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SPACE ISOTOPE POWER SUPPLY FOR NAVY ADVANCED NAVIGATION SATELLITE -- SYSTEMS STUDY

Space Isotope Power Department, 9330

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ABSTRACT

This report presents the results of a study conducted to provide a technical basis for the development of a space isotope power system for the Navy Advanced Navigation Satellite (NANS). The study recommends a design approach and includes a proposed program plan and estimated costs.

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FOREWORD

The Department of the Navy has requested (References 1 and 2) that the AEC undertake the development of an isotope power source for use in the Navy Advanced Navigation Satellite (NANS). The development of this power source which is to be capable of reliable and extended operation in a space environment must be accomplished within a relatively short time schedule: the tradeoffs between performance, technology, and schedule are to be definitive.

In support of this request and in partial fulfillment of its responsibility to the AEC for the technical management of space isotope power projects, the Space Isotope Power Department of Sandia Laboratory has conducted a study to provide an adequate technical basis for the development of a power source that will fulfill the Navy requirements. Supporting technical effort in the areas of structural and thermal analyses, materials properties, safety, quality control, and reliability has been employed to identify performance goals, evaluate the feasibility and reliability of various design approaches, and to identify and propose solutions to areas of technical uncertainties.

This report summarizes the results of the study in the areas of physical requirements, performance, technology, development times, and costs. The information presented in this report is that available as of September 1, 1966.

TABLE OF CONTENTS

	Page
FOREWORD	3
SUMMARY	8
SECTION I -- SPACE ISOTOPE POWER SYSTEM	9
Introduction	9
Mission Requirements	10
Isotope Power System Characteristics	11
SECTION II -- TECHNOLOGY DISCUSSION	12
Converter Technology	12
Lead Telluride	12
Silicon Germanium	20
Fuel Capsule	27
Insulation Technology	29
Vacuum-Foil Insulation	29
Fibrous or Bulk Insulation	30
Reliability	31
Preliminary Safety Criteria	32
SECTION III -- ISOTOPE POWER SYSTEM DESIGN CHARACTERISTICS	33
System Approach 1	33
System Approach 2	34
System Approach 3	34
System Approach 4	35
Spacecraft Integration	36
Thermal Integration	36
Structural Integration	38
Electrical Integration	38
SECTION IV -- SYSTEM AND DEVELOPMENT RECOMMENDATIONS	39
System Recommendations	39
Recommendation 1 -- System Approach 3	39
Recommendation 2 -- System Approach 4	40
Recommendation 3 -- System Approach 2	40
Recommendation 4 -- System Approach 1	41
Development Recommendations	41

TABLE OF CONTENTS (cont)

	Page
SECTION V -- PROGRAM PLAN AND ESTIMATED COST	42
Known Problem Areas	42
Capsule Design	42
Fuel Form	43
Isotec Panels	43
Effects of Delaying Initiation of Program	43
Technology Versus Time	43
Costs Versus Time	44
Recommended Events and Schedules	44
Other Development and Production Factors	49
Quality Control	49
Reliability	50
Safety	50
REFERENCES	51
BIBLIOGRAPHY	58

LIST OF ILLUSTRATIONS

Figure		Page
1	Average Figure of Merit for n and p Lead Telluride Thermoelectric versus Temperature	12
2	Calculated Conversion Efficiency versus Hot Junction Temperature	13
3	n-Type Lead Telluride Isothermal Tests	17
4	p-Type Lead Tin Telluride Isothermal Tests	17
5	Average Figure of Merit versus Temperature for n and p Silicon Germanium Thermoelements	22
6	Material Efficiency as a Function of Hot and Cold Junction Temperatures	22
7	Variation of Source Temperature with Hot Shoe Surface Temperature as a Function of Thermal Flux Density for Radiation Coupling	26
8	Proposed Program Schedule	45

LIST OF TABLES

Table		Page
I	Preliminary System Design Goals	10
II	Physical Properties of Lead Telluride	14
III	Summary of Isotec Element Life Testing	16
IV	Thermoelectric Test Data Summary–Gradient Temperature, July 25, 1966	18
V	Physical Properties of Silicon Germanium	21
VI	Bonding Technology Summary	24
VII	Silicon Germanium (Air Vac) Thermoelectric Module Life Tests	24
VIII	Comparison of Design Approaches	37
IX	Explanation of Events	46
X	Special Studies and/or Tests	48

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SUMMARY

This study evaluates the present technology applicable to a space isotope power system for use on the Navy Advanced Navigation Satellite (NANS) and recommends a power supply for this application.

Mission requirements and performance goals for the power supply are identified in Section I and various technologies for converter systems, fuel capsules, and insulation are evaluated in Section II.

Of particular interest in Section II are the discussions of the advantages and disadvantages of converter systems using lead telluride thermoelements (sealed and unsealed) and silicon germanium thermoelements (unsealed) and those of fuel capsule technology. Within the current state-of-the-art, an isotope power supply using either a silicon germanium or Isotec lead telluride converter system could fulfill the Navy requirements. However, the major consideration in this technology is that of demonstrated reliability. The capsule technology is the current item pacing the development of light-weight systems and growth potential in terms of power to weight ratio.

Reliability concepts and preliminary safety criteria are also presented in Section II, and system design characteristics are described in Section III.

The study recommends, in Section IV, a silicon germanium thermoelectric energy conversion system as the best approach to reliability and a fuel capsule based on SNAP 27 heat-source technology and designed for fuel containment under all conditions as the best approach to safety. Therefore, a space isotope power system combining these features is recommended for NANS application.

Section V presents a program plan and an estimate of costs.

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SECTION I -- SPACE ISOTOPE POWER SYSTEM

Introduction

In July 1966, Sandia Laboratory was requested by the Atomic Energy Commission, Space Nuclear Systems, to undertake a system design study for a space isotope power supply for the Navy Advanced Navigation Satellite (NANS).

The primary purpose of the study is to provide an adequate technical basis for proceeding with the development of the isotope power supply. The study, conducted by the Space Isotope Power Department of Sandia Laboratory, attempts to (1) assure that the mission and performance goals are identified, (2) evaluate the feasibility and reliability of various design approaches and technologies, (3) identify areas of technical uncertainty and suggest plans for resolution, and (4) provide a preliminary safety criteria assessment of the system. The study recommends a design approach to be followed and includes a program plan and estimated costs.

In conducting this study, Sandia Laboratory has (1) reviewed information submitted in mid-1965 by various contractors to the Applied Physics Laboratory (APL), Johns Hopkins University, (2) met with these and other contractors and discussed current isotope power supply development sponsored by both the AEC and industry, (3) studied the technologies available, and (4) examined with the Applied Physics Laboratory the NANS/power supply interface and the effects of mission requirements on the isotope power supply design. The documents used in support of this study are listed in the Bibliography. Supporting technical effort of the Sandia Laboratory in the areas of structural and thermal analysis, materials, quality control, and reliability have been employed in this study. The preliminary safety design criteria were prepared by the Sandia Aerospace Nuclear Safety Department at the request of the Safety Branch of the Space Electric Power Office.

Mission Requirements

The Department of Defense request for development, the preliminary specifications, and the program goals for delivery of isotope power supplies for the NANS were forwarded to the AEC by References 1 and 2. The preliminary system goals presented in Table I were derived from these references and were modified by discussion with the System Manager for NANS, the Applied Physics Laboratory, to best fulfill the purposes of this study and of the proposed development program.

TABLE I

Preliminary System Design Goals

Characteristics	Requirements
Electrical Performance	Deliver a minimum 20 watts at 3-6 volts at the end of 5 years in polar circular orbit at 450-750 nautical miles.
Weight	Less than 13 pounds including attachment and connectors.
External Configuration	Of minimum cross section, closely integrated with spacecraft: in general, less than 10 inches high and 16 inches in diameter.
Reliability	0.96 based on a minimum 20 watts electrical at the end of 5 years.
Heat Load to Spacecraft	50-300 watts thermal (100-150 watts thermal probably most desirable)
Environmental Conditions	Acceleration, vibration, shock, acoustical noise, and pressure transition (from sea level to vacuum) associated with the Scout launch vehicle.
Ground Operation and Handling	Capable of operating under ground ambient conditions with space operation a determinable function of ambient ground operation. Ability to operate open-circuited for short periods of time (1 minute). Provision to be made for convenient ground handling.
Safety	Consistent with the safety required by the Atomic Energy Commission.

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Isotope Power System Characteristics

For purposes of this system study, the fuel form was restricted to plutonium dioxide only, and the disposal mode was to be intact reentry.

The desirability of closely integrating the isotope power supply with the spacecraft precludes detailed study of a specific configuration at this time. However, the program plan presented in Section V, Program Plan and Estimated Cost, includes provision during the preliminary design phase for working closely with the Department of the Navy and APL to assure compatibility and optimum utilization of the heat and structure of the isotope power supply in the spacecraft design.

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SECTION II -- TECHNOLOGY DISCUSSION

The technologies of power converter systems, fuel capsules, and insulation are discussed in this section, and the preliminary safety criteria which influence the disposal mode and fuel containment of the isotope power system are presented.

Converter Technology

Lead telluride and silicon germanium thermoelectric materials are considered in this report for application to space isotope power systems because of certain practical advantages inherent in each material.

Lead Telluride

Two types of lead telluride power converter systems are evaluated: lead telluride elements in a sealed, inert-gas environment and lead telluride elements in Isotec panels in vacuum. This material is characterized by low-current density, low hot-junction temperatures, low strength, and poor fabrication qualities.

Basic Properties of Lead Telluride -- The thermoelectric, physical, and chemical properties of lead telluride alloys are briefly summarized.

1. Thermoelectric Properties

The average figure of merit is presented as a function of temperature in Figure 1.

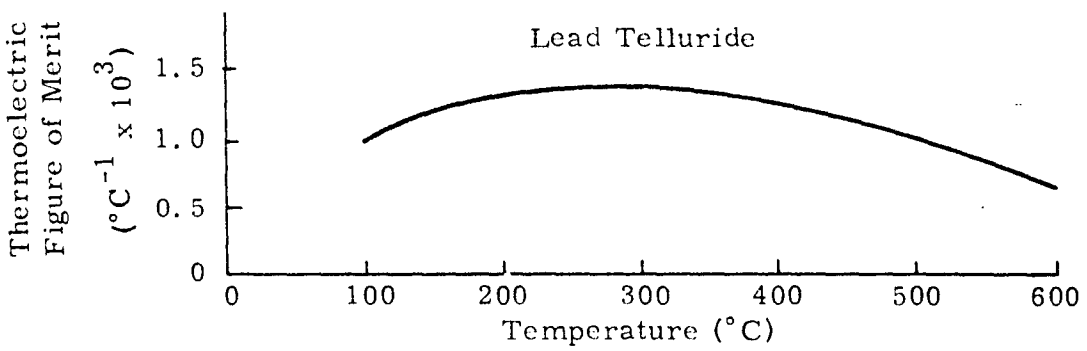

Figure 1. Average Figure of Merit for n and p Lead Telluride Thermoelectric versus Temperature

Figure 2 shows the conversion efficiency versus the hot junction temperature of lead telluride; the cold end temperature is constant at 177°C.

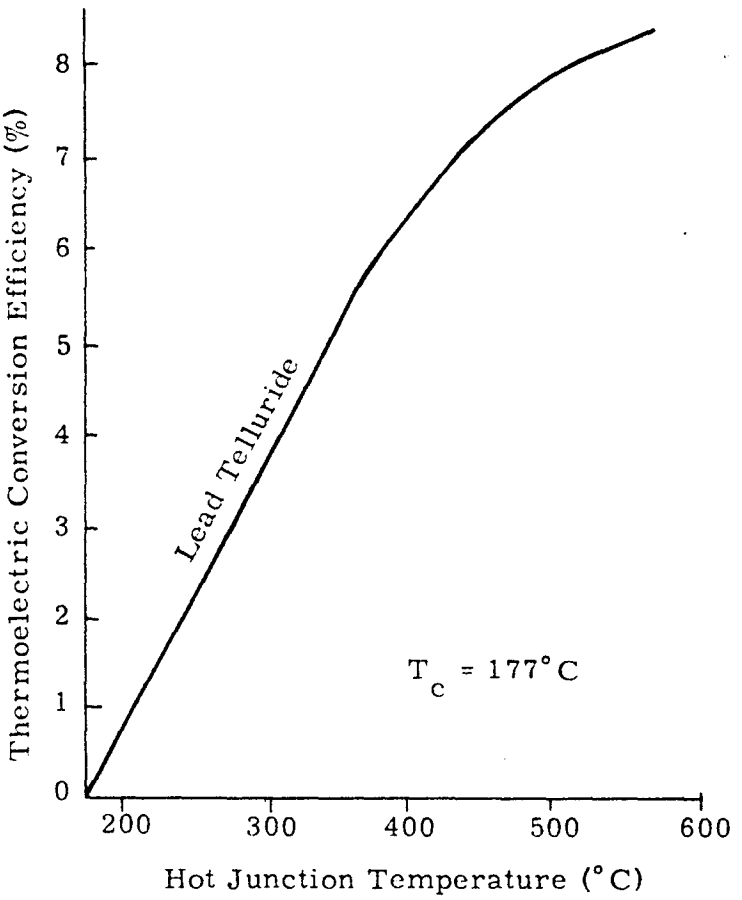

Figure 2. Calculated Conversion Efficiency versus Hot Junction Temperature

2. Physical Properties

Lead telluride is a covalent intermetallic compound. A list of important physical properties is given in Table II.

TABLE II

Physical Properties of Lead Telluride

Structure	Face centered cubic crystal
Melting temperature	922°C
Thermal expansion	18×10^{-6} per °C
Tensile strength	>1000 psi
Vapor pressure (400°C)	4.2×10^{-7} torr
Density	8.25 gm/cc

3. Chemical Properties

The lead telluride alloy has poor oxidation resistance. When Mn is added to form PbMnTe for the p-type material, MnTe may precipitate at operational temperature. The metal Mn, however, retards the sublimation because of its lower vapor pressure.

Inert Gas Operation -- Thermoelectric power generators using lead telluride elements are designed with one constraint that has caused serious questions concerning operational reliability for long-term space missions. At operating temperatures in the space environment, lead telluride sublimes at a rate which makes lead telluride power converter systems seem impractical for long missions. Sublimation occurs when the vapor pressure of the material is greater than the background pressure. The obvious solution is to seal the power converter system in an inert gas atmosphere; several

of these sealed systems have been produced. Seals are not desirable for two reasons: (1) system failure can be caused by one seal failure unless redundant seals are used and (2) the inert gas container imposes a substantial generator weight penalty.

Vacuum Operation -- The Isotec power converter design, rather than an array of elements sealed within an inert-gas atmosphere, is an array of lead telluride elements each surrounded by an individual barrier which serves as an effective molecular shield. When the Isotec panels are operated in a vacuum the shields reduce sublimation. The thermocouples are made up of n-type lead telluride and p-type lead tin telluride. At 400°C, the vapor pressure of lead telluride is 4.2×10^{-7} torr and of tin telluride is 1.7×10^{-6} torr. In that the space vacuum is four or five orders of magnitude lower than the vapor pressure, it might appear that there would be a sizable pumping pressure tending to draw off the surface molecules of the elements. However, the difference between 4.2×10^{-7} and space vacuum in the order of 1×10^{-10} is 4.199×10^{-7}; therefore, the pressure differential is not significant.

The reduction of sublimation by the individual barriers is based on the mean free path of the vaporized molecules. Between the end caps (shoes) and completely surrounding each element, Al_2O_3 fibers have been packed for insulation. At 5×10^{-5} torr, the mean free path for the gaseous molecules is one meter and at 3×10^{-7} torr is 1000 meters. The molecules from the subliming elements are trapped by the insulation barrier long before they can encounter other gaseous molecules or atoms. The insulation immediately adjacent to the element (at a distance <1mm) stops the molecular flow and becomes coated with the escaping molecules. Since the element and the adjacent coated insulation are at the same temperature, the sublimation continues from both surfaces at an equal rate. Thus, after the initial coating, there is no further net loss of material from the elements unless there is a change in the operating temperature.

Isotec Thermoelectric Testing Summary -- Several methods of testing have been used in the investigation of the long life operation of bonded lead telluride and lead tin telluride Isotec thermoelectric elements. A summary of the Isotec element life testing for both isothermal and gradient temperatures is presented in Table III and test data are shown in Figures 3 and 4 and Table IV. In isothermal testing, the whole element is held at the maximum (hot junction) temperature. Thus, vaporization or metallurgical reactions which are temperature sensitive are amplified. Gradient testing provides a simulated operating environment.

TABLE III

Summary of Isotec Element Life Testing

Isothermal		
n-type, PbTe	Longest test (hours)	Total element hours
400°C	5,000	110,000
450°C	4,000	75,000
p-type, PbSnTe		
400°C	6,300	255,000
450°C	4,000	130,000
Gradient		
		Total couple hours
Isotec 400°C Modules (2 couples)	10,600	90,000
Isotec 400°C Panels (18 couples)	2,200	124,000

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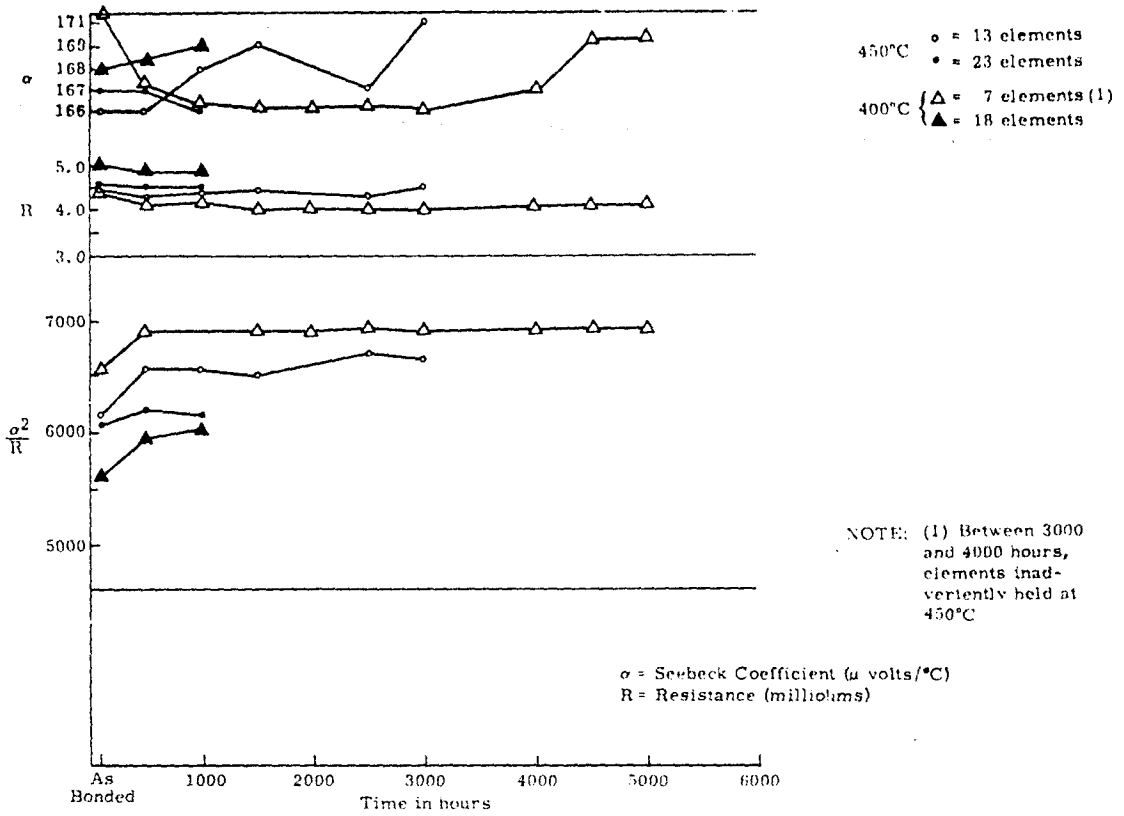

Figure 3. n-Type Lead Telluride Isothermal Tests

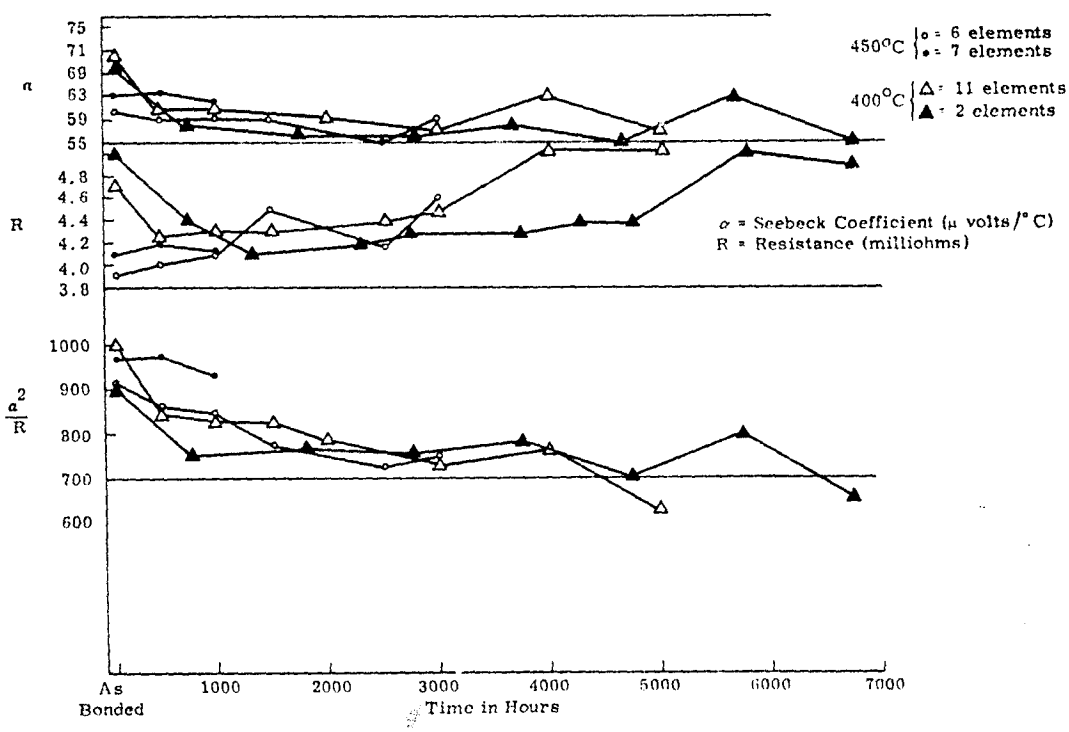

Figure 4. p-Type Lead Tin Telluride Isothermal Tests

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TABLE IV

Thermoelectric Test Data Summary
Gradient Temperature
July 25, 1966

	Hours	Output Power	
		% Change total	% Change Since 8000 hours
Module Test (2 couples)			
X-30	9717	0	0
X-34	9254	-2.8	0
X-35	9155	-8.3	0
X-40	1770	+0.5	
X-42	1770	-3.2	
Panel Test (18 couples)			
OP-1	1301	-2.7	
OP-2	1301	+1.4	
OP-4	200	0	
OP-5	200	0	

Test conditions:

Vacuum environment (10^{-7} torr)

$T_h = 400^{\circ}C$, $T_c \approx 170^{\circ}C$

Continuous monitoring of electrical power output

Radiation heat transfer on hot and cold side

Thermal cycle about every 1,000 hours

Isothermal tests on bare lead telluride and lead tin telluride in vacuum at operating temperature showed a rapid loss of material which occurred because of the long mean free path and relatively large dimensions of the furnace. The measured loss rates were a factor of ten lower than the calculated values based on vapor pressures. This discrepancy is probably due to the decrease in loss rate for the p-type material by a factor of seven during the first 200 hours. During the first 200 hours, the manganese, with a vapor pressure lower than that of lead telluride, forms a protective layer on the element surface. After isothermal tests of bonded elements surrounded by insulation (as in Isotec panels), the presence of the PbTe on the insulation was detected. From tests performed to date, it appears that the insulation becomes coated during the first 1000 hours of operation and that there is relatively little depositing from the elements after this time. Temperature gradient tests of a two-couple module have shown the characteristic deposit on the insulation, but there has been no measurable material loss from the elements in 7800 hours.

Material Characteristics -- One of the serious disadvantages associated with the use of lead telluride has been the variability of the material characteristics; however, it appears that the fabricator of Isotec panels has arrived at a reasonable solution. Incoming lead telluride is screened, and acceptable material is pulverized, pressed, sintered, and tested again. By this reprocessing, homogeneous elements have been produced in the laboratory. Adaptation of this laboratory processing to element production has not been demonstrated. However, the amount of material per Isotec power supply is small (approximately 2 ounces).

Silicon Germanium

Silicon germanium power converter systems are capable of operation in air or in vacuum without requiring encapsulation. This material is characterized by high-strength and low-weight density, ease of fabrication, good chemical-mechanical properties, and stability of operation.

Basic Properties of Silicon Germanium -- The thermoelectric, physical, and chemical properties of silicon germanium alloys are briefly summarized.

1. Thermoelectric Properties

The average figure-of-merit for a typical silicon germanium thermocouple is presented in Figure 5, and a parametric graph for the maximum material efficiency as a function of hot and cold junction temperatures (degrees K) is presented in Figure 6. The thermoelectric characteristics of silicon germanium alloys with respect to time are reproducible and predictable over a wide range of temperatures up to levels in excess of 1000°C.

2. Physical Properties

The important physical properties of silicon germanium are summarized in Table V.

3. Chemical Properties

An attractive chemical property of silicon germanium alloys is the ability to form a thin protective oxide film. This film is stable in air, vacuum, and products of combustion environments up to 1000°C for long periods of time.

TABLE V

Physical Properties of Silicon Germanium

Structure	Single Phase Solid Solution
Solidus Range	1180 - 1300°C
Thermal Expansion	4.8 to 5.0 x 10^{-6} per °C
Tensile Strength	p-silicon germanium ~ 3,900 psi
	n-silicon germanium ~ 4,400 psi
Compressive Strength	> 150,000 psi
Average Modules of Rupture	3,600 psi
Vapor Pressure	3 x 10^{-9} mm of Hg at 800°C
Density	3 to 3.5 g/cm^3

General Characteristics of Silicon Germanium Thermoelectric Generators -- Although the theoretical efficiency of thermoelectric materials is important, the practical aspects of reliable device fabrication require that the thermoelectric materials possess electrical, mechanical, and chemical stability at the proposed temperatures of operation. In addition, it is desirable that the material be capable of operation in ambient environment over a range of temperatures without a need for accurate control of hot side temperatures or precautions against temperature excursions.

1. Environmental Capability

The low vapor pressure at high temperature and the protective oxide film of silicon germanium alloys permit the operation of these alloys in air and/or vacuum without the use of encapsulants or other protective devices.

2. High-Temperature Capability

The high-temperature capability of silicon germanium alloys is compatible with (a) high heat rejection temperatures, (b) conductive or

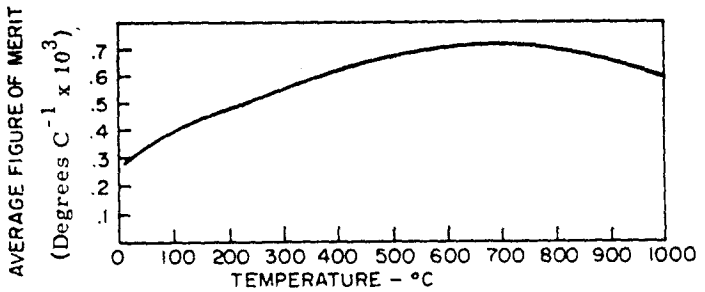

Figure 5. Average Figure of Merit versus Temperature for n and p Silicon Germanium Thermoelements

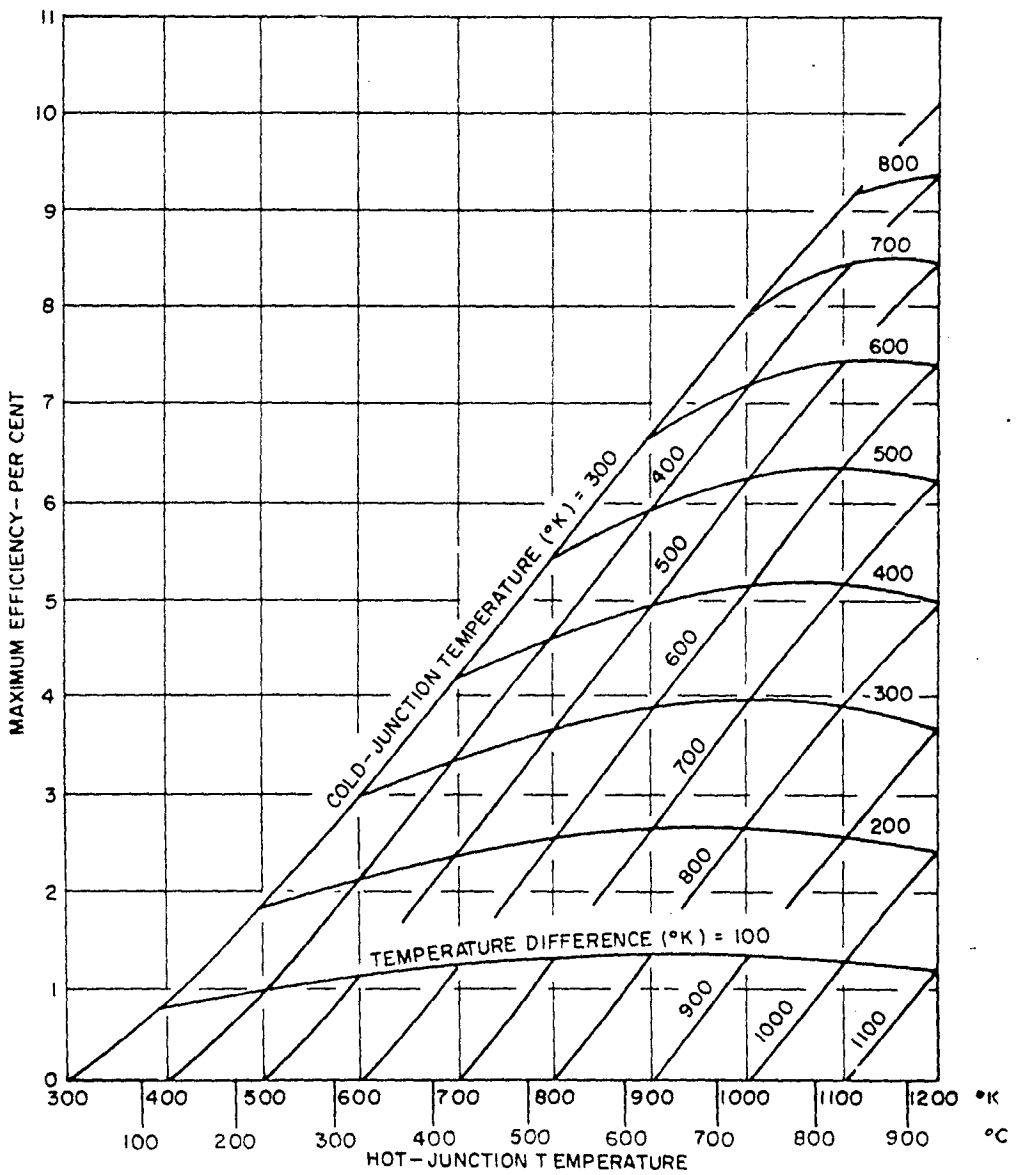

Figure 6. Material Efficiency as a Function of Hot and Cold Junction Temperatures

Silicon germanium devices may be operated over large temperature ranges without the need for accurate temperature control of hot junction temperatures or precautions against temperature excursions. This is possible because there are no abrupt changes with temperature in the important chemical, physical, or electrical properties, i.e., tensile strength, vapor pressure, compressive strength, thermal expansion, and figure of merit up to 1000°C. This capability permits the coupling of silicon germanium devices to high-temperature heat sources to obtain maximum capability of the alloys and it also results in minimum system complexity.

3. Mechanical Properties

The mechanical strength and low thermal expansion of silicon germanium alloys allow design of thermoelectric generators in which silicon germanium is a structural member. The low-thermal expansion allows operation over large temperature gradients. Also, the sensitivity to thermal shock is reduced because thermal shock stresses are proportional to the expansion coefficient. These factors and the low specific weight of silicon germanium alloys lead to systems with improved shock and vibration characteristics.

Demonstrated Performance Testing -- Life performance data illustrating the stability that can be attained with silicon germanium thermoelectric conversion systems is shown in Tables VI and VII. Table VI is a summary of bonding technology showing types of bonds, operating conditions, method of heat source coupling, and longest life test. Table VII tabulates, as of June 24, 1966, silicon germanium, Air Vac thermocouple module life tests indicating test hours, number of thermocouples, operating conditions, and percentage of 500-hour power output. (After 2 years of operation, the power output of the five modules is in the range of 88.5 to 98.5 percent of the 500-hour power output with hot side temperatures of 792-933°C.)

[redacted]

TABLE VI

Bonding Technology Summary

Type of bond	Heat source coupling	Anticipated T_H temperature range (°C)	Longest life test (hrs)	Accumulated thermocouple hours	Operating condition	Status
SNAP-10A Type (Tungsten)	Conduction	483 to 590	33,000	16,380,000	Vacuum	Complete
Advanced SNAP-10A (Carbide)	Conduction	704 to 850	11,468	1,228,000	Vacuum	Pilot Stage
(Graphite)	Conduction	850 to 950	10,500	1,004,300	Vacuum	Development
Air-Vac (Si-Alloy)	Radiation	800 to 1020	18,000 +	572,000 +	Vacuum	Various stages from development to complete
	Radiation	800 to 930	16,000 +	402,000 +	Air	

TABLE VII

Silicon Germanium (Air Vac) Thermoelectric Module Life Tests

Date - June 24, 1966

Module number	Module hours total	Number of thermocouples	Leg diameter (inches)	Pressure torr	T_h (°C)	T_c (°C)	Measured ΔT (°C)	% of 500 hour power output	Thermocouple hours
MTA4A-9	7,017	6	0.275	Air	800	215	*		42,102
MTA8A-17	4,850	6	0.275	Air	930	250			29,100
MTA4-5	18,065	6	0.230	7×10^{-7}	833	258	575	98.5	108,390
MTA7-10	17,202	6	0.275	1×10^{-6}	810	270	540	88.5	103,212
MTA8A-9	16,636	6	0.275	1×10^{-6}	933	294	639	96.6	99,816
MTA8A-18	14,368	6	0.275	7×10^{-7}	808	275	533	94.3	86,208
MTA9-1	15,876	14	0.275	Air	792	204	588	93.4	222,264
								Total thermocouple hours	691,092

*Not operating - Test discontinued after hours shown at nominal temperatures indicated.

[redacted]

radiation coupling to heat sources, (c) temperature excursions, (d) operation in range of maximum figure of merit, and (3) high system growth potential with minimum system redesign.

In a thermoelectric energy conversion system, a given amount of thermoelectric material is capable of supplying more power if the heat source temperature is increased or if the heat rejection temperature is decreased. Because the amount of power which can be radiated per unit area is a function of the fourth power of the heat rejection temperature, higher heat rejection temperatures lead to reduced radiator areas. Since the radiator area is almost directly proportional to radiator weight, the heat rejection temperature may be a limiting factor where weight is a primary consideration. Silicon germanium alloys permit high rejection temperatures while maintaining a large temperature differential across the thermocouple in the temperature range where the figure-of-merit is a maximum.

Contact bonding techniques have been developed for conduction coupling of heat sources to silicon germanium devices capable of stable, long term operation in the temperature range of 850-900°C (this represents the upper limit of the present state-of-the-art). Limitations in the state-of-the-art stem from the difficulty of achieving practical metallurgical combinations which can serve as electrical contacts and mechanical stress balance members between heat source and the thermocouple hot junctions at the higher temperature levels.

Where ground handling procedures, safety, and reentry requirements dictate separate or separable concentrated heat sources and thermoelectric converter structures, the radiation-coupled system is more applicable than a conductively coupled system. Radiation-coupled systems introduce a thermal drop, which is dependent upon such factors as thermal flux density and the characteristics of the boundary surfaces. Present designs

can minimize this thermal drop, particularly in association with heat sources of relatively low-flux density (in the order of one-to-five watts thermal per square centimeter). Figure 7 gives an indication of the thermal drops encountered between the heat source and the hot shoe of a radiation-coupled system. Either air or vacuum operation of silicon germanium thermoelectrics up to 1000°C at the hot junction is indicative of current radiation-coupled system state-of-the-art.

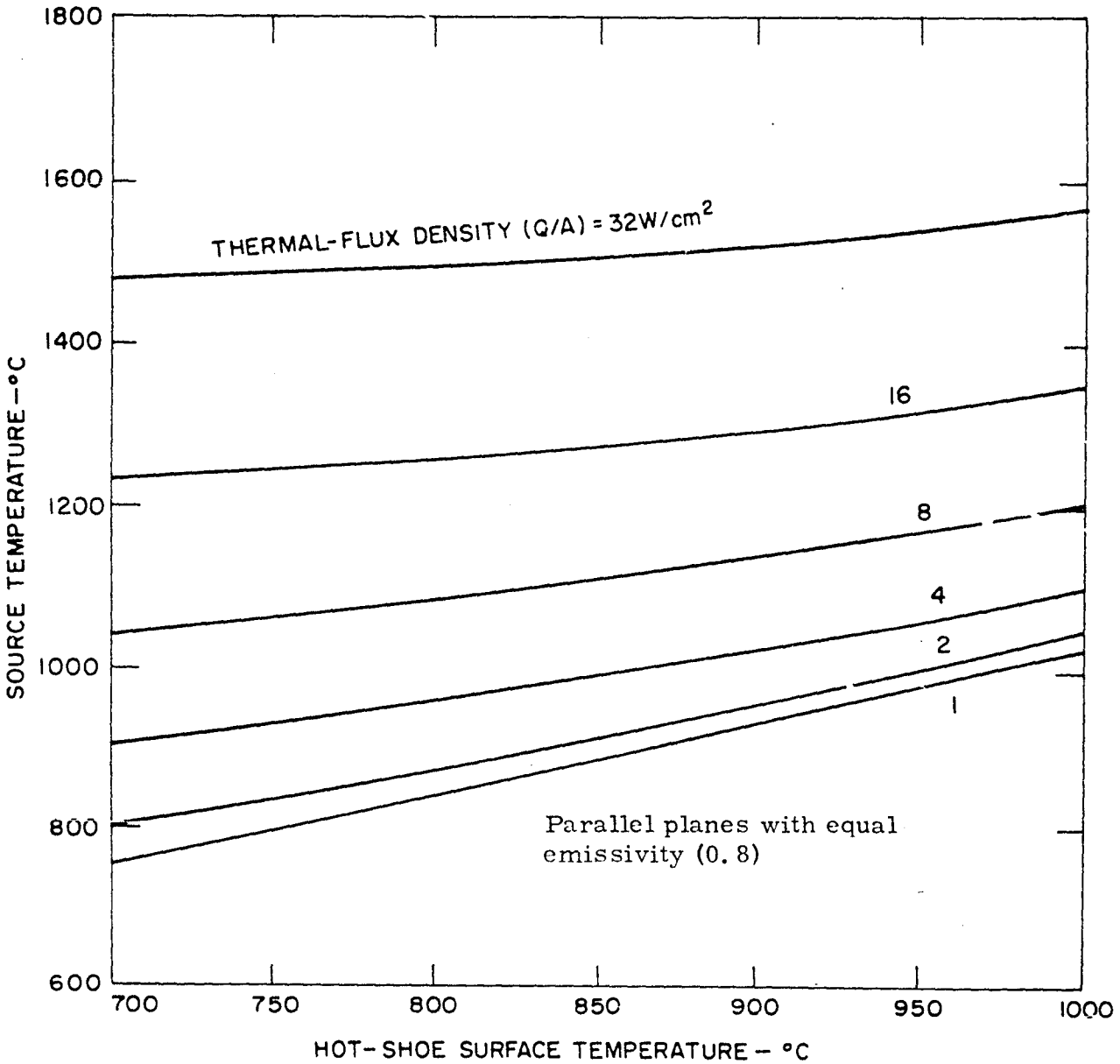

Figure 7. Variation of Source Temperature with Hot Shoe Surface Temperature as a Function of Thermal Flux Density for Radiation Coupling

Fuel Capsule

The state-of-the-art in fuel capsule technology for the containment of plutonium dioxide fuel is represented by the SNAP 27 fuel capsule design approach (deliveries of the SNAP 27 fuel capsule in a fueled configuration will begin in mid-1967). This technology is defined by the following characteristics:

1. Clad and liner material: Cobalt base, Haynes-25 alloy.
2. Clad operating temperature: Approximately 760°C.
3. Helium temperature: Calculated to be 950°C.
4. Fuel liner temperature on the inner surface: Calculated to be approximately 950°C.
5. Clad wall thickness: 0.060 inch.
6. Liner wall thickness: 0.020 inch.
7. Capsule surface (GE Radifrax plasma sprayed coating), emissivity = 0.85.
8. Capsule design incorporates a pressure-relief feature to (1) permit helium containment throughout the operating life of the generator (one year) and (2) provide a heat transfer medium between the liner and clad to maintain the fuel center-line temperature within the range of experience for chemical compatibility between plutonium dioxide microspheres and Haynes-25

In addition, testing is underway to evaluate long term material compatibility, mechanical properties, vent performance, and terminal velocity impact resistance.

The impact survivability of capsules geometrically similar to the type of capsule required for this application has been extensively tested as part of the SNAP 27 and SNAP 17B programs. Fuel containment sections of SNAP 27 fuel capsules (at 590°C) have survived 200 ft/sec impacts at 45 degree incidence angles against granite. Helium leak testing after these impact tests yielded flow rates of less than 3.6×10^{-5} cc/sec.

Retention of helium during capsule operating life is desirable since it significantly aids internal heat transfer and minimizes fuel center-line temperatures. This gas retention aspect could be important in forestalling reactions between the fuel and liner.

The rise in temperature across the thickness of the fuel annulus depends on the effective thermal conductivity of the fuel form. A temperature increment associated with the fit between the liner and cladding is dependent on the presence of helium in this region. Thus the calculated inner-liner temperature of the present SNAP 27 capsule is approximately 950°C with helium present and 1120°C without helium present. Compatibility testing between plutonium dioxide microspheres and Haynes-25 alloy has shown satisfactory results after 10,000 hours at 980°C.

Present evidence supports the use of this capsule design to an external temperature up to about 870°C from the standpoint of fuel-to-liner material compatibility; however, this conclusion is dependent on the retention of helium gas for its effect on internal heat transfer. The actual implications of venting the gas and accepting a liner meltdown or decomposition are hard to assess; hence, use of a post-mission rupture diaphragm appears desirable.

Another effect of temperature is the resultant change in the properties of Haynes-25 alloy after prolonged aging at elevated temperatures. Experimental evidence has shown that intergranular precipitation occurs during aging at temperatures of 760 - 980°C; this results in embrittlement of the alloy. The effect of this action is to reduce the ultimate strength at low temperature and increase the ultimate strength at higher temperature, with the cross-over occurring at about 540°C. In later production of Haynes-25 alloy, the silicon content has been reduced to minimize the embrittlement problem. Long term aging of SNAP 27 capsules is in process to further clarify intergranular precipitation.

Insulation Technology

Thermal insulations for isotope power supplies can be divided into two major categories: fibrous or bulk-type insulations and vacuum-foil insulations. For isotope power supplies, the insulation used to obtain maximum thermal efficiency is dependent on the power supply configuration. These configurations will usually require a combination of the two types of insulation.

Three AEC-sponsored thermal-insulation development contracts (to be completed in 1967) are presently underway. Thermo Electron Engineering Corporation (TEECO) will develop and evaluate vacuum-foil insulation systems for use in the 980 - 1700°C temperature range. The Linde Division of Union Carbide will develop and evaluate vacuum-foil insulation systems for use in the 200 - 980°C temperature range. Johns-Manville will develop and evaluate fibrous or bulk-type insulations for use in the 200 - 980°C temperature range. The status of each category of insulation is as follows.

Vacuum-Foil Insulation

Linde Division Union Carbide -- The vacuum foil insulation systems under development consist of alternating layers of metal foil and spacer

materials inside a vacuum enclosure. Candidate foil materials are tantalum (980 - 870°C), nickel (870 - 700°C), copper (700 - 540°C), and aluminum (540 - 40°C). Candidate spacer materials being evaluated include glass-fiber paper, astroquartz cloth, astrosil cloth, refrasil, and metal-flake opacified-glass-fiber paper. For efficient insulation properties, the foil system must be in at least 10^{-3} torr vacuum. Because of this vacuum enclosure requirement, the vacuum-foil insulation systems are not easily adapted to intricate or complex geometric shapes. However, their thermal conductivity is at least an order of magnitude lower than bulk or fibrous-type insulations.

TEECO -- This vacuum-foil insulation system will be made up of 20 to 40 layers of 0.0005 to 0.001 inch thick refractory foil such as tantalum, molybdenum, tungsten, or tungsten with 25 percent rhenium. The metal foil will be separated by thoria or yttria. The development of this type insulation is directed toward use in devices where the heat source temperature will be about 1740°C. Insulation similar to this was developed by TEECO on the SNAP 13 thermionic program.

Fibrous or Bulk Insulation

Johns-Manville -- The bulk or fibrous insulations being evaluated include astroquartz felt, micro-quartz felt, Irish refrasil, dyna-quartz, and MIN-K formulations. The most promising development is a MIN-K formulation containing no organic binder and yet demonstrating moldability, machinability, and strength. The absence of organic binder will minimize undesirable outgassing.

Reliability

The system requirements specify a minimum reliability of 0.96, i.e., the probability of the power supply withstanding ground operation, handling, and orbit injection on a Scout launch vehicle and providing at least 20 watts for 5 years is to be 0.96 or greater. This probability can be divided into two parts: a probability of providing proper output after orbit injection and a probability of providing at least 20 watts for 5 years given proper output at the start of orbiting. The former, orbit injection success probability, is dependent on how well the power supply is designed and manufactured to withstand shock, vibration, acceleration, etc., and on the thermally induced stresses resulting from operating cycles conducted before launch. The latter, 5-year continuous-operation success probability, is dependent on the stability of the power output and the part failure rates.

SNAP experience with both silicon-germanium and lead-telluride systems has shown that if there is a thermocouple-failure-probability-density function that can be characterized by the exponential distribution, it must have a failure rate that is small enough that this mode of failure can be neglected in comparison with the probability of failure resulting from power output gradually dropping below an acceptable level. This is particularly important in the design of power supplies using Isotec panels because the number of thermocouples required is a factor of 10 greater than with a power supply using silicon germanium thermocouples at the same voltage and current. Redundancy has been used so that, if an element opens, there is a parallel path for current flow.

Closely related to the above in terms of design and production effort, is the ability to consistently manufacture a power supply that will withstand the launch-associated environments. However, the ability to control unit-to-unit variability in strength has not been demonstrated because of the

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small numbers of power supplies produced to date. Even so, this uncertainty should not be too great a concern in most areas if proven techniques of design analysis and environmental testing are used to assure an adequate design and if statistical quality control is used to assure production of homogeneous product of high quality. However, these capabilities must be assured by data verification.

The major problem in obtaining reliable systems is the rate of degradation in power output for the various thermoelectrics over 5 years, which in turn is dependent on the stability and the repeatability of material characteristics.

Preliminary Safety Criteria

This section, which has been deleted at the request of George P. Dix, Chief, Safety Branch, Division of Space Nuclear Systems, will be supplied at a later time.

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SECTION III -- ISOTOPE POWER SYSTEM DESIGN CHARACTERISTICS

Isotope power systems based on the technologies of thermoelectric materials, fuel capsules, insulation, reliability, and safety which are evaluated in Section II are described in this section and the influence of structural, thermal, and electrical integration with the NANS on the isotope power system configuration is discussed.

Four basic power converter system approaches, each with its advantages and disadvantages, are identifiable. These approaches are:

1. Lead-telluride in a sealed, inert-gas system.
2. Lead-telluride (Isotec panel), unsealed.
3. Silicon-germanium, unsealed.
4. Cascaded (thermally in series) silicon-germanium, lead telluride (Isotec), unsealed.

System Approach 1
(Lead Telluride - Sealed)

System Approach 1 is characterized by design concepts employed in SNAP 19 and SNAP 27. Under the guidelines given in Section I, such a generator for NANS would weigh 15.7 pounds, yield 0.047 electrical watts per thermal watt ($W_e EOL / W_t SOL$),* and operate at a 590°C hot shoe temperaature. Undesirable characteristics of this approach are the required seals,

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*$\frac{W_e EOL}{W_t SOL} = \frac{\text{Watts electrical, end of life}}{\text{Watts thermal, start of life}}$

[redacted]

the large radiator area required by the low cold-shoe temperature, and the quality control difficulties inherent in obtaining consistent quality lead telluride elements. Because this construction uses magnetic materials extensively, the effects of such materials on spacecraft electronics should be considered.

System Approach 2
(Lead Telluride - Unsealed)

System Approach 2 represents the highest power-to-converter system weight identified: approximately 9 watts per pound. With these panels, a NANS generator would weigh from 8 to 10 pounds (depending on the fuel capsule configuration selected), yield 0.035 to 0.031 electrical watts per thermal watt, and operate at 400°C hot shoe temperature. Undesirable characteristics of this approach are (1) the inherent potential degradation on performance associated with the many electrical connections required for the 200 to 300 thermocouples, (2) the limited demonstrated performance in the operating environment (up to 8-percent degradation during the first year with total testing only to 1.3 years with a 1 percent per year predicted additional degradation), (3) the weight and area penalty associated with radiators operating at the low cold junction temperature and the attendant large cross-section, (4) the difficulty of radiating thermal power directly to the spacecraft at these temperatures, and (5) the undemonstrated mechanical performance of the Isotec panels in a generator configuration. The difficulty of procuring consistent quality lead telluride has been alleviated but not totally corrected.

System Approach 3
(Silicon Germanium - Unsealed)

System Approach 3, based on silicon germanium technology, results in designs for NANS generators weighing from 8.3 pounds to 13 pounds

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(depending on the configuration and fuel capsule considered). The silicon germanium technology considered is that of the Air Vac and of direct radiation modular assemblies; the type of bond used (either tungsten, carbide, or graphite for the direct radiation module or silicon alloy for Air Vac modules) would be determined by the power supply configuration. The yield in electrical watts (EOL) to thermal watts (SOL) ranges from 0.044 to 0.035, and the generator operates at 700°C hot junction temperature. The silicon germanium is not operated at a temperature range where the figure of merit is a maximum, because the capsule temperature approaches its state-of-the-art limit (SNAP 27); this characteristic enables future growth of power-to-weight ratio with improved capsule technology. This system is not degraded by outgassing of organically-wound fibrous insulating because it operates in an unsealed environment. Advantages of this approach over the previously described approaches are: (1) demonstrated long-term thermocouple performance without failure at high temperatures, hence assurance of thermoelectric bond integrity; (2) multiplicity of testing in an environment applicable to the NANS system; (3) the higher radiator temperature, hence lower cross-sectional area and weights attributable to the radiators; (4) greater Carnot efficiency; (5) thermoelectric material that can be consistently produced and that possesses acceptable strength characteristics; and (6) magnetic materials are not required in this isotope power system.

System Approach 4
(Cascaded - Unsealed)

System Approach 4 combines Approaches 2 and 3 and offers an overall system efficiency of 6 percent compared to system efficiencies of 4 to 4.5 percent for Approach 2 and system efficiencies of 3 to 4.5 percent for Approach 3. A cascaded system using silicon germanium (Air Vac) at 700°C hot shoe to 450°C cold shoe and lead telluride (Isotec) at 400°C hot shoe to 150°C cold shoe would yield 0.06 watt electrical (EOL) per thermal watt (SOL) and would weigh from 8 to 13 pounds depending on capsule

configuration. This approach has the disadvantage of incorporating the undesirable features of both lead telluride (Isotec) and silicon germanium used independently. The power generated by such a cascaded system with the silicon germanium and lead telluride operated in electrical series would be approximately 60 percent for the lead telluride (Isotec) and 40 percent for the silicon germanium. It is conceivable that a cascaded system could, with increased weight, produce sufficient NANS power through parallel operated power converter system to provide the highly desirable system redundancy.

Table VIII summarizes the operating characteristics of the four design approaches.

Spacecraft Integration

In addition to the conventional finned cylinder design, other configurations have been identified as applicable. These are characterized as follows:

1. Flat-sided figure - compatible with the Isotec flat-panel module
2. Flat-plate configuration .

In selecting the power supply configuration, detailed attention must be given the structural, thermal, and electrical integration. While it is beyond the scope of this study at this time to attempt to define a configuration for the NANS Power Supply, several salient features warrant consideration.

Thermal Integration

In general, for the specific case where the power supply is mounted atop the spacecraft with the radiator normal, the heat radiation into the spacecraft is highest when the effective radiator diameter is one-half the

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TABLE VIII

Comparison of Design Approaches

Materials	Weight (pounds)	Fuel factor $\frac{\text{EOL Watts}_e}{\text{SOL Watts}_t}$	Hot junction temp. (^oC)	Radiator* area approx. (ft^2)	System efficiency (%)	Major disadvantage
1. PbTe (sealed)	<16	0.047	600	4 - 7	5	Seals and associated Weight
2. PbTe (Isotec)	<10	0.035 - 0.031	400	4 - 8	4 - 4.5	Undemonstrated (1) performance (2) production capability.
3. SiGe (Air-Vac and Direct Radiating)	<13	0.044 - 0.035	700	2	3 - 4.5	Operating temperature lower than desired.
4. SiGe/PbTe (Isotec)	<13	0.06	700/400	3	6	Combines 2 and 3

*Based on radiation coupling to the spacecraft.

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effective spacecraft diameter. Under these conditions, a radiator operating at 100°C would require 10 square feet to radiate approximately 40 watts thermal into the spacecraft. At 260°C, the area required to radiate 100 to 150 watts into the spacecraft is 2 to 5 square feet. At 430°C, less than 1 square foot of radiator is required normal to the top surface of the spacecraft. This indicates that a detailed study of the thermal integration is necessary if maximum advantage is to be taken of the isotope heat for thermal heating of the spacecraft. One interesting approach to this area is a power supply scaled down from the RCA, Astro Electronics proposal for SNAP 25, "flat-plate configuration." This device uses a flat array of silicon germanium thermoelectrics heated by an "egg-crate" of spherical capsules (could be cylinders) with a flat-ribbed radiator. If the radiator is used as a closing plate of the spacecraft, heat could be conducted uniformly through a thermal resistance joint into the spacecraft structure. Additional heat could be radiated into the spacecraft environs by controlled internal radiator insulation on the spacecraft side.

Structural Integration

The compact structure of any isotope power supply has utility as a structural member of the spacecraft either in providing structural redundancy or as a primary spacecraft structural member, e.g., as a closing plate as previously mentioned. The possibility of using such a flat radiator as an antenna ground plane to minimize the total spacecraft weight is certainly worth investigating.

Electrical Integration

The power supply output of 3 to 10 volts has been investigated during the course of this study, and the tradeoff of voltage level versus reliability has been examined. The voltage level of 3 to 4 volts is optimum within the range considered. Detailed examination of the effects of voltage conditioning, load versus thermal response, and associated effects must be given detailed consideration during the development.

SECTION IV -- SYSTEM AND DEVELOPMENT RECOMMENDATIONS

From the results of this study, it appears that an isotope power supply using either a silicon germanium or Isotec lead telluride power converter system could be built within the proposed NANS time scales to fulfill the system requirements delineated in Section I. The major consideration or tradeoff is in the area of demonstrated reliability versus safety as a function of fuel-operating temperature (capsule technology). The capsule technology is the current item pacing (1) development of lightweight systems and (2) growth potential in terms of power-to-weight ratio. Within the current state-of-the-art, the SNAP 27-type capsule designed for fuel containment under all conditions offers the best approach to the safety side of the tradeoff. Silicon germanium offers the best approach to the demonstrated reliability side of the tradeoff. Therefore, a space isotope power system combining these features appears most desirable for NANS application.

System Recommendations

The following system recommendations, based on contemporary technology for the System Approaches described in Section III are presented in the order in which they best fulfill the mission and performance requirements.

Recommendation 1 -- System Approach 3 (Silicon Germanium - Unsealed)

System Approach 3, based on silicon germanium as described in Isotope Power System Design Characteristics, Section III, is considered the most feasible within the NANS time scales. The fuel capsule must be designed to

survive impact, incorporate a helium pressure relief feature, and operate at least at the same fuel temperature as the SNAP 27. Currently available test data have demonstrated very low degradation rates for silicon germanium. The ability of silicon germanium to operate in air or vacuum obviates the need for sealing and thereby reduces weight and provides maximum design flexibility to meet the needs of capsule reentry protection. The lower thermopile weight of silicon germanium, compared to that of System Approach 1, provides a weight advantage if additional weight is required for ablation shielding material.

Recommendation 2 -- System Approach 4 (Cascaded - Unsealed)

System Approach 4 (cascaded silicon germanium and Isotec panels) offers many attractive advantages such as improved efficiency, fuel economy, etc. However, there are several design and test queries that need further consideration prior to development commitment. These include:

1. Is the power-to-weight ratio realistic?
2. Is the predicted degradation rate of the Isotec panel realistic?
3. Is it possible to supply a uniform thermal flux to the Isotec panels when they are thermally operated in series with silicon germanium panels?
4. Are there any unidentified materials or thermal incompatibilities in this design approach?

Recommendation 3 -- System Approach 2 (Lead Telluride - Unsealed)

System Approach 2, which uses Isotec panels, does not offer sufficient weight advantage to overcome the present inadequate supply of test information even when the higher confidence in lower fuel capsule

temperatures is considered. The present difficulties in obtaining quality lead telluride and the lack of a thorough understanding of its production sensitivities detract from the potentialities of the Isotec panels. The time scales of the NANS and the quantities of generators involved versus undemonstrated production of the Isotec panels further reduce confidence in this design.

Recommendation 4 -- System Approach 1 (Lead Telluride - Sealed)

The lead telluride-inert gas system described as System Approach 1 in Section III, while having a demonstrated performance capability, requires seals; this requirement complicates ground handling and introduces a first-order failure mechanism at an appreciable cost in weight.

Development Recommendations

The development program recommended to fulfill the NANS requirements is directed to a detailed evaluation of Recommendation 1, System Approach 3 and its final development. The plan, presented in detail in Section V, is based on a three-phase effort.

SECTION V -- PROGRAM PLAN AND ESTIMATED COST

Program planning involves the examination of known problem areas, estimations of the technological advances of the immediate future, analyses of specific tasks, and formulation of the specific schedule of events.

Known Problem Areas

Capsule Design

Problems in weight, pressure relief, materials, configuration, reentry protection, and intact burial must be considered during development.

It may not be practical to keep the capsule sufficiently light in weight while providing adequate resistance to both reentry burnup and earth impact.

Early decisions on capsule pressure relief will be required. It will be necessary to establish both the requirement for pressure relief and the method to be used.

The design of the capsule may involve several materials problems. The embrittlement of Haynes alloy at elevated temperatures may have a significant effect on the capsule design because of the need for relatively high temperature for a period in excess of 5 years. In the event that tungsten zirconium molybdenum alloy (TZM), tantalum, or other alloys are proposed, it will be necessary to obtain assurance of practicability.

The feasibility of developing a spherical (or hemispherical) capsule should be established in the near future, because such a shape appears desirable for some power supply designs.

The ability of the capsule to remain intact during earth burial must be evaluated in relation to specific safety criteria.

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Fuel Form

Fuel properties and particle integrity must be defined for the power supply system.

The properties of production-type fuel must be established, made available to the designer, and updated as new or changed information becomes available.

The effect of impact shock on fuel needs to be ascertained. Fuel retention upon impact would be less important if particle breakup did not occur.

Isotec Panels

Confidence in the ability of Isotec panels to withstand normal handling and the usage conditions of inertial forces, vibrations, etc. is needed. Extended-life test data and demonstrated production and quality control performance are also needed.

Effects of Delaying Initiation of Program

In an examination of some of the effects of program delay, those of technical advances which could accrue and of the cost advantage that might develop are considered in this study.

Technology Versus Time

No technology advance is guaranteed by delaying the overall schedule for a reasonable (e. g., 6 months) period. Certainly technology of high temperature metals, thermoelectric materials, fuels, etc. will advance; however, at this time, no significant breakthrough warranting program delay appears imminent.

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However, a technology gain can be made by delaying one particular part of the suggested schedule (Reference 2). It is proposed that the delivery of the two electrically-heated prototypes be moved from September 1967 and January 1968 to January 1968 and March 1968 as shown in Figure 8 to preclude premature design freeze.

Costs Versus Time

The costs anticipated for a normal program are 3 to 5.5 million dollars for development (including delivery of two electrically heated and one flight protytype without fuel) and $50,000 to $75,000 per unfueled flight unit. This estimate is based on estimated program costs, submitted to APL in mid-1965. Quality Control requirements may increase these costs.

The cost of the program is not expected to be changed appreciably by the time of program initiation. This tendency toward stable cost results from the historical increase of cost (product and service) with calendar time and the offsetting effect of technological advance.

No shortening of program time (initiation to delivery of last unit) appears assured by delaying initiation of the program by an increment of less than 1 year. It is true that applicable "know how" may be developed by other programs, but a delay of less than 1 year to take advantage of such an uncertainty does not seem to be justified.

Recommended Events and Schedules

The proposed schedule of events is presented in Figure 8, and explanations of the events are presented in Table IX. Table X explicates the Special Studies and/or Tests referenced in Figure 8 and Table IX.

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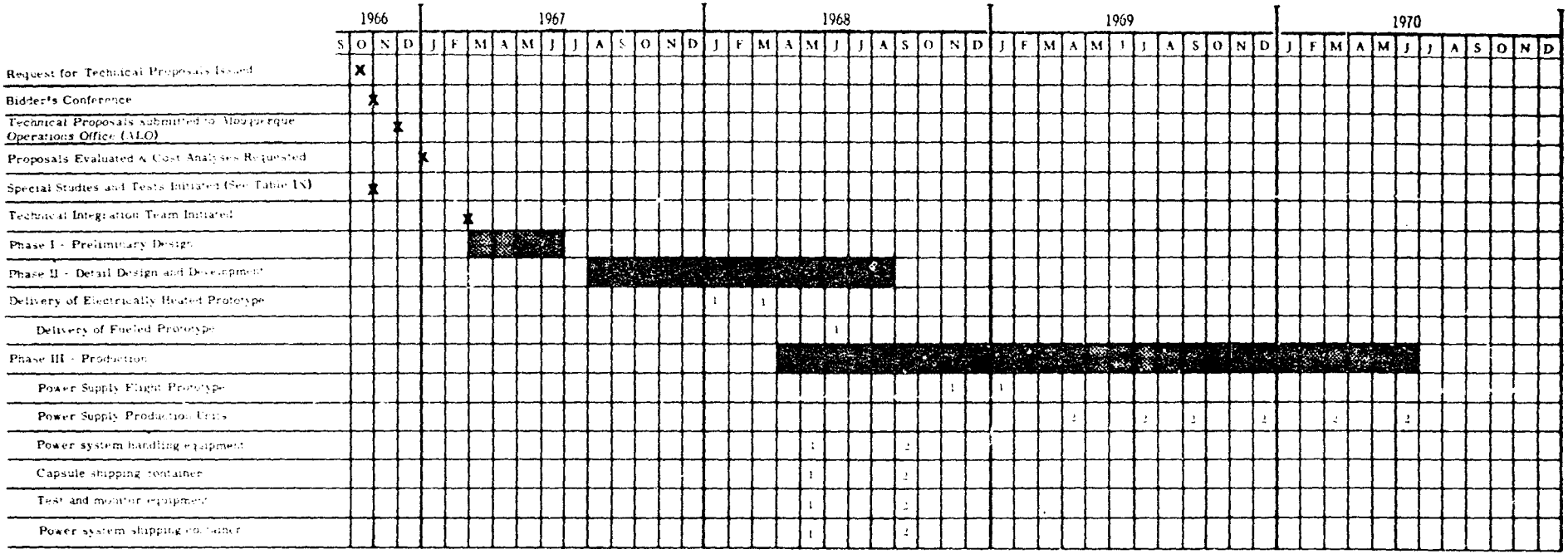

Note: Numbers refer to quantity of units.

Figure 8. Proposed Program Schedule

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TABLE IX

Explanation of Events

Event	Explanation
Request for Technical Proposals	Request for technical proposal prepared by ALO and SL with concurrence of SNS. Cost information will be specifically excluded.
Bidder's Conference	A meeting (possible suppliers, ALO, SL, and others) to discuss a previously distributed request for technical proposals.
Technical Proposals Submitted	The documented proposals prepared by contractors are delivered to ALO and SL.
Technical Proposals Evaluated and Cost Analyses Requested	ALO and SL evaluate proposals. Cost analyses will be requested from only those contractors not excluded by the technical evaluation.
Special Studies and/or Tests Initiated (see Table X)	This work will be done to obtain information needed to guide the contractors and/or to evaluate proposals.
Technical Integration Team	This technical team is formed under joint AEC/DOD agreement and is comprised of representatives from APL, Space Projects Office of Navy, the spacecraft contractor, the power supply contractor, and SL. The purpose of this team is to define and control the interface between the power supply and the NANS.

Note:
ALO = Albuquerque Operations Office, AEC
SL = Sandia Laboratory
SNS = Space Nuclear Systems, AEC
APL - Applied Physics Laboratory, Johns Hopkins University

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TABLE IX (cont)

Event	Explanation
Phase I - Preliminary Design	Several Phase I contracts would be placed if the proposals warranted multiple efforts because of different promising approaches or because of need for a backup system. The purpose of Phase I would be to further define the proposed design and to direct development. A nonfunctional mockup of the power supply and the mating portion of the NANS would be required of the contractor.
Phase II - Detail Design and Development	This phase would be under a new contract and would probably be limited to a single contractor. It is proposed that the contract for Phase II and Phase III include provision for termination at the end of Phase II. In Phase II, the contractor may be authorized to order long-lead items needed in Phase III. The Phase II schedule for production of prototype hardware is believed achievable because of the preliminary work done by the contractor in response to the request for proposal and during Phase I. Also, it is expected that the special studies and tests (Table X) together with information gained from other power system programs will benefit the development effort.
Phase III - Production	The production of the power supply and the ancillary equipment would be included in this phase.

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TABLE X

Special Studies and/or Tests

Study and/or Test Subjects	Comments
Capsule	
Design Guidance	SL to document, by Nov. 1, 1966, considerations, preferences, and requirements related to scheduling, materials, venting, reentry, heating, and burial. The Request for Proposal (RFP) will reference this document. Fuel capsule testing at a temperature increment above SNAP 27 fuel capsule operating temperatures should begin by Nov. 1, 1966.
Fuel	
Properties	SL to publish an estimate of the physical properties of production fuel by Nov. 1, 1966. RFP will reference this document.
Isotec Panels	
Structural adequacy	SL to evaluate available information and testing of several panels. This work should be completed by June 1, 1967.
Lead Telluride	
Sublimation suppression characteristics	SL to evaluate the adequacy of barrier protection by June 1, 1967. SL to estimate by survey the quality of material available in 1968. This should be completed by June 1, 1967.
Quality Control (QC)	
Production Guidance	SL to publish a document of QC considerations, preferences, and requirements by Nov. 1, 1966. RFP will reference this document.

Other Development and Production Factors

Quality Control

As part of his contractual obligation, the contractor will be required to conduct destructive and acceptance tests on components, subassemblies, and systems. The sampling rate for destructive testing of components and subassemblies will exceed that of the systems. The severity of environmental test conditions for the acceptance testing of components and subassemblies will exceed that of the systems.

Policy -- The development of the space isotope power system should be carried out under a quality control program which will: (1) minimize the occurrence of defects during the production processes, (2) determine the quality of the material produced, and (3) provide data from all quality control activities to be used as a basis for program decisions and actions.

In order to provide such a quality program, the contract for development of the space isotope power system should specify the application of AEC-ALO Quality Control Policy QC-1. QC-1 will soon be replaced with an AEC quality specification which applies to space isotope power systems.

The contract should also specify that the Sandia Quality Control Department is to function as Quality Control consultant in the program. To carry out this responsibility, Sandia Quality Control representatives will require access to the contractor's plant and facilities to observe all operations and processes, including access to all applicable manufacturing, quality, and inspection records.

Specification -- Achievement of quality control program objectives may be realized through incorporation of such specifications as the AEC-ALO Quality Program Specification, the MIL-Q-21549B(WEP), Product Quality Program Requirements, or equivalent.

Reliability

As part of his contractual obligation, the contractor will be required to submit the following in order to provide a reasonable assurance of adequate design margin, an acceptably low rate of output degradation, an interim reliability prediction, and a final reliability evaluation:

1. A reliability analysis and allocation study to establish failure rate limits and performance distribution mean and variance limits for components and subassemblies.

2. Plans for a proper mix of experiments and tests (a) to validate design assumptions; (b) to measure variability of material properties; (c) to measure initial variability of performance characteristics of components, subsystems, and systems; (d) to define the stability of performance with increasing age; (e) to establish levels for design testing, qualification testing, and lot testing; and (f) to perform all tests and analyze results.

3. An interim reliability evaluation study in which the results of all testing up to the time the first electrically heated assembly is delivered are used to make a system reliability prediction.

4. A final reliability evaluation study in which system reliability is assessed; this assessment will be based on all development testing and initial production testing.

Safety

The contractor will be required to submit preliminary, interim, and final safety reports in accordance with AEC safety specifications.

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REFERENCES

Reference 1

COPY COPY

DIRECTOR OF DEFENSE RESEARCH AND ENGINEERING
Washington, D. C. 20301

Honorable Glenn T. Seaborg
Chairman, U. S. Atomic Energy Commission
Washington, D. C. 20545

Thru: The Chairman, Military Liaison Committee to the Atomic Energy Commission

Dear Glenn:

The Department of Defense has a requirement for a radioisotope power source for the Navy Advanced Navigation Satellite Program. It is requested that the Atomic Energy Commission initiate development of a power source with the characteristics proposed in the attached letter. We will plan to work closely with the AEC to assure compatibility and to assure that appropriate safety requirements be met.

It is noted that the proposed delivery schedule indicated by the attachment is short. Your comments regarding economics which might be effected by extending this schedule or by eliminating the need for redundancy by other means would be particularly appreciated. We would also like your estimate of the cost of the sources.

Sincerely,

s/Johnny
John S. Foster, Jr.

Enclosure 1
as stated

Reference 2

COPY COPY

DEPARTMENT OF THE NAVY
Office of the Chief of Naval Operations
Washington, D. C. 20350

From: Chief of Naval Operations
To: General Manager, Atomic Energy Commission
Via: Chairman, Military Liaison Committee to the Atomic Energy Commission

Subj: Radioisotope Power Source for Advanced Navy Navigation Satellite (U)

Encl: (1) Preliminary Specifications for Radioisotope Power Source
(2) Proposed Delivery Schedule for Radioisotope Power Sources

1. (U) The Navy Advanced Navigation Satellite Program is directed toward the development of a long life satellite with a goal of five years of useful lifetime in orbit. The program for this second generation navigation satellite has progressed to the definition of major satellite sub-systems in terms of meeting long life requirements in orbit.

2. (C) The definition of the power supply sub-system has concluded with a design requirement for the utilization of a radioisotope power source. This requirement is predicated on a power capability of 30 watts; to be developed in the form of 3 modular 10 watts units which will permit the use of these units in a redundant manner through switching techniques to provide 20 watts of electrical power output.

3. (C) Flight experience has indicated batteries and solar cells to be the weakest part of present Navy satellite systems, whereas the radioisotope thermoelectric generators employed as a cooperative effort with the AEC in the earlier Transit navigation satellites were capable of reliable and extended operations in a space environment.

4. (U) It is, therefore, requested that the Atomic Energy Commission undertake the development of a radioisotope power source for application to the Advanced Navy Navigation Satellite. Enclosures (1) and (2) furnish preliminary technical specifications and program goals for delivery of the radioisotope power source units.

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5. (C) It is desired to have the safety analysis study and product safety assurances conducted by the Commission. Further, technical assistance may be required of the Commission in obtaining satellite launch approval of the radioisotope device.

6. (U) Your cooperation with the Navy in the development of this radioisotope power source will be appreciated. Detailed guidance in connection with this development will be furnished through the following working committee:

(a) Navy Coordinator:
Director, Nuclear Power Division, NFEC.
Commander J. C. LeDoux, Telephone 697-1209

(b) Program technical representatives:
Commander C. W. Meyrick, NASC, 696-3630
Commander G. M. McCabe, SP, 696-3368
Mr. Ted Wyatt, APL, 776-7100 X-2800

s/Harold G. Bowen, Jr.
Deputy Chief, of Naval Operations
(Development)

Copy to: (w/encls.)
CNM
NFACENGCOMD
NAVIRSYSCOMD
DIR, SPECPROJ

[redacted]

Preliminary Specification for Radioisotope Power Source

The following are requirements for a radioisotope power source for an earth orbiting satellite.

Electrical performance - deliver 20 watts at 3-6 volts at the end of 5 years in orbit.

Weight - less than 13 pounds including attachment and connector.

External configuration - stay within a right octagonal prism 16 inches flat to flat, 10 inches high; mounting flange may extend beyond 16 inches dimension. The skin of the spacecraft will be used as part of the radiator for heat disposal. At least 50 watts and at most 300 watts will be radiated by spacecraft skin. Spacecraft is right octagonal prism approximately 20 inches high and 22 inches flat to flat.

Orbit - polar, circular, 600 nautical miles altitude, minimum percent sunlight - 70%.

Ground operation and handling - must be capable of safe operation under ground ambient conditions, not necessarily at full power, but space operation must be determinable function of ambient operation. Provision must be made for convenient ground handling. Should be able to operate open circuited for a short period of time. (1 minute)

Environmental condition - during the launch phase the generator will experience acceleration, vibration, shock, acoustical noise and pressure transition from sea level pressure to vacuum.

Mechanical Environment

A) Acceleration

Axis	Level, (g's)	Duration, (Min.)
Thrust	36	3
Transverse (2 axes)	3	1

(Enclosure (1))

B) Shock - Thrust Axis

Half sine-wave pulse-duration 10 to 15 milliseconds - 30g peak. Must withstand three applications of this pulse.

C) Spin

1. 230 ±10 rpm about thrust axis for a duration of 15 to 20 minutes.

2. Despin from 230 rpm in 1 second.

3. Feet radius (3)

D) Vibration - Sinusoidal

Axis	Freq. Range - (cps)	Duration (Min.)	Accel. g, (0-peak)
Thrust	5 - 50	1.66	2.3
	50 - 500	1.66	10.7
	500 - 2000	1.00	21.0
	2000 - 3000	0.30	54.0
	3000 - 5000	0.36	21.0
Lateral (X-X and Y-Y)	5 - 50	1.66	0.9
	50 - 500	1.66	2.1
	500 - 2000	1.00	4.2
	2000 - 5000	0.66	17.0

E) Vibration - Random

Axis	Freq. Range - (cps)	Test Duration - (Min.)	PSD Level (g^2/cps)
Thrust Lateral (X-X and Y-Y)	20 - 2000	4	0.07

Instrumentation - install instrumentation to measure hot and cold junction temperatures, outside shell temperature, and pressure (if pressurized).

(Enclosure (1))

Proposed Delivery Schedule for Radioisotope Power Sources*

Item	Deliver
1 Electrically Heated Unit	September 1967
3 Electrically Heated Units	January 1968
1 Fueled Prototype Unit	September 1968
3 Fueled Flight Units	November 1968
3 Fueled Flight Units	January 1969
6 Fueled Flight Units	April 1969
6 Fueled Flight Units	July 1969
6 Fueled Flight Units	September 1969
6 Fueled Flight Units	December 1969
6 Fueled Flight Units	March 1970
6 Fueled Flight Units	June 1970

*This schedule makes the following assumptions:

1. Each unit produces 10 watts at the end of 5 years.
2. Three 10 watt units are required for each 20 watt satellite, thereby providing redundancy
3. The 43 units requested will provide power sources for 14 satellites.

(Enclosure (2))

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