container was containment of the steady-state operation helium pressure buildup. The T-222 wall thickness required for the reference LRHSS five-year mission lifetime capsule is 0.240 inches. The platinum and glass are minimum manufacturing thickness of 0.02 inches, and 0.005 inches, respectively. The reference 5-year Pu^{238} capsule from the LRHSS is used for all of the Pu^{238} systems in this study. If the capsule wall thicknesses were reduced specifically for the 2-year mission, a shielded heat source weight savings of approximately 10 to 15% could be obtained.

Even though the inert fuel form for plutonium precludes the necessity for complete containment upon accidental earth burial, the allowable power loading per capsule is limited by this accident mode. The limiting case is $\text{Pu}^{238}\text{O}_2$ vaporization from a shallow buried capsule whose end cap has been lost when the capsule burst. A surface temperature of less than 2400°F must be maintained in this case to limit the Pu concentration in the air. This results in a maximum allowable capsule size of 2.25-in. diameter by 9.25-in. long, as in Figure V-2. The maximum power loading is 900 watts thermal at launch.

Because of the small void volume in the plutonium fuel capsule, it is limited to a temperature of 2200°F during the reentry transient. A relatively low-temperature ablator, AlF_3 , which sublimates at 2100°F , is used with the plutonium capsule. The ablator thickness is 1.04 inches.

The resulting plutonium fuel capsule outer dimensions are 4.33 in. diameter by 11.33 in. long.

The heat source assembly is similar to that shown in Figure IV-9, but there are fewer capsules and panels than in the polonium heat source. To accommodate the larger fuel capsules the modular plutonium panels are 13.50 in. high by 17.75 in. long by 0.650 in. wide. Their design and

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FUEL MAT'L.	BOL (watt)	EOL (watt)	LIFE (yr)	DIMENSION A
Pu ²³⁸	900	860	5.5	-
Cm ²⁴⁴	1500	1205	5.5	0.115

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Figure V-1(b). Pu²³⁸ Isotope Capsule

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fabrication are similar to the Po^{210} panel shown in Figure IV-8. Each panel accommodates four plutonium capsules, making a complete panel a 3.600-kwt module. An almost continuous spectrum of heat sources can be built with completely and partially filled modules.

Two sets of parametric calculations were generated for the Pu^{238} heat source. The first is the unshielded heat source weight as a function of power shown in Figure V-3. As a result of the long half-life of plutonium, its power density is relatively low, and fuel weight, capsule cladding weight, and reentry protection specific weight are substantially greater than those of the Po^{210} heat source.

The second parametric characteristic of interest is the heat source pressure drop-flowrate characteristic. As with the Po^{210} panels the dominant pressure drops are the panel entrance and exit losses; moreover, the frictional losses and the individual channel entrance and exit losses are negligible. The result is that the Pu^{238} panel, although larger, is hydraulically identical to the Po^{210} panel, and the hydraulic parametrics in Figure IV-10 can be used.

b. Shield

The dose criterion for the Pu^{238} heat sources is 10 rem/90 days, based on an earth-orbital mission where crew rotation can be expected. The heat sources are placed in the Service Module, as was shown in Figure IV-71(a). The dose plane is 16 ft from the heat source.

The gamma source characteristics of Pu^{238} are shown in Table V-1 and Figure V-2. Table V-1 presents the gamma ray source strength of pure Pu^{238} . The Pu^{238} is assumed to contain 1.2 ppm of Pu^{236} . In the shielding analysis the Pu^{238} fuel is assumed to have aged for one year. The capsule self-shielding was calculated; Figure V-2 presents the ratio of clad to unclad gamma ray dose rate for the Pu^{238} capsules. The Pu^{238} capsules are oriented in the heat source with their axes perpendicular to the axis of the Service Module.

The major $\text{Pu}^{238}\text{O}_2$ neutron source is the (α, n) reaction with trace amounts of O^{18} present. The Pu^{238} is assumed to be in the form of the oxide with oxygen enriched in O^{16} , so that the neutron source level from the (α, n) reaction is reduced to the same magnitude as from spontaneous fission of Pu^{238} . Thus, the total neutron source is 9.34×10^3 n/sec-watt, or approximately 320 n/sec-curie of Pu^{238} .

Figure V-2. Ratio of Clad to Unclad Gamma Ray Dose Rate for Pu^{238} Capsules

Figure V-3. Unshielded Heat Source Weight - Pu^{238} Capsules

TABLE V-1
GAMMA RAY SOURCE SPECTRUM FOR Pu²³⁸
(Mev/sec-watt)

E (Mev)	Pu ²³⁸ *			
	1 day	1 yr	2.5 yr	5 yr
0.8	6.6×10^5	6.8×10^5	7.8×10^5	9.6×10^5
1.5	1.8×10^4	1.9×10^4	2.5×10^4	3.7×10^4
2.5	9.4×10^3	5.9×10^4	2.9×10^5	7.5×10^5
4.0	1.4×10^3	1.4×10^3	1.4×10^3	1.3×10^3
6.0	3.4×10^2	3.4×10^2	3.4×10^2	3.3×10^2

*1.2 ppm Pu²³⁶

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For Pu²³⁸ heat sources, a maximum k_{eff} of 0.50 was calculated. This results in a subcritical multiplication factor of 2.0. The neutron source is, therefore, increased by a factor of 2, resulting in an increase in the LiH shield thickness of 1.7 inches over shields calculated with a k_{eff} of zero.

Slab shield weight optimization was also performed for the Pu²³⁸ heat sources and the optimum fraction of dose rate from gamma rays was calculated to be 0.854. For this gamma ray fraction at the dose plane, the capsule self-shielding is sufficient and no uranium shield is required. The LiH neutron shield is shaped similar to the Po²¹⁰ heat source shield, as shown in Figure IV-46.

Shielding calculations were performed to determine the shield weight as a function of power. Figure V-3 presents a curve of shield weight as a function of BOL thermal power. Since Pu²³⁸ has a long half-life in comparison to the mission length, the average power used in shielding was assumed to be equal to the BOL power. As previously noted, the dose rate is 10 rem/90 days at a separation distance of 16 feet.

Detailed calculations were performed for the two reference Pu²³⁸ heat sources. The shield geometry is similar to that presented in Figure IV-46. Table V-2 presents shielding information for the two reference designs.

In the Westinghouse design, a 35.5-kwt heat source is required. On the basis of an integer number of capsules, 40 capsules, or 36.0-kwt, were used in the

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Figure V-4. Pu^{238} Westinghouse
Heat Source

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Figure V-5. Pu^{238} RCA Heat Source

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TABLE V-2
2-kwe Pu²³⁸ SHIELD PARAMETERS

Material	Westinghouse (36.0 kwt)		RCA (47.7 kwt)	
	Thickness (in.)	Weight (lb)	Thickness (in.)	Weight (lb)
Lithium Hydride				
Top	5.80	106.3	6.70	142.1
Sides	1.80	81.6	1.98	91.8
Back	3.61	131.1	4.16	177.1
Total LiH Weight		319.0		411.0

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shield analysis. Using the 40 capsules, 10.5 panels will be required. Since the panels were stacked two high, 12 panels were used, as shown in Figure V-4.

In the RCA design, 46.9 kwt were required, and 53 capsules or 47.7 kwt were used. In this case, 14 panels were used, as shown in Figure V-5.

B. REFERENCE DESIGN POINT SELECTION

This section contains the Pu²³⁸ system requirements, the Pu²³⁸ system performance tradeoff studies, and the selection of the reference design points based on optimum performance within the design and integration constraints.

1. System Requirements

The only significant difference between the Pu²³⁸ system requirements and the system requirements discussed in Section IV-B-1 for Po²¹⁰ systems is the mission lifetime. The mission life for the Pu²³⁸ systems is 2 years, as compared to 90 days for the Po²¹⁰ systems.

The Pu²³⁸ systems use the RCA and Westinghouse converters at the same operating conditions as the Po²¹⁰ systems, i. e., 1500 and 1100 °F converter inlet temperatures, respectively. However, the performance of the converters has been adjusted to reflect the increased degradation expected for the longer mission lifetimes.

The same reliability approach is used for the Pu^{238} systems as that discussed for the Po^{210} systems. The systems employ a single secondary NaK loop and are designed for a full-power reliability of 0.98. As discussed in Section V-E, the longer mission lifetime does result in a higher meteoroid nonpuncture probability requirement for the single secondary loop systems. The nonpuncture probabilities consistent with the 0.98 full-power reliability goal are 0.996 and 0.999 respectively for the RCA and Westinghouse Pu^{238} systems at 2 kwe.

The Pu^{238} systems have also been designed for integration into the Apollo service module and the integration area limits previously discussed and listed in Table IV-7 were used in the selection of the Pu^{238} reference design points.

Table V-3 contains a summary of the Pu^{238} system requirements.

2. System Tradeoffs and Design Point Selection

Based on the Pu^{238} system requirements summarized in Table V-3 and on the component parametric data presented in Section V-A-2, the parametric

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TABLE V-3

SUMMARY OF 2-kwe Pu^{238} SYSTEM REQUIREMENTS

Requirement	RCA Compact Converter System	Westinghouse Compact Converter System
System net power (kwe)	2.1	2.1
Mission life (yr)	2	2
Full power reliability	0.98	0.98
Number of secondary loops	1	1
Meteoroid nonpuncture probability required to meet system reliability	0.996	0.999
Converter performance	From RCA Compact Converter Report	From Westinghouse Compact Converter Report
Converter inlet temperature (°F)	1500	1100
Integration Scheme	Apollo SM	Apollo SM
Radiator	Must withstand launch aerodynamic loads	Must withstand launch aerodynamic loads
Radiator area constraints	See Table IV-6	See Table IV-6

performance of 2.1 kwe Pu^{238} systems using the RCA and Westinghouse compact converters has been calculated for varying Carnot efficiency and NaK flow rates. The system thermal performance includes all system losses, and the system weights include all items necessary for an operational system in a configuration compatible with integration in the Apollo service module.

The weight, area, and efficiency for a 2.1-kwe Pu^{238} system using the RCA compact converter are shown in Figure V-6. The trends of the various parameters as a function of Carnot efficiency are the same as described for the Po^{210} systems. However, it will be noted that the weights of the Pu^{238} systems are almost a factor of two higher than those of the Po^{210} systems. The heavier weights of the Pu^{238} systems can be attributed almost completely to the increased weight of the heat source and associated shielding. The Pu^{238} heat sources are more than four times as heavy as the Po^{210} heat sources for the same thermal power.

The increased specific weight of the Pu^{238} heat sources places a premium on system efficiency and accounts for the minimum Pu^{238} system weight occurring

Figure V-6. Pu^{238} RCA System Performance vs Carnot Efficiency

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Figure V-7. Pu²³⁸ RCA System Weight vs Radiator Area

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Figure V-8. Pu²³⁸ Westinghouse System Performance vs Carnot Efficiency

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at a higher Carnot efficiency (55 to 60%) than for the Po^{210} systems (50 to 55%). The higher Carnot efficiency results in the minimum weight Pu^{238} system having significantly larger radiator than the corresponding Po^{210} system. The overall Pu^{238} system efficiency as a function of Carnot efficiency is slightly lower than for Po^{210} systems due to the increased converter degradation over the longer mission lifetime.

Figure V-7 shows the Pu^{238} RCA system weight as a function of radiator area. Referring back to Table IV-7, it is seen that the applicable integration area limits are 140 ft^2 or 250 ft^2 . Since the Pu^{238} systems do not require power-flattening radiators, essentially the total available area can be used for the primary system radiator. From Figure V-7 it is seen that the 135-ft^2 area limit can be met with less than a 5% weight penalty. Therefore, 135 ft^2 has been selected as the reference area for the Pu^{238} RCA systems (allowing 5 ft^2 for access doors). It should be noted that the high cost of Pu^{238} may have a strong influence on the selection of the design point. If the probability of recovery of the Pu^{238} is not high on a specific mission it may be desirable to accept the penalties associated with higher radiator areas in order to increase the system efficiency and, hence, decrease the Pu^{238} cost.

Figure V-8 shows the weight, area, and efficiency for a 2.1-kwe Pu^{238} system using the Westinghouse compact converter. It is interesting to note that while the use of the RCA and Westinghouse converters resulted in essentially the same system weight for Po^{210} systems, the use of the Westinghouse converter in Pu^{238} systems results in a system more than 10% lighter than the corresponding system with the RCA converter. This occurs because of the higher efficiency of the Westinghouse converter and the increased significance of heat source weight in Pu^{238} systems.

Figure V-9 shows the weight of the Pu^{238} Westinghouse system as a function of radiator area. From Table IV-7 the applicable integration area limits are 250 ft^2 and 320 ft^2 . The 250-ft^2 area was selected as the reference for this study.

As with the Po^{210} systems the RCA system performance has been shown for a NaK loop ΔT of 200°F and the Westinghouse system performance for a NaK loop ΔT of 100°F . The tradeoff on system weight as a function of ΔT for Pu^{238} systems is shown in Figure V-10. Again it appears that the Westinghouse

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Figure V-9. Pu²³⁸ Westinghouse System Weight vs Radiator Area

Figure V-10. Pu²³⁸ System Weight vs NaK Loop ΔT

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converter is designed with the proper pressure drop for the Pu^{238} systems while some performance gain can be obtained by reducing the pressure drop of the RCA converter (see Section VI).

The reference design points selected for the Pu^{238} systems are summarized in Table V-4.

TABLE V-4
REFERENCE Pu^{238} SYSTEM DESIGN POINTS

Design Point	RCA Compact Converter	Westinghouse Compact Converter
Net power (kwe)	2.1	2.1
Converter inlet temperature ($^{\circ}\text{F}$)	1500	1100
NaK loop ΔT ($^{\circ}\text{F}$)	200	100
Average converter hot junction temperature ($^{\circ}\text{F}$)	1400	1050
Carnot efficiency	49.5	47.5
Radiator temperature ($^{\circ}\text{F}$)	480	335
Radiator area (ft^2)	135	250
EOL system efficiency* (%)	4.45	5.6
Thermal power, EOL* (kwt)	47.2	37.5
Thermal power, BOL* (kwt)	47.8	38.0
Total system weight* (lb)	3250	2820

*Approximate performance from parametric studies. See Section V-C for detailed design and performance of Reference Systems.

C. REFERENCE DESIGN DESCRIPTION AND SPACECRAFT INTEGRATION

1. Introduction

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A thorough review of the projected AA Program (Section III) indicates that a major goal of the earth laboratory program will be a rapid buildup in mission lifetime. This will be accomplished by the extension of Apollo spacecraft lifetime from the present 14 days to 28, then 45, and finally 90-day mission capability. In conjunction with lifetime extension of the spacecraft, there will be early emphasis on the techniques of successive rendezvous missions with a single laboratory module. It is apparent that an Apollo spacecraft powerplant lifetime capability of up to 90 days will satisfy the great majority of the forecasted AA missions through the 1970-1972 time period. In addition, availability of Pu^{238} in quantities sufficient for 2-kwe power supplies in this period is questionable. For these reasons, the major emphasis in system design was placed on the 90-day Po^{210} system.

Power system designs for using the Po^{210} heat source and the Pu^{238} heat are very similar. The basic descriptions of system components, system design, and system integration are given in Section IV. This section will discuss only the major differences in system design caused by the use of the Pu^{238} heat source.

The 89.6-year half-life of Pu^{238} results in only a 1-1/2% decay in heat source thermal power during a 2-year mission lifetime. Therefore, a power-flattening device is not required. In general, the Pu^{238} heat source design is heavier and bulkier than the Po^{210} heat source. This necessitates some shifting of components in Bay IV to make room for the larger heat source and also necessitates strengthening the heat source support structure. The two-year mission lifetime with the Pu^{238} heat source results in greater pump and TE degradation at end of life. This is compensated for by a slightly increased thermal power rating of the Pu^{238} heat source at beginning of life. The excess electrical power at beginning of life can be dissipated with resistance heaters.

Although the Pu^{238} fuel is transferred to a CM fuel recovery cask for reentry at the end of mission lifetime, it is not located in the CM during normal operation. There are a number of reasons for this. Chief among them is the fact that no ejectable door may be cut through the CM heat shield. Thus the heat source would not have capsule eject capability in the event of launch abort. The confined

quarters of a CM location and the lack of an exterior access door would also make installation, servicing, and adjustment of the heat source very difficult. Finally, there is a substantial shield weight penalty if the heat source is located in the CM throughout design lifetime.

2. Reference Systems Performance Summary

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a. Pu²³⁸ RCA System

Figure V-11 shows the schematic for the Pu²³⁸ system with the RCA converter. The primary NaK flow rate is 3460 lb/hr. The NaK enters the converter at 1500°F, leaves the converter at 1300°F, passes through the integral source thermoelectric pump, and returns to the heat source. The power produced by the Pu²³⁸ heat source at BOL is 46.9 kw, which degrades to 46.2 kw at EOL. Located on the primary NaK loop is the ground water cooler which is used to maintain system temperatures below the hydrogen ignition point of 932°F prior to vehicle launch. The operation of the cooler was described in Section IV-C. The thermal loads required to be rejected by the cooler are less than those of the Po²¹⁰ fueled systems due to the significantly lower BOL power level of the Pu²³⁸ systems.

The secondary NaK flow rate is also 3460 lb/hr, NaK leaving the converter at 580°F. From there it flows to the radiator which consists of two sections. One section of 70 ft² is located exterior to Bay I; the second section of 65 ft² is located exterior to Bay IV. A flow-splitting device is employed to maintain the mean temperature the same in both sections of the radiator. The secondary NaK flow leaves the radiator, passes through the cold junction side of the TE pump and returns to the converter.

Located on the cold legs of both the primary and secondary NaK loop are expansion compensators to provide adequate coolant pressurization to prevent void formation during all phases of operation. The compensators are of the all-metal, welded-bellows type.

The electrical output of 2.1 kw from the converter passes through the voltage regulator and is available to the load at 28 vdc.

Table V-5 presents a summary of the reference Pu²³⁸ RCA system operating conditions.

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Figure V-11. Pu^{238} RCA System Schematic,
Normal Operation

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Figure V-12. Pu^{238} Westinghouse System Schematic,
Normal Operation

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	Pu ²³⁸ RCA		Pu ²³⁸ RCA		Pu ²³⁸ RCA		Pu ²³⁸ RCA
Spacecraft Integration		System Temperatures (°F)		Converter Summary		Reliability (Continued)	
Vehicle hardware	AAP	Maximum capsule clad temperature	<1650	Carnot efficiency (%)	49.5	Secondary coolant system	
Heat source and TE converter location		Primary coolant loop (BOL)		Converter efficiency - EOL (%)	4.9	Piping	0.9993
Launch and normal operation	Bay IV of SM	Converter inlet	1500	Number of submodules	20	ECU	0.99996
Reentry	CM	Converter exit	1300	Voltage/submodule - matched load (volts)	1.59	Radiator	
Radiator location and area (ft ²)		Heat source inlet	1300	Voltage/submodule - design (volts)	1.4	Performance	0.9963
Main		Heat source exit	1500	Element length (in.)	0.4	Meteoroid requirements	0.9957
Bay I	70	Power flattening inlet	-	Element diameter (in.)	-	Capsule safety eject	0.9984
Bay IV	65	Power flattening exit	-	Power degradation (%)	6	Across-the-line pump	0.9958
SLA	-	ΔT across converter	200	Pump Summary		Performance Reliability	0.984
Total	135	Secondary coolant loop (BOL)		Type	Across-the-line, dc conduction	Total reliability	0.98
Power-flattening		Converter inlet	380	Primary loop		Materials	
Bay IV	-	Converter exit	580	Flow rate (lb/hr)	3460	Heat source	
Crew dose	10 rem/90 days	Mean radiator	480	ΔP (lb/in. ²)	3.1	Fuel	Pu ²³⁸ O ₂
Mission Definition		ΔT across converter	200	Hydraulic power (watts)	12.5	Clad	T-222
Type	200-n. mi. earth orbit	Maximum expansion compensator temperature	<600	Thermal power (watts)	580	Oxidation coating	Pt
Lifetime (yr)	2	System Pressure Drops (lb/in. ²)		Secondary loop		Diffusion barrier	Glass
End-of-life power (kwe)	2.1	Primary loop		Flow rate (lb/hr)	3460	Ablator	AlF ₃ -Mo
Launch date	1972	NaK flow rate (lb/hr)	3460	ΔP (lb/in. ²)	3.2	Insulation	Ta-multifoil
Overall System Performance		Heat source	0.003	Hydraulic power (watts)	13	TE converter	
Specific weight (lb/kwe)	1555	Converter	3.08	Thermal power (watts)	600	Hot plate	Hastelloy X
Specific power [w(e)/lb]	0.644	Piping	0.03	Shield Summary		Submodule stack	See Figure IV-14
Specific area (w/ft ²)	15.5	Total	3.11	Type	Shaped shadow	Cold plate	316L SS
Total energy (kwe-hr)	36,288	Secondary loop		Dose plane separation (ft)	16	Coolant loops	
Specific energy (kwe-hr/lb)	11.1	NaK flow rate (lb/hr)	3460	Pu ²³⁶ full concentration	1.2	Coolant	NaK-78
Full-power reliability	0.98	Converter	2.6	Pu ²³⁸ age at start of mission (yr)	1	Piping	316 SS
Number of primary coolant loops	1	Radiator	0.3	k _{eff}	0.5	ECU (primary and secondary)	Inconel 718, AM 350, SCT 1000
Number of secondary coolant loops	1	Piping	0.3	Fraction of dose from gamma rays	0.854	Pump	
Overall system efficiency	4.45	Total	3.20	Lithium hydride thickness (in.)		Flow channel	316 SS
Weight Summary (lb)		Heat Source Summary		Top	6.7	Electrical conductor	Cu
Heat source	2230	Thermal power - BOL (kwt)	46.9	Sides	2.0	Magnet	Columax
Shielding	375	Thermal power - EOL (kwt)	46.2	Back	4.2	Power-flattening Radiator	
Pump	65	Number of capsules	53	Uranium hydride thickness (in.)	-	Fin	-
TE converter	60	Capsule power - BOL (watts)	900	Reliability		Tube	-
NaK	80	Basic capsule outer diameter (in.)	2.25	Heat source		Prime radiator	
Expansion compensator	50	Clad wall thickness (in.)	0.24	Isotope capsules	0.99907	Support	2014 Al
Radiator and piping	275	Oxidation clad thickness (in.)	0.020	Heat exchanger	0.9979	Tubes	316 SS
Power flattener	-	Diffusion barrier thickness (in.)	0.005	Shield	0.99993	Fins	6061 Al
Structure	60	Ablator thickness (in.)	1.04	Converter electrical	0.9982	Water boiler	
Instrumentation and control	70	Overall capsule diameter (in.)	4.33	Primary coolant system		Tubing	316 SS
Total	3265	Overall capsule length (in.)	11.33	Piping	0.9993	Structure	Ti (6 Al - 4V) 300 series stainless 7075 T6 Al 7178 T6 Al
Power Balance - EOL (kw)		Capsule weight (lb)	36	ECU	0.99996	Shield	
Net electrical power	2.1	Number of panels	14	Power-flattening system		Neutron shield	LiH
Main radiator power and thermal losses	40.7	Panel dimensions (in.)		Radiator	-	Gamma shield	-
Converter thermal power	42.8	Height	13.5	Shutters and mechanism	-	Can	316 SS
Pumping power	1.2	Length	17.75	Control	-		
Thermal losses	2.2	Thickness	0.65				
Heat source power	46.2						
Thermal dump - BOL	-						
Heat source power - BOL	46.9						

Table V-5. Summary of Pu²³⁸
RCA Reference System
Design Conditions

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b. Pu²³⁸ Westinghouse System

The Pu²³⁸ system utilizing the Westinghouse converter is shown schematically in Figure V-12. It is similar to the RCA system, differing primarily in the location of the radiator. In this system the radiator is again split into two sections. The first section is located exterior to Bay IV and has an effective area of 65 ft². The second section is located exterior to the SLA skirt and has 185 ft² of radiating surface. The secondary NaK flow rate of 5600 lb/hr is split to these two radiator sections to maintain a mean radiator temperature of 335°F in both sections. After leaving the radiator, the NaK flow passes through the cold junction side of the across-the-line TE pump and then enters the converter. The NaK exits the converter at 385°F with a 100°F ΔT through the converter.

The primary NaK flow rate is 5600 lb/hr. NaK exits the heat source at 1100°F, enters the hot side of the converter, and exits the converter at 1000°F. It then passes through the hot side of the TE pump and returns to the heat source after passing through the ground cooler. The thermal load on the ground cooler is less than that of the Pu²³⁸ RCA system.

The Westinghouse converter, consisting of 12 submodules, has an electrical output of 2 kw which passes thru the voltage regulator and is available to the load at 28 vdc.

Expansion compensators of all-metal construction are provided for both the primary and secondary loops.

Table V-6 presents a summary of the reference Pu²³⁸ Westinghouse system operating conditions.

3. System Design and Vehicle Integration Details

Structural design and system integration is identical to the Po²¹⁰ heat source designs except that a heavier support structure is required. The service module propulsion system access door must be moved up 54 inches to allow unobstructed access past the Pu²³⁸ RCA system. With the Pu²³⁸ Westinghouse system, the door must be moved up 50 inches.

Component configurations for the Pu²³⁸ system are identical to the Po²¹⁰ system, except that the pump of the Pu²³⁸ Westinghouse system is mounted from the heat source can. Power-flattening devices are not required.

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	Pu ²³⁸ Westinghouse		Pu ²³⁸ Westinghouse		Pu ²³⁸ Westinghouse		Pu ²³⁸ Westinghouse
Spacecraft Integration		System Temperatures (°F)		Converter Summary		Reliability (Continued)	
Vehicle hardware	AAP	Maximum capsule clad temperature	-	Carnot efficiency (%)	47.5	Secondary coolant system	
Heat source and TE converter location		Primary coolant loop (BOL)		Converter efficiency - EOL (%)	6.4	Piping	0.9993
Launch and normal operation	Bay IV of SM	Converter inlet	1100	Number of submodules	12	ECU	0.99996
Reentry	CM	Converter exit	1000	Voltage/submodule - matched load (volts)	2.08	Radiator	
Radiator location and area (ft ²)		Heat source inlet	1000	Voltage/submodule - design (volts)	2.33	Performance	0.9949
Main		Heat source exit	1100	Element length (in.)	-	Meteoroid requirements	0.9993
Bay I	-	Power flattening inlet	-	Element diameter (in.)	1.75	Capsule safety eject	0.9984
Bay IV	65	Power flattening exit	-	Power degradation (%)	8	Across-the-line pump	0.9958
SLA	185	ΔT across converter	100	Pump Summary		Performance Reliability	0.984
Total	250	Secondary coolant loop (BOL)		Type	Across the line, dc conduction	Total reliability	0.98
Power-flattening		Converter inlet	285	Primary loop		Materials	
Bay IV	-	Converter exit	385	Flow rate (lb/hr)	5600	Heat source	
Crew dose	10 rem/90 days	Mean radiator	335	ΔP (lb/in ²)	1.5	Fuel	Pu ²³⁸ O ₂
Mission Definition		ΔT across converter	100	Hydraulic power (watts)	9.8	Clad	T-222
Type	200-n.m. earth orbit	Maximum expansion compensator temperature	<600	Thermal power (watts)	600	Oxidation coating	Pt
Lifetime (yr)	2	System Pressure Drops (lb/in. ²)		Secondary loop		Diffusion barrier	Glass
End-of-life power (kwe)	2	Primary loop		Flow rate (lb/hr)	5600	Ablator	AlF ₃ -Mo
Launch date	1972	NaK flow rate (lb/hr)	5600	ΔP (lb/in ²)	1.95	Insulation	Ta-multifoil
Overall System Performance		Heat source	0.002	Hydraulic power (watts)	12.8	TE converter	
Specific weight (lb/kwe)	1435	Converter	0.77	Thermal power (watts)	800	Hot plate	Inconel X-750
Specific power [w(e)/lb]	0.70	Piping	0.70	Shield Summary		Submodule stack	See Figure IV-15
Specific area (w/ft ²)	8.0	Total	1.47	Type	Shaped shadow	Cold plate	316 SS
Total energy (kwe-hr)	36,288	Secondary loop		Dose plane separation (ft)	16	Coolant loops	
Specific energy (kwe-hr/lb)	12.7	NaK flow rate (lb/hr)	5600	Pu ²³⁶ full concentration	1.2	Coolant	NaK-78
Full-power reliability	0.98	Converter	0.75	Pu ²³⁸ age at start of mission (yr)	1	Piping	316 SS
Number of primary coolant loops	1	Radiator	0.1	k _{eff}	0.5	ECU (primary and secondary)	Inconel 718, AM 350, SCT 1000
Number of secondary coolant loops	1	Piping	1.1	Fraction of dose from gamma rays	0.854	Pump	
Overall system efficiency	5.7	Total	1.95	Lithium hydride thickness (in.)		Flow channel	316 SS
Weight Summary (lb)		Heat Source Summary		Top	5.8	Electrical conductor	Cu
Heat source	1660	Thermal power - BOL (kwt)	35.5	Sides	1.8	Magnet	Columax
Shielding	270	Thermal power - EOL (kwt)	35.0	Back	3.6	Power-flattening Radiator	
Pump	65	Number of capsules	40	Uranium hydride thickness (in.)	-	Fin	-
TE converter	150	Capsule power - BOL (watts)	900	Reliability		Tube	-
NaK	85	Basic capsule outer diameter (in.)	2.25	Heat source		Prime radiator	
Expansion compensator	30	Clad wall thickness (in.)	0.24	Isotope capsules	0.99926	Support	2014 Al
Radiator and piping	480	Oxidation clad thickness (in.)	0.020	Heat exchanger	0.9979	Tubes	316 SS
Power flattener	-	Diffusion barrier thickness (in.)	0.005	Shield	0.99993	Fins	6061 Al
Structure	60	Ablator thickness (in.)	1.04	Converter electrical	0.9958	Water boiler	
Instrumentation and control	70	Overall capsule diameter (in.)	4.33	Primary coolant system		Tubing	316 SS
Total	2870	Overall capsule length (in.)	11.33	Piping	0.9993	Structure	T1 (6 Al - 4V) 300 series stainless 7075 T6 Al 7178 T6 Al
Power balance - EOL (kw)		Capsule weight (lb)	36	ECU	0.99996	Shield	
Net electrical power	2.0	Number of panels	12	Power-flattening system		Neutron shield	LiH
Main radiator power and thermal losses	29.5	Panel dimensions (in.)		Radiator	-	Gamma shield	-
Converter thermal power	31.5	Height	13.5	Shutters and mechanism	-	Can	316 SS
Pumping power	1.4	Length	17.75	Control	-		
Thermal losses	2.1	Thickness	0.65				
Heat source power	35.0						
Thermal dump - BOL	-						
Heat source power - BOL	35.5						

Constant power operation

Table V-6. Summary of Pu²³⁸ Westinghouse Reference System Design Conditions

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Capsule surface temperature vs emissivity is shown in Figure V-13. As indicated previously, the wall thickness for the Pu^{238} capsules are based on creep rupture criteria. The design point for the reference Pu^{238} capsules is $\sim 1800^\circ\text{F}$ for a 5-year mission. For NaK temperatures below 1550°F , the capsule temperature will be below 1800°F for all emissivities above 0.45.

Table V-7 shows the calculated number of submodules required to produce 2.1 kw at matched load conditions and shows integral numbers of submodules and electrical arrangement of these submodules which would produce output power near the required level at an output voltage of 28 volts. The power output at 28 volts can be compared to the matched load power. Also shown is the matched load voltage for each case.

The best arrangement for the Pu^{238} RCA system is two parallel circuits of ten submodules in series in each circuit. This arrangement produces an output power of 2070 watts, very close to the design goal of 2100 watts. It is also operating very near the matched load condition.

Three parallel circuits of four submodules were chosen for the Pu^{238} Westinghouse system based on the same reasoning as for the Po^{210} Westinghouse system.

Figure V-13. Pu^{238} Capsule Surface Temperature

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TABLE V-7
ELECTRICAL LOAD MATCHING - RCA AND WESTINGHOUSE Pu²³⁸ SYSTEM

Case	Calculated Number of Submodules	Number of Parallel Circuits	Number of Submodules in Each Parallel Circuit	Power Output at 28 Volts (watts)	Power at Matched Load (watts)	Matched Load Voltage (watts)
Pu ²³⁸ RCA	20	4	5	885	2100	15.9
		2	10	2070	2100	31.8
		3	7	2070	2210	22.3
		2	11	2220	2310	35.0
Pu ²³⁸ Westinghouse	12.6	2	6	1870	1995	37.5
		3	4	1965	1998	24.9
		2	7	2030	2330	43.5
		3	5	2460	2480	31.0

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D. SAFETY

1. Introduction

This section discusses the ramifications of using Pu^{238} as a fuel material for the AAP. Most of the operational sequences and safeguards presented in the corresponding Po^{210} section (Section IV-D), apply equally well to both fuel materials. However, there are some basic differences with Pu^{238} which require a somewhat different technical approach in the design of the inherent safety for the system: (1) the long half-life (89.4 yr), (2) the low chemical activity in sea water and low vapor pressure of the oxide microsphere fuel forms at elevated temperatures. (3) The possibility of accidental criticality.

The same format will be used in this section that was used in the previous safety section; only the differences associated with the use of the Pu^{238} fuel material are discussed.

2. Operational Sequence

a. Shipment and Ground Handling

(1) Potential Accidents

Accidental criticality must be considered when Pu^{238} is used as a fuel material. A loss-of-cooling accident during shipment or ground handling which resulted in fuel capsule meltdown into a critical configuration would produce a power excursion and subsequent Pu^{238} atmospheric dispersion of the source.

(2) Safeguards

The shipping casks and storage facilities for the fuel capsules have design safeguards to prevent capsule meltdown and to maintain a subcritical configuration. Shielding is provided to limit the neutron dose from normal spontaneous fission.

b. Launch Site Operations

(1) Potential Accidents

Loss-of-cooling accidents in storage facilities, in ground handling equipment, in the Apollo SM after fuel loading, and in launch pad abort environments lead to potential capsule rupture and potential fuel meltdown.

(2) Safeguards

The storage facilities and ground handling equipment are designed to provide secondary cooling capability in the event of the failure of the primary system, thus preventing fuel capsule meltdown. The heat source is a noncritical configuration, such that criticality is precluded even with full water reflection of the system. The fuel capsules have been designed to withstand the thermal and mechanical environment of a launch pad abort. In the event a capsule should rupture, the low vapor pressure of the fuel form limits the release rate of the fuel material into the environment.

c. Launch Through Orbit Injection

(1) Potential Accidents

Land impact could occur from vehicle malfunction and shallow burial and rupture of the fuel capsules could result. Fuel material would be released to the environment prior to significant radioactive decay of the fuel inventory. Similarly, coastal water impacts in water depths of 100 to 200 meters are possible. Sea water corrosion of the capsule and subsequent rupture could result before significant radioactive decay occurs, thus releasing fuel material into the ocean environment.

(2) Safeguards

Design of a plutonium capsule which provides containment until significant radioactive decay of the fuel material occurs is impractical. Therefore, the fuel capsule has been designed to limit the fuel capsule temperature for shallow earth burial to a level where the amount of fuel material which could be volatilized and released to the environment is at an acceptable level. After rupture of the capsules in the ocean environment, the relative chemical inertness of the fuel form limits the release rate of the fuel material.

d. Orbital Operations and Reentry

(1) Normal Operations

The economics involved with using plutonium as a fuel material make it highly desirable to recover the fuel for reuse. As a normal operational sequence, the fuel capsules will be removed from the CM at the end of the mission and transferred to the command module for reentry and recovery. Cooling for the fuel

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capsules in the command module will be maintained during this interval by lines connecting the command module with the service module radiator. The deboost of the command module from orbit will be accomplished by ignition of the engine in the service module. At the point of separation of the command and service module, the coolant lines will be severed. Fuel capsule cooling will then be maintained for the remainder of the reentry sequence by a beryllium heat sink. After splashdown, a hatch will be ejected and the fuel capsules will then be cooled by sea water.

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(2) Potential Accidents

A loss-of-cooling accident could occur during the mission, resulting in potential capsule rupture. If emergency action by the astronauts to limit the temperature rise fails, the fuel capsules are ejected from the SM. Such an action would result in a random reentry mode for the fuel capsules either individually or in a source block configuration depending upon the system design. As previously discussed, two principal accident modes must be considered during the reentry phase: (1) loss of fuel capsule containment during reentry from aerodynamic heating; and (2) loss of fuel material containment by impact.

(3) Design Safeguards

Gamma and neutron shielding material will be provided in the handling equipment to assure that radiation exposures during the fuel transfer operations are not excessive. Shielding will be provided in the command module to maintain radiation dose rates from the fuel capsules at acceptable levels during the reentry sequence.

The loss of fuel capsule containment during reentry is prevented by the ablative coating protection provided for the fuel capsules and/or the source block.

As previously discussed, the fuel capsules have been designed to withstand terminal velocity impact onto granite, thus minimizing the probability of fuel capsule rupture on land impact, although such a capsule rupture would be technically acceptable with the inert PuO_2 fuel form.

3. Radiological Hazard Analysis

The radiological hazard analysis for the plutonium fuel was presented in Section IV-D.

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4. Accident Probability Analysis

The accident probability analysis for the plutonium fuel was presented in Section IV-D-4.

5. Conclusions

Although it becomes impractical to design plutonium fuel capsules which do not rupture over time periods which would permit significant radioactive decay of the fuel material, the chemical inertness of the fuel form, and the low vapor pressure of the fuel material at elevated temperatures, make it possible to reduce the probability of an accident of major consequence from the accidental release of the fuel material into the human environment to 10^{-5} to 10^{-6} .

E. Pu²³⁸ SYSTEM RELIABILITY

The reliability objectives for the Pu²³⁸ isotope systems differ from those of the Po²¹⁰ systems in mission time only. The long half-life Pu²³⁸ systems are intended for two years operation for which the same system reliability objectives apply (0.95 for full power and 0.98 for partial power).

1. Component Reliability

The basic component failure rates for the Pu²³⁸ system remain the same as for the Po²¹⁰ system. Any differences in the application of component failure rates are due to changes in size or number of isotope capsules, converter modules, and radiator area.

2. System Reliability

The basic system reliability using Pu²³⁸ fuel is enhanced by the deletion of a power-flattening system. In addition, the number of fuel capsules is reduced significantly to 40 capsules for the Westinghouse system and 53 capsules for the RCA system. Radiator area is slightly greater for the long-life systems, which accounts for the only increase in component failure rate. The number of required converter modules changes only for the RCA system which requires 5 instead of 5-1/2 modules.

The system reliability breakdown is shown in Table V-8 for the Pu²³⁸ system. The total system reliability for full power is 0.98, just as it is for the Po²¹⁰ 90-day system.

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TABLE V-8
RELIABILITY BREAKDOWN FOR Pu²³⁸ 2-kw, 2-YEAR SYSTEM

Subsystem or Component	RCA		Westinghouse	
	$\lambda \times 10^7$	Reliability	$\lambda \times 10^7$	Reliability
Heat Source				
Isotope capsules	0.53	0.99907	0.42	0.99926
Heat exchanger	1.2	0.9979	1.2	0.9979
Shield	0.04	0.99993	0.04	0.99993
Primary coolant system				
Piping	0.4	0.9993	0.4	0.9993
ECU		0.99996		0.99996
Converter electrical	1.0	0.9982	2.4	0.9958
Heat rejection system				
Piping	0.4	0.9993	0.4	0.9993
ECU		0.99996		0.99996
Radiator				
Performance	2.13	0.9963	2.9	0.9949
Meteoroid requirements		0.9957		0.9993
Capsule safety eject	0.92	0.9984	0.92	0.9984
Across-line pump	2.4	0.9958	2.4	0.9958
Performance reliability		0.984		0.981
Total Reliability		0.98		0.98

A tradeoff is possible with the two-year system where the converter and heat rejection loop can be segmented to provide partial power reliability. This could be accomplished with a saving in meteoroid armor weight, allowing the system to meet the 0.95 full-power reliability and also the 0.98 partial-power reliability from one unfailed out of two or more converter segments. This arrangement, unfortunately, would require the addition of a power dump system on the primary coolant loop to reject excess isotope source heat under partial-power operating conditions. In effect, this adds the power-flattening system weight and failure rates back into the Pu²³⁸ system and causes a significant reduction in full-power

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reliability. The results of considering such a system can be summarized as shown in Table V-9. Considerations of total system weight have resulted in favor of the single-segment approach including the more stringent meteoroid protection requirement to meet the 0.98 full-power reliability.

TABLE V-9
PARTIAL POWER RELIABILITY BREAKDOWN
FOR Pu²³⁸ 2-kw, 2-YEAR SYSTEM
WITH TWO CONVERTER HEAT
REJECTION SEGMENTS

Subsystem	RCA Reliability	Westinghouse Reliability
Primary system	0.9931	0.9933
Power dump	0.9874	0.9874
Converter — heat rejection (Per segment)		
Performance	0.9936	0.9917
Meteoroid P_o^*	0.9905	0.9923
Full power performance	0.968	0.965
Full power total	0.950	0.950
Partial power performance	0.981	0.981
Partial power total	0.980	0.980

*Meteoroid P_o is for one radiator segment; for n segments the total meteoroid nonpuncture probability is P_o^n .

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SECTION VI.
PARAMETRIC SYSTEM PERFORMANCE

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VI. PARAMETRIC SYSTEM PERFORMANCE

The previous sections have dealt with the design and performance of 2-kwe systems using the reference RCA and Westinghouse compact converter designs. This section describes the effects on system performance of possible modifications in the converter design and/or operating conditions and changes in the system requirements such as power level or reliability. The effects on 2-kwe system performance of changes in the converter pressure drop, changes in the converter thermoelectric element length, off-design performance of the converter or heat source, and changes in the required system reliability, are discussed. The performance of Po^{210} and Pu^{238} systems over the range of 1 to 5 kwe is also presented.

A. CONVERTER PRESSURE DROP

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In examining the reference 2-kwe systems for the effect of NaK flow, it was found that the optimum NaK loop ΔT for the Westinghouse systems is 100°F , while the optimum ΔT for the RCA systems is 200°F . As discussed in Section IV-B, the optimization at 100°F NaK loop ΔT for systems using the Westinghouse converter was controlled primarily by system hydraulic characteristics rather than those of the converter. It was, therefore, concluded that the Westinghouse converter pressure drop is sufficiently low that no significant system performance increases will be achieved by further reduction of the converter pressure drop. On the other hand, the flow rate optimization for systems using the RCA converter (which has a higher pressure drop than the Westinghouse converter) was controlled almost completely by the converter pressure drop. It therefore appears that system performance gains might be achieved by reducing the RCA converter pressure drop. To evaluate these potential system gains, it was arbitrarily assumed that the pressure drop of the RCA converter can be reduced to the same level as the Westinghouse converter for equal flow rates. On this basis, the system flow rate tradeoffs were repeated with the results shown in Figure VI-1. For the reduced converter pressure drop the optimum system NaK loop ΔT is about 100°F , the same as for the Westinghouse systems. Comparing these results at 100°F ΔT with the data in Figure IV-52 shows that the reduced converter pressure drop has resulted in a system weight savings of approximately 6%, an area savings of approximately

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Figure VI-1. Po^{210} RCA System Performance
vs NaK Loop ΔT (Reduced Converter ΔP)

3%, and an overall efficiency increase of 3%. On the basis of these results it appears that the RCA converter pressure drop should be reduced to the same level as that of the Westinghouse converter if such a reduction in pressure drop does not seriously complicate the RCA converter design.

On the basis of the reduced RCA converter pressure drop and a NaK loop ΔT of 100°F, the performance of Po^{210} and Pu^{238} RCA systems as a function of Carnot efficiency has been recalculated. These data are shown in Figure VI-2 for the Po^{210} systems and Figure VI-3 for the Pu^{238} systems.

The reduced RCA converter pressure drop has been used in calculating the parametric system performance shown in Section VI. If the reduced converter pressure drop cannot reasonably be obtained, then the performance parameters shown in Section VI for RCA systems should be adjusted by the percentages discussed in the previous paragraph.

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Figure VI-2. Po^{210} RCA System Performance vs Carnot Efficiency (Reduced Converter ΔP)

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Figure VI-3. Pu^{238} RCA System Performance vs Carnot Efficiency (Reduced Converter ΔP)

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B. ELEMENT LENGTH

The effect of thermoelectric element length on converter performance was discussed in Section IV-A-2. Reducing element length results in a decreased converter weight and efficiency and an increased converter power output. The effect of these changes on the system weight has been calculated and is shown in Figure VI-4. The curves in this figure are based on the reference system design points.

The reference thermoelement length for the RCA converter is 0.4 inch. For the Westinghouse converter, the element length is reflected in the submodule OD. The ID of the converter is fixed at 0.5 and the reference OD is 1.75 inches.

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Figure VI-4. Weight vs TE
Element Length

As is shown in Figure VI-4, the system weights have a minimum as a function of element length. From this minimum point, the use of longer thermoelectric elements increases the converter weight more than the resulting increase in converter efficiency reduces heat source weight. Conversely, if shorter element lengths are used, the decrease in converter efficiency causes a faster increase in the weight of the heat source than decrease in weight of the converter.

As indicated by the figure, both the RCA and Westinghouse thermoelectric elements lengths are near the optimum from a weight standpoint and changes in the reference element length would not result in significant weight savings in isotope systems.

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The changes in overall system efficiency corresponding to the weight curves shown in Figure VI-4 are directly proportional to the changes in converter efficiency with element lengths as shown in Section IV-A-2-c. Section IV-A-2-c also shows the change in converter volume with element length. However, the compact converter volumes for these high Carnot efficiencies are small and do not appear to be a significant variable in isotope system design.

C. OFF-DESIGN PERFORMANCE

Implicit within this study is the assumption that certain levels of technological development will be reached before these systems are flown. In this section the effect of any deviations from anticipated heat source and converter technology are discussed.

1. Heat Source

For polonium, a Ta-DyPo²¹⁰ cermet fuel is used. Development testing of this fuel form is in progress and no fundamental problems are anticipated. However, if brittleness tests or other tests show that this form is undesirable, Po²¹⁰ metal can be readily substituted in the same fuel capsule with little or no delay in development schedules.

An alternate fuel form for Pu²³⁸ which would meet the requirements that the oxide microspheres fulfill would be substantially harder to develop. If tests of the oxide microspheres, such as the ingestion tests in progress, prove unfavorable, a sizable plutonium fuel form program will be necessary. This would be

particularly true in light of the sparse information available today on plutonium compounds other than the oxide. Since it is not apparent at this time what the alternate to PuO_2 microspheres would be, if one were required, it is not possible to say what system effects would be occasioned by use of a substitute fuel form.

The 316-stainless-steel-NaK compatibility places a limit on maximum heat source temperature capability for the present designs. This potential problem was discussed in detail in Sections IV-A-2-a and IV-A-2-d. If stainless-steel-NaK compatibility should prove a problem at 1500°F or above, the most favorable solutions appear to be: (1) reduce the system temperature or (2) substitute potassium for NaK. The effects on the system of reduced temperature operation are discussed in Section VI-E. The major effects of substituting potassium for NaK are a 20% increase in pumping power, which results in a 2 to 3% increase in system weight, and the requirement for ground operations which include heating of the potassium to prevent freezing.

The heat source design is predicated on the use of one inch of evacuated multifoil insulation and high thermal resistance supports to limit heat loss to less than 5% of thermal power with a maximum temperature difference of 1400°F. If this insulation results in a greater heat loss the thermal power of the source would have to be increased, with a corresponding weight increase, or the amount of insulation will have to be increased. The weight penalty from increased insulation would be caused primarily by the added shield area, volume, and weight. For example, if 2 inches of insulation are required rather than 1 inch, heat source-shield weight will increase by roughly 6 to 10%.

The predicted heat source pressure drop is very small. Even if the actual value exceeds by two or three times those predicted, no significant system penalty will result.

As can be seen from the integration drawings in Section IV-C, the entire system takes up only about 20% of the volume available in Bay IV of the SM. Any volume deviations, therefore, would not be a serious problem except that the volume of the heat source would directly affect the weight of the shield. Shield weight goes approximately as source volume to the 2/3 power.

Any change in heat source weight reflects directly in the overall system weight. Most probably, however, heat source weights will not increase over the weights presented in this report because of the conservative design. To the contrary, future heat sources should become lighter as development progresses. The major potential for weight reduction will be improvements in the fuel re-entry protection mode.

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2. Thermoelectric Converters

The major performance goals of the thermoelectric compact converters can be classified in the areas of temperature capability, efficiency, degradation rate, weight and volume. The effects on the system of operating at different converter inlet temperatures are discussed in detail in Section VI-E. The following paragraphs discuss the effects on the overall system of off-design performance of the converters in the remaining areas.

The reference converter efficiency as a function of hot junction temperature and Carnot efficiency was presented in Section IV. Failure of the converter to meet the efficiency goals would result in increased system weight for the same power level. In general, system weight varies inversely with system efficiency and for relatively small changes in efficiency near the optimum design point, these changes are linear. For example, a 10% decrease in converter efficiency would necessitate a 10% increase in system weight and area to maintain a constant end-of-life power output.

The effects of changes in the converter degradation are essentially the same as the effects of changes in converter efficiency since the degradation rates do establish the end-of-life converter efficiency to be used in a system design. Therefore, as an example, a 10% increase in converter degradation over the mission life would necessitate a 10% increase in system weight and area to maintain a constant end-of-life power output. Increases in converter degradation would also increase the excess electrical power generated by constant temperature systems at the beginning of life. However, the equipment required for dissipation of this excess power does not represent a significant portion of the system weight.

The above discussion regarding the system effects of changes in converter efficiency and degradation does not account for the fact that converter submodules come as integral units. For example, a 2% change in the number of converter

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submodules in a system is not physically possible. However, in the design of the reference 2-kwe system it was found that the efficiency, and hence weight and area penalty, associated with matching converter power and voltage for a given design point, was a maximum of 3 to 4%. This potential penalty must be considered as an uncertainty until detailed design is accomplished on a specific system. As discussed earlier, this uncertainty would decrease with increasing system power.

Changes in the thermoelectric converter weight would reflect directly in the system weight. However, in isotope systems the Carnot efficiency is high and the converters generally represent a small portion of the system weight. The RCA converter represents about 3% of the total Po^{210} system weight and 1 to 2% of the Pu^{238} system weight. The Westinghouse converter is about 10% of the total Po^{210} system weight and about 5% of the Pu^{238} system weight. Therefore, relatively large changes can be made in the converter weight without significant effects on the total system weight.

The high Carnot efficiencies of the isotope systems also result in relatively small converter volumes. In the integration of the reference isotope systems into the Apollo SM, the converter volume is not significant and it is anticipated that this will be the case in most isotope manned system applications.

D. SYSTEM POWER PARAMETRICS

The effect on isotope compact converter system weight and radiator area resulting from varying the net system power output between 1 kwe and 5 kwe has been investigated. In evaluating a power system over a range of power outputs, two approaches are possible. The system design can be maintained constant and the system reliability allowed to vary with power. Or, the system reliability can be maintained constant, in which case the design will vary with power. In order to describe accurately the performance variations with power of the reference designs shown in Sections IV and V, the former approach has been used in the analysis. That is, the system configurations have been held constant and the reliability allowed to vary with power, as shown in Table VI-1. The design modifications required to vary the system reliability over the range of 0.95 to 0.99 for various system powers are discussed in Section VI-F.

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TABLE VI-1
VARIATION OF SYSTEM FULL-POWER RELIABILITY
WITH POWER

Net power output (kwe)	1	2	3	4	5
Full power reliability	0.991	0.981	0.971	0.962	0.952

The system weight as a function of electrical power output for Po^{210} systems, using the RCA converter, is shown in Figure VI-5. The weights shown are total shielded system weights based on the system configuration, components, integration scheme, and mission parameters discussed for the Reference 2-kwe system designs. The only exception is that the reduced converter pressure drop (as discussed in Section VI-A) has been used. UNCLASSIFIED

The weights are shown in Figure VI-5 for several overall end-of-life system efficiencies. It will be noted that the relationship of the system weight curves for various efficiencies corresponds to the shape of the system weight as a function of Carnot efficiency which has been shown previously for 2-kwe systems. That is, the total system weight decreases as the system efficiency is increased from 4 to 5% (by operating at higher Carnot efficiency or lower radiator temperature) and then increases as the system efficiency is raised above 5%.

As indicated in the figure, the system weight as a function of power, for constant system efficiency, is nearly a straight line. This is due to the fact that, for constant efficiency, the source weight, converter weight, and radiator weight vary directly with system power. And, while the shield weight does not vary exactly as power, the relationship is close to linear because of the increasing size of the heat source. The component weights, which do not vary directly with power, are the pump, piping, and structure weights. However, these are a fairly small part of the total system weight.

The corresponding system radiator area variation with power is shown in Figure VI-6. As with system weight, the radiator area variations are shown for several overall end-of-life system efficiencies. As indicated, the area for any particular power increases exponentially with system efficiency since the increased efficiency is being obtained by operating with lower radiator temperatures. It will be noted that the area variation with power is linear for a constant efficiency since at a given efficiency the radiator temperature is fixed and the radiator area varies indirectly with the thermal power rejected.

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Figure VI-5.
 Po^{210} RCA System
Weight vs Power

Figure VI-6.
 Po^{210} RCA System
Area vs Power

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Similar data on the weight and area versus power for Po^{210} systems using the Westinghouse converter and Pu^{238} systems with both the RCA and the Westinghouse converter, are presented in Figures VI-7 through VI-12. Typical weight versus power data for all four systems are summarized in Table VI-2.

TABLE VI-2
SYSTEM WEIGHT VS POWER

System	Weight (lb)				
	1 kwe	2 kwe	3 kwe	4 kwe	5 kwe
Po^{210} RCA					
System efficiency = 4.0%	900	1765	2580	3320	4000
4.5%	800	1550	2260	2930	3550
5.0%	740	1425	2090	2700	3260
5.5%	760	1460	2140	2760	3320
Po^{210} Westinghouse					
System efficiency = 5.0%	860	1670	2450	3180	3860
6.0%	750	1490	2190	2850	3470
7.0%	810	1600	2350	3050	3700
Pu^{238} RCA					
System efficiency = 4.0%	1680	3450	5180	6850	8420
4.5%	1460	3050	4620	6150	7640
5.0%	1360	2800	4200	5600	6950
5.5%	1280	2700	4100	5480	6820
Pu^{238} Westinghouse					
System efficiency = 5.0%	1380	2960	4500	6020	7520
6.0%	1280	2680	4050	5400	6730
7.0%	1440	3020	4610	6150	7650

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Figure VI-7. Po^{210} Westinghouse System Weight vs Power

Figure VI-8. Po^{210} Westinghouse System Area vs Power

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Figure VI-9. Pu²³⁸ RCA System
Weight vs Power

Figure VI-10. Pu²³⁸ RCA System
Area vs Power

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Figure VI-11. Pu²³⁸ Westinghouse System
Weight vs Power

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Figure VI-12. Pu²³⁸ Westinghouse
System Area vs Power

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E. HOT JUNCTION TEMPERATURE

Variations in the hot junction temperature can produce significant changes in the performance of the power systems. In general, increasing the allowable hot junction temperature results in a decreased system weight, a decreased system area, and an increased system efficiency. However, increasing the hot junction temperature generally results in an increased degradation rate which partially offsets the gains to be made in efficiency and the weight reductions.

Figure VI-13 shows the effect of average primary NaK temperature on the weight of a Po^{210} RCA system. For this analysis the assumption was made that the RCA converter design would utilize the tubing changes described in Section VI-A. These changes result in a lower pressure drop through the converter which in turn reduces the pumping power. Therefore, a NaK ΔT of 100°F is used as the optimum ΔT for both the RCA and Westinghouse designs.

For the Po^{210} RCA system the minimum system weight decreases approximately one pound per degree F increase in average primary temperature in the range 1250 to 1550°F .

As the average primary temperature is increased, the Carnot efficiency of the minimum weight system increases. This is due to the reduced fraction of the total system weight that the radiator comprises. This shift makes the fuel weight more significant and results in a tendency to reduce the fraction that the fuel weight comprises by operating the converter at a higher efficiency.

The effect of average primary NaK temperature on converter degradation was discussed in Section IV-A-2-c. In general, the degradation rate of the RCA converter is affected little by changes in the average primary NaK temperature in the range of interest.

The overall end-of-life system efficiency for the Po^{210} RCA system is shown in Figure VI-14. As indicated, the system efficiency increases with increasing Carnot efficiency and with increasing converter hot junction temperature.

The effect of hot junction temperature on radiator area is shown in Figure VI-15 for the Po^{210} RCA system. In general, the area at constant Carnot efficiency decreases 15 to 20% per 100°F of increase in the converter hot junction temperature.

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Figure VI-13. Po^{210} RCA System Weight as a Function of Hot Junction Temperature

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Figure VI-14. Po^{210} RCA System Efficiency as a Function of Hot Junction Temperature

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Figure VI-15. Po^{210} RCA System Area as a Function of Hot Junction Temperature

Figures VI-16, -17, and -18 show the effect of converter hot junction temperature on the weight, efficiency, and area of Po^{210} systems using the Westinghouse converter. The effects of hot junction temperature changes on the Westinghouse systems are essentially the same as those described for the RCA systems. It should be noted, however, that the Westinghouse converter degradation is affected significantly by the hot junction temperature (reference Section IV-A-2-c). This effect has been included in the weight, area, and efficiency calculations.

The effect of hot junction temperature on the Pu^{238} systems is shown in Figures VI-19 through -24. The system efficiencies and areas behave the same as for the Po^{210} systems. However, the changes in the hot junction temperatures have a stronger effect on Pu^{238} systems weight, approximately 2 lb/°F at the minimum weight point. This is due to the fact that changes in the heat source weight (through changes in converter efficiency) have a more pronounced effect on total system weight in the Pu^{238} systems.

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Figure VI-16. Po^{210} Westinghouse System Weight as a Function of Hot Junction Temperature

Figure VI-17. Po^{210} Westinghouse System Efficiency as a Function of Hot Junction Temperature

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Figure VI-18. Po^{210} Westinghouse System Area as a Function of Hot Junction Temperature

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Figure VI-19. Pu^{238} RCA System Weight as a Function of Hot Junction Temperature

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Figure VI-20. Pu^{238} RCA System Efficiency as a Function of Hot Junction Temperature

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Figure VI-21. Pu^{238} RCA System Radiator Area as a Function of Hot Junction Temperature

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Figure VI-22. Pu^{238} Westinghouse System Weight as a Function of Hot Junction Temperature

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Figure VI-23. Pu^{238} Westinghouse System Efficiency as a Function of Hot Junction Temperature

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Figure VI-24. Pu^{238} Westinghouse System Area as a Function of Hot Junction Temperature

F. RELIABILITY FOR PARAMETRIC SYSTEM STUDIES

The reliability analyses for the parametric system variations are concerned with a variation in total system power and an increased reliability objective.

The relationship of system power with reliability is estimated on the basis of the effects on individual system components in order to meet different power requirements. The power range of interest is from 1 to 5 kw, and a reduction from 2 to 1 kw in general provides a reliability improvement over the reference system.

In addition to the power considerations, various methods have been determined by which the system, over the power range of interest, can meet a more stringent reliability goal of 0.99 for full power for two-year operation.

The component complexities for the isotope heat source, converter, piping, and pump are estimated to vary directly with system power requirements. The respective failure rates for these components are determined by direct system power ratio with the reference system. The complexity of the radiator is estimated to vary directly with the square root of the radiator area; the radiator

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area varies directly with system power. All other components are considered to be approximately equal in complexity over the system power range of interest. Table VI-3 shows the failure rate tabulation for reference type systems for three power levels.

The reliability estimates for 1- to 5-kw systems can be readily determined from Table VI-3. These reliability estimates are applicable to systems with the same configuration as the 2-kw reference system in Section IV. The results are summarized in Table VI-4 for comparison. These values are in terms of performance reliability only; the meteoroid nonpuncture probability is a controlled variable which determines the amount of decrease in total reliability below the performance reliability shown.

The results in Table VI-4 indicate that a basic 5-kw system will not meet the system reliability objective of 0.98 for partial and full power. The lower power systems can meet 0.98 probability and allow adjustment for meteoroid nonpuncture. The 5-kw systems were analyzed to determine the possible ways by which they could meet the 0.98 partial-power and 0.95 full-power objectives. The segmented converter and heat rejection loop concept as mentioned in Section IV-E could be utilized to meet the objectives, but this would require a power dump system and result in a more costly and heavier system. A breakdown of the 5-kw system reliability using RCA converters shows that by improving the pumping and converter reliabilities the objectives can be met. Adding one more converter module in parallel redundancy, and providing redundant, separate-source pumps for both the primary and heat rejection loops, are estimated to increase the performance reliability to 0.9817. This is within the realm of meeting full power with 0.98 probability and allowing adequate adjustment for meteoroid protection.

The 5-kw Westinghouse converter system needs the redundant converters and pumps and, in addition, an improvement in radiator failure rate to 3.7×10^{-7} failures per hour. This failure rate improvement over the estimated value of 4.6×10^{-7} appears reasonable to expect in light of the accuracy to which these failure rates are determined. With these adjustments the Westinghouse 5-kw system is estimated to provide a full-power performance reliability of 0.9815.

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TABLE VI-3
SYSTEM POWER LEVEL EFFECTS ON COMPONENT
FAILURE RATES
(Pu²³⁸ 2-Year System)

Component	RCA			Westinghouse		
	Failure Rates x 10 ⁷			Failure Rates x 10 ⁷		
	1 kw	2 kw	5 kw	1 kw	2 kw	5 kw
Heat Source						
Isotope capsules	0.265	0.53	1.325	0.21	0.42	1.05
Heat exchanger	1.2	1.2	1.2	1.2	1.2	1.2
Shield	0.04	0.04	0.04	0.04	0.04	0.4
Primary Coolant System						
Piping	0.2	0.4	1.0	0.2	0.4	1.0
ECU	Reliability = 0.99996 for 2 years			Reliability = 0.99996 for 2 years		
Converter Electrical	0.5	1.0	2.5	1.2	2.4	6.0
Heat Rejection System						
Piping	0.2	0.4	1.0	0.2	0.4	1.0
ECU	Reliability = 0.99996 for 2 years			Reliability = 0.99996 for 2 years		
Radiator	1.51	2.13	3.37	2.05	2.9	4.6
Capsule Eject	0.92	0.92	0.92	0.92	0.92	0.92
Across-the-line Pump	1.2	2.4	6.0	1.2	2.4	6.0

TABLE VI-4
RELIABILITY SUMMARY FOR BASIC SYSTEMS
OF VARYING POWER LEVEL
(Pu²³⁸ 2-Year Systems)

System Power Level	RCA	Westinghouse
1 kw	0.989 x P _o	0.987 x P _o
2 kw	0.984 x P _o	0.981 x P _o
5 kw	0.970 x P _o	0.962 x P _o

P_o = Meteoroid nonpuncture probability

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From Table VI-4 it can be seen that none of the basic two-year systems are estimated to meet a system reliability of 0.99 for full power. The 1- and 2-kw systems are estimated to meet this objective with slight modification and improvement. The 2-kw system will meet 0.99 reliability if one redundant converter module is added and the across-the-line pump, primary heat exchanger, and radiator failure rates can be improved. These improvements in failure rate are shown in Table VI-5 and are felt to be within the realm of achievement. Redundant weld techniques might be used to improve the radiator and heat exchanger failure rates, and the pumps can be improved by derating, or allowing for greater performance degradation. Redundant separate-source pumps could also be utilized. Meeting the 0.99 objective for a 1-kw system requires the same changes and improvements as the 2-kw system, but the degree of required improvement is somewhat less.

The present reliability estimates do not support the approach of meeting a 0.99 reliability for a 5-kw system by relying on component improvement. The degree of required improvement is more than can be presently justified; therefore, it is felt to be more reasonable to obtain the higher objective through redundancy. With no improvement in component failure rate, the system is estimated to meet 0.99 full-power reliability by utilizing a standby converter segment to back up two active converter segments, and redundant, separate-source EM pumps on the primary system. Providing a two-out-of-three standby redundancy concept for the converter segments and associated heat rejection loops requires a shutoff arrangement for the heat rejection loops. This can be accomplished by motor-driven valves or possibly by TE or EM pumps acting as check valves. With no additional partial-power requirement, the system could then meet the objective without employing a power dump system in the primary coolant system. Table VI-5 summarizes the changes necessary to achieve 5 kw at the reference system objective, and the requirements to meet 0.99 reliability at all system power levels are also tabulated.

The remainder of this section discusses the system design and performance effects which would result from the modifications discussed in Table VI-5. Consider, first, the modifications required to achieve a full-power reliability of 0.99 for 2-kw systems. For both the RCA and Westinghouse systems the converter

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TABLE VI-5
PARAMETRIC SYSTEM RELIABILITY SUMMARY

System Power	2-Year Reliability Objective	Converter Manufacturer	Changes to Basic System Which Can Meet Requirements and System Estimates
2 kw	0.99	RCA	One redundant converter module Primary heat exchanger — improve λ from 1.2×10^{-7} to 0.9×10^{-7} Radiator — improve λ from 2.13×10^{-7} to 0.91×10^{-7} Across-the-line pump — improve λ from 2.4×10^{-7} to 0.91×10^{-7} Reliability = $0.991 \times P_0$
		Westinghouse	One redundant converter module Primary heat exchanger — improve λ from 1.2×10^{-7} to 0.9×10^{-7} Radiator — improve λ from 2.9×10^{-7} to 1.25×10^{-7} Across-the-line pump — improve λ from 2.4×10^{-7} to 0.91×10^{-7} Reliability = $0.9908 \times P_0$
1 kw	0.99	RCA - Westinghouse	Similar to above, but less stringent
5 kw	0.98	RCA	Redundant separate-source pumps for primary and heat rejection One redundant converter module Reliability = $0.9817 \times P_0$
		Westinghouse	Redundant separate-source pumps for primary and heat rejection One redundant converter module Radiator — improve λ from 4.6×10^{-7} to 3.7×10^{-7} Reliability = $0.9815 \times P_0$
5 kw	0.99	RCA - Westinghouse	Redundant separate-source pumps in primary Two active converter-heat rejection segments + one standby segment Shutoff valves on heat rejection Performance reliability RCA 0.9902 Westinghouse 0.9905 Required meteoroid P_0 per radiator segment RCA 0.997/radiator segment Westinghouse 0.997/radiator segment

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reliability must be improved. When the increased converter reliability is obtained by adding a redundant converter module, the system area remains constant and the system weight increases by the weight of the added converter module which is negligible compared to the total system weight (less than 1%). However, it should be noted that in order for the extra converter module to accomplish the goal of redundancy, the capability must exist of switching out any failed converter module and switching the redundant module into its place. This will involve both electrical and hydraulic switching.

If electrical and hydraulic switching are not available, then the converter reliability cannot be increased by the techniques of converter redundancy. The alternative then is to add an additional converter series circuit with associated heat source and radiator increases and to design the system for greater than rated power such that the failure of any converter series circuit would not reduce the power below the rated output. This is the technique of overdesign of the total system and results in substantial system weight and area penalties for low-power systems since one converter series circuit represents a substantial portion of the system power output. For example, in the reference 2-kwe Pu²³⁸ systems which are designed for 28-vdc power output, there are 2 converter series circuits in the RCA system and 3 in the Westinghouse system. Therefore, the above approach to increasing full-power reliability (i. e., adding another converter circuit and associated system components) would result in a 50% weight and area penalty to the RCA system and a 33% weight and area penalty to the Westinghouse systems. Clearly this situation improves for higher powered systems which have a greater number of series circuits in the converter, since the addition of an extra series circuit represents a smaller percentage of the total system.

If this approach to increasing the converter reliability were actually to be used in a 2-kwe system, it would probably be desirable to reduce the system voltage output. For example, if the systems were designed for 7 vdc rather than 28 vdc, there would be four times as many series circuits in the converter. An additional converter module would then result in a weight and area penalty to the RCA and Westinghouse systems of only 12 and 8%, respectively.

From the above discussion, it is clear that the preferable solution to increasing the converter reliability is through true converter redundancy and, therefore, the development of electrical and hydraulic switching circuits (with manual overrides) should be investigated in more detail.

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The only other item listed for improving the 2-kwe systems to 0.99 reliability which might significantly affect the system weight is the required meteoroid non-puncture probability (P_0). For the 0.99 reliability systems P_0 must be approximately 0.999 for both systems vs 0.996 for the reference systems. However, for these relatively small radiators this represents a penalty of only about 15 lb in radiator meteoroid armor.

Raising the 1-kwe system to a full-power reliability of 0.99 involves the same considerations discussed above. In all cases any weight or area penalty is less severe than for the 2-kwe systems.

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In Table VI-4 it was shown that the 5-kwe systems with the reference configuration will have a full-power reliability of 0.97 and 0.962, respectively, for the RCA and Westinghouse converters. As indicated in Table VI-5, raising this reliability to 0.98 again requires raising the converter reliability with converter redundancy (and associated electrical and hydraulic switching capability). It is also necessary to raise the pump reliability significantly. It is recommended that this be done through the use of redundant pumps. For RCA systems using redundant pumps, the separate-source rather than across-the-line pumps appear preferable in that pump switching can be accomplished electrically and the pump, on standby or in a failed condition, will consume no electrical or thermal power. For systems using a redundant separate-source pump the system weight penalty will be 2 to 3%, the weight of the pump alone, and no radiator area penalty will be incurred. For systems using across-the-line or integral source pumps, the system weight and area penalty will be 5 to 6% because the pumps consume thermal power while in the standby or failed condition. This penalty could be reduced to the 2 to 3% pump weight penalty by providing hydraulic switching for moving pumps into or out of the system.

The meteoroid nonpuncture probability for the 5-kwe systems at 0.98 is again about 0.999. The additional meteoroid armor over the reference configuration will be about 50 pounds.

The last modifications shown in Table VI-5 are for raising the 5-kwe full-power reliability to 0.99. This improvement requires redundant pumps as discussed above. Also required is redundancy in the converter/heat rejection loop as differentiated from the previous systems which required redundancy in the

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converter alone. The redundant loop indicated in Table VI-5 would require a 50% increase in converter weight and about a 100% increase in secondary loop piping weight. However, the redundant radiator section would be a shared-fin radiator (sharing the fins of one of the active loops) and there would, therefore, be no increase in radiator area. The total system weight penalty for this configuration is estimated at about 6% for the RCA systems and 12% for the Westinghouse systems. The percentage increase in the Westinghouse systems is greater because of the heavier Westinghouse converter and the lower total system weight.

It will be noted that in all cases discussed above, methods of improving system reliability which affect the heat source and shield weights have been avoided. And in most cases the radiator area has been held approximately constant. Since these three items, heat source, shield, and radiator comprise 80% or more of an isotope power system's weight, great flexibility can be allowed for changes or redundancy in the remaining components without significantly affecting total system weight. This approach should generally be used in attempting to improve isotope system reliability.

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SECTION VII.
CASCADED SYSTEM PERFORMANCE
AND DESIGN

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VII. CASCADED SYSTEM PERFORMANCE AND DESIGN

The relatively high efficiency of the Westinghouse converter in the lower temperature ranges and the high temperature capability of the RCA converter suggest that very attractive system performance can be obtained by cascading the two converters. A simple method of doing this is shown schematically in Figure VII-1. The heat source, either the Po^{210} or the Pu^{238} , is connected to the RCA converter by a high-temperature NaK loop. The RCA converter, in turn, is connected to the Westinghouse converter by an intermediate-temperature NaK loop. The Westinghouse converter dumps its waste heat to the radiator by way of a low-temperature NaK loop. In this way the only physical interface between the two converters is the intermediate NaK loop.

The high-temperature NaK loop is pumped by a separate source dc conduction pump taking its power from the RCA converter. The RCA converter is suggested as the power source due to its better versatility in supplying high-current power. The high-temperature NaK loop would contain the power-flattening radiator in the case of systems using a Po^{210} heat source.

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The intermediate loop and the low-temperature loop are pumped by an across-the-line dc conduction pump. The performance of this type of cascaded system has been calculated for converter inlet temperatures used in the previously described reference systems. The primary NaK inlet temperature to the RCA converter is 1500°F ; the primary inlet temperature of the Westinghouse converter is 1100°F . All of the calculations for the cascaded system assumed that the RCA converter would be of the low pressure drop design described in Section VI-A. Therefore, the NaK ΔT for both the RCA and the Westinghouse converter was set at 100°F . Figure VII-2 shows the resulting performance for a 2.1-kwe system as a function of overall Carnot efficiency. Comparisons with the data in Section IV-B for systems using the RCA or Westinghouse converters separately shows that significant savings in weight and radiator area are possible with the cascaded system. For the Po^{210} -fueled system, the minimum weight is about 1200 lb (compared to 1600 lb and 1550 lb, respectively, for the RCA or Westinghouse systems alone), and the required radiator area at minimum weight is 155 ft^2 (compared to 160 ft^2 and 215 ft^2 , respectively, for the individual systems). The minimum weight for the Pu-fueled cascaded system is 2120 lb (compared to 3100 lb and 2800 lb, respectively, for the RCA and Westinghouse

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Figure VII-1. Cascaded System Schematic

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Figure VII-2. Cascaded System Performance

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converters alone), and the radiator area is 220 ft² (in comparison to 240 ft² and 300 ft², respectively, for the RCA and Westinghouse systems). At the minimum weight, the system efficiency for the cascaded system is approximately 8.9%, compared to 5% and 6% for the RCA and Westinghouse systems. The minimum weight for the Po²¹⁰ cascaded system occurs at an overall Carnot efficiency of 61%.

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A brief analysis was performed to determine the effect of a change in the intermediate-loop temperature. At a Carnot efficiency of 60% (about the minimum weight value for both the Po²¹⁰ and the Pu²³⁸ systems) the intermediate-loop average NaK temperature of the Po²¹⁰ system was reduced from 1050°F to 900°F. The resulting radiator area, system efficiency and system weight were within 5% of the values obtained with a 1050°F intermediate NaK temperature. This analysis was based on perturbation of selected system designs rather than the optimization of the system design for each intermediate temperature. The fact that the change is small for the unoptimized perturbation indicates that changes would be even smaller for the optimized perturbation. It can, therefore, be concluded that the effect of the intermediate NaK temperature on system performance is very small within the range of 900°F to 1050°F for systems near the optimum overall Carnot efficiency.

Because of the flat response of the system performance to changes in the intermediate NaK temperature in the range of 900 to 1050°F, the lower intermediate temperature should probably be used in order to reduce the degradation rate of the Westinghouse converter to a value similar to that of the RCA converter. This would result in more conservative system design and better long-term performance of the cascaded system.

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