~~SECRET~~

DECLASSIFIED
UNCLASSIFIED

NAA-SR-7355
COPY 67 OF 115
71 PAGES
SERIES A

MASTER

THERMOELECTRIC CONVERSION FOR
ADVANCED SNAP SYSTEMS
(Title Unclassified)

AEC Research and Development Report

~~RESTRICTED DATA~~

This document contains restricted data as defined in the Atomic Energy Act of 1954. Its transmittal or the disclosure of its contents in any manner to an unauthorized person is prohibited.

Classification Cancelled
Or Changed To **UNCLASSIFIED**

By Authority Of DOC
By W.H. Haydel Date 10-26-71

Exempt from CCRP Re-review Requirements
(per 7/22/82 Duff/Caudle memorandum)
HA 3/104

GROUP 1

EXCLUDED FROM AUTOMATIC
DOWNGRADING & DECLASSIFICATION

ATOMICS INTERNATIONAL

A DIVISION OF NORTH AMERICAN AVIATION, INC.

1 2 11

UNCLASSIFIED

~~SECRET~~

DECLASSIFIED

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

0310501000

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

Printed in USA

Price \$1.45

Available from the

U. S. Atomic Energy Commission
Technical Information Extension,
P. O. Box 1001
Oak Ridge, Tennessee.

Please direct to the same address inquiries covering the procurement of other classified AEC reports.

0310291000

~~SECRET~~

UNCLASSIFIED

RESTRICTED

NAA-SR-7355
SPECIAL

THERMOELECTRIC CONVERSION FOR
ADVANCED SNAP SYSTEMS
(Title Unclassified)

By
C. J. MORSE

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

~~RESTRICTED DATA~~

This document contains restricted data as defined in the Atomic Energy Act of 1954. Its transmittal or the disclosure of its contents in any manner to an unauthorized person is prohibited.

ATOMICS INTERNATIONAL

A DIVISION OF NORTH AMERICAN AVIATION, INC.
P.O. BOX 309 CANOGA PARK, CALIFORNIA

CONTRACT: AT(11-1)-GEN-8
ISSUED: DECEMBER 15, 1962

UNCLASSIFIED

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

~~SECRET~~

QR

~~SECRET~~
UNCLASSIFIED

DISTRIBUTION

Category: SPECIAL

Copy No.

Aeronautical Systems Division	1-3
Aerospace Test Wing (AFSC)	4
Air Force Special Weapons Center	5-10
Air Force Systems Command	11
Air Technical Intelligence Center	12
Air University Library	13
Argonne National Laboratory	14
Army Ballistic Missile Agency	15
Atomic Energy Commission, Washington	16-20
Brookhaven National Laboratory	21
Bureau of Naval Weapons	22-23
Bureau of Ships	24-25
Bureau of Yards and Docks	26
California Patent Group	27
Central Intelligence Agency (NED)	28
Chicago Patent Group	29
Defense Atomic Support Agency, Sandia	30
Department of the Army	31-33
Director of Defense Research and Engineering (OABCW)	34
Jet Propulsion Laboratory	35-36
Johns Hopkins University (APL)	37
Los Alamos Scientific Laboratory	38
NASA Goddard Space Flight Center	39
NASA Lewis Research Center	40
NASA Western Operations Office	41
Naval Air Development Center	42
Naval Ordnance Laboratory	43-44
Naval Postgraduate School	45
Naval Radiological Defense Laboratory	46
Naval Research Laboratory	47-48
Naval Underwater Ordnance Station	49
New York Operations Office	50
Office of the Assistant General Council for Patents (AEC)	51
Office of the Chief of Naval Operations	52-54
Office of the Chief of Naval Operations (OP-03EG)	55-56
Office of Naval Research	57-58
RAND Corporation	59
Rome Air Development Center	60
Sandia Corporation	61
School of Aviation Medicine	62
Union Carbide Nuclear Company (ORNL)	63
USAF Headquarters	64
USAF Headquarters (DCS/O)	65
AI Library (Includes 2 copies for CPAO)	66-115

UNCLASSIFIED

NAA-SR-7355

UNCLASSIFIED

~~SECRET~~

DECLASSIFIED

SECRET

CONTENTS

	Page
Abstract	5
I. Introduction.	7
II. Summary	8
III. System Analysis	13
A. System Selection	13
B. Design Point	19
IV. Converter Analysis	23
A. Converter Design	23
B. Equations for Weight and Area	30
C. Converter Materials	37
D. Electrical Circuitry	38
V. Converter-Radiator Estimates	43
A. Basis of Estimates	43
B. Weight	43
C. Radiator Area	47
D. Number of Elements	47
VI. 30 kw Thermoelectric System.	52
VII. Applications for Thermoelectric Systems	56
VIII. Appendix.	58
A. Radiator Area	58
B. Converter Weight	61
C. Germanium-Silicon Data	64
Nomenclature	69
References	71

TABLES

I. Typical Ge-Si Pellet Design	26
II. 30 kw System Design.	53

UNCLASSIFIED

NAA-SR-7355

DECLASSIFIED

SECRET

03115587030

~~SECRET~~

FIGURES

	Page
1. Variation of Conversion Efficiency With Temperature for a Ge-Si Converter.	9
2. Variation of Converter-Radiator Weight and Area With Temperature for a Ge-Si Converter	11
3. Variation of Converter-Radiator Weight With Power for a Ge-Si Converter.	12
4. Possible System Configurations	14
5. Comparison of Radiator Area Requirements for Two System Configurations	17
6. Comparison of the Minimum Area and Minimum Weight Conditions for a 30-kw Converter-Radiator	21
7. Thermoelectric Element Configuration	24
8. Possible Module Designs	25
9. Comparison of Converter-Radiator Weights for Close-Spaced and Optimally Spaced Pellet Arrangements	28
10. Fin Efficiency <u>vs</u> Radiation Modulus	32
11. Material Thickness <u>vs</u> Vulnerable Area (Steel)	36
12. Sublimation Rates of Materials in Space	39
13. Schematic Representation of Converter Electrical Circuitry	40
14. Variation of Referred Efficiency With Temperature for a Ge-Si Converter.	45
15. Variation of Converter-Radiator Weight With Temperature for a Ge-Si Converter.	46
16. Variation of Converter-Radiator Weight With Temperature for a Device Efficiency of 0.1, 0.15, and 0.2	48
17. Variation of Radiator Area With Temperature for Converters of Various Efficiencies	49
18. Copper Hot Strap Requirement for 5% Hot Strap Factor in a Ge-Si Converter.	51
19. Variation of Seebeck Coefficient With Temperature for Ge-Si.	65
20. Variation of Electrical Resistivity With Temperature for Ge-Si	66
21. Variation of Thermal Conductivity With Temperature for Ge-Si	67
22. Variation of Figure of Merit With Temperature for a Ge-Si Couple	68

NAA-SR-7355

03112281030

~~SECRET~~

DECLASSIFIED

SECRET

ABSTRACT

The use of thermoelectric conversion in advanced nuclear space power systems is investigated. A converter design conducive to low weight and high reliability at high power levels is established, and this design is used as a model for estimating weights and radiator areas associated with thermoelectric conversion systems. The range of hot junction temperatures considered is 1200 to 2000°F. The thermoelectric material of primary interest is the germanium-silicon alloy which is used in SNAP 10A.

A converter reliability analysis is presented, and a discussion of applications for thermoelectric systems is given. It is concluded that thermoelectric systems offer significant potential for meeting requirements in this decade for highly reliable, long-term auxiliary power.

SECRET

DECLASSIFIED

UNCLASSIFIED

03115307030

7580-1077

SNAP 10A System

NAA-SR-7355

6

031712201030

UNCLASSIFIED

DECLASSIFIED

SECRET

I. INTRODUCTION

The basic design requirements for space power systems may be stated as low weight, long life, unattended operation in the environment of space, high reliability, and compatibility with vehicle and payload. With the possible exception of the weight consideration, static conversion systems are almost uniquely suited to meeting these requirements. It is expected, for example, that nuclear-thermoelectric systems will ultimately be capable of operating for periods of one to three years or longer at reliabilities which will be highly favorable by comparison with other power systems of interest.

With the SNAP 10A nuclear-thermoelectric system, as described in Reference 1, 500 watts of electrical power will be produced at a specific weight of about 1900 lb/kw (shielded system) and a specific radiator area of 120 ft²/kw. This system operates at temperature and power conditions which are considerably below reactor limitations in order to meet a passive nuclear control requirement. With the addition of active reactor control, an uprated SNAP 10A would be capable of producing 2 kw, within the approximate 10A reactor limitations of 100 kw at 1215°F coolant outlet, at a system specific weight of about 650 lb/kw (shielded) and a radiator area of 75 ft²/kw. Further reductions in specific weight and area for thermoelectric systems can be achieved at increased power and higher temperature conditions.

Presented in this report is an analysis of high temperature thermoelectric conversion systems. Consideration is given both to thermoelectric material efficiencies and temperature capabilities which are currently being realized and to those which might be achieved with modest improvements during this decade. The results of the analysis are thus indicative of the relatively short-range potential for thermoelectric systems, barring, of course, a breakthrough in materials efficiency.

The initial sections of the report are concerned with converter and system analyses, from which a suitable converter design is established. On the basis of this design, generalized estimates of converter size and weight are made for various temperature and efficiency conditions of interest. Finally, the preliminary design of a 30-kw power plant is presented as being typical of what may be expected in a fairly high power thermoelectric system.

SECRET

DECLASSIFIED

II. SUMMARY

It is recognized that state-of-the-art thermoelectric converters are relatively inefficient and bulky items; and, for this reason, systems to date have been limited to relatively low power outputs. However, the possibility of achieving long life and exceptionally high reliability with thermoelectric systems provides a strong incentive for extending power levels into the kilowatt range. If increased power is to be obtained with power plants of attractive size and weight, some increase in system temperatures and/or efficiency over current design levels will be required.

In terms of temperature capability and device efficiency, the most promising thermoelectric material currently available is an alloy of germanium and silicon being used in the SNAP 10A system. An estimate of conversion efficiency* vs hot junction temperature for this material is shown in Figure 1. The efficiency is based on estimated materials properties for germanium-silicon which represent a modest improvement over currently measured properties. The temperature limitation of this thermoelectric material is not known accurately but is believed to be upwards of 1600°F.

An analysis of various possible power plant configurations indicates that, for systems achieving significant power outputs, minimum weight and minimum area are obtained with a one-loop, direct-radiating system. A liquid metal coolant is used to transfer heat from the reactor to the converter assembly. The converter assembly consists of a cylindrical or conical array of coolant tubes with thermoelements brazed to the tube sides which face outward to space (see Frontispiece). The temperature difference across the thermoelements is maintained by rejecting heat to space via radiator fins brazed to the element cold junctions.

A two-loop system, utilizing a compact thermoelectric generator, would be heavier than the one-loop system but might offer the advantage of easier vehicle integration. Use could be made of redundant radiator loops to reduce meteoroid armor requirements and thus alleviate the weight problem for this system.

For the one-loop system configuration, the optimum cold junction temperature, based on minimum radiator area, is about 80% of the hot junction temperature. For hot junction temperatures above about 1200°F, the thermoelectric

*With a Carnot efficiency of 20%, chosen to minimize radiator area.

SECRET

NAA-SR-7355

9

11-28-62

7561-0160

Figure 1. Variation of Conversion Efficiency With Temperature for a Ge-Si Converter

SECRET

~~SECRET~~

0310507030

elements may be closely spaced along the coolant tubing. This is desirable because, in closely spaced designs, the thermoelectric pellets carry the major burden of shielding the coolant tubes from meteoroid particles. Some additional shielding may be required for the inward tube surfaces, although this is greatly reduced by the meteoroid "bumper" effect of the radiator fins.

The inherent reliability against tubing puncture of this design represents a distinct advantage over configurations involving indirect radiators. High reliability in the generator itself is achieved through cross-coupling parallel modules, so that an open circuit results in the loss of a single module rather than the whole system.

Radiator specific areas and converter-radiator assembly weights for a germanium-silicon converter are shown in Figures 2 and 3. These curves are based on a fin efficiency of 0.8, on assumed radiator emissivity of 0.9, and the device efficiency given by Figure 1. Included in the curve of specific weight are the weights of the radiator fins, thermoelectric pellets, electrical straps, and converter coolant tubing. The shaded area in Figure 2a represents an uncertainty in weight due to possible variations in thermoelectric pellet design. The upper limit is conservative and reflects the use of a pellet design similar to that used in SNAP 10A, in which rather large amounts of tungsten and molybdenum are included to provide materials compatibility and thermal stress relief. The lower limit is an estimate of the minimum weight which might ultimately be achieved, with an advanced converter design, by eliminating those components which are extraneous to actual power production (i.e., all but the thermoelectric material, straps, and electrical insulation). Weights for actual designs should fall somewhere between these limits.

Over most of the temperature range shown in Figures 2 and 3, the converter materials are beryllium for the radiator fins, copper for the hot straps, and either steel or niobium for the coolant tubes. Above about 1400°F, sublimation of the copper straps is inhibited by nickel plating, which is useful to about 1750°F. At higher temperatures, molybdenum may be substituted for copper at a small (overall) weight penalty.

A preliminary design is presented for a 30-kw thermoelectric system utilizing either a UC-ZrC fast or an yttrium hydride thermal reactor to achieve an average thermoelectric hot junction temperature of 1600°F. The estimated weight of this system (shielded) is 2700 lb. The required radiator area is 575 ft².

NAA-SR-7355

0310507030

~~SECRET~~

UNCLASSIFIED

NAA-SR-7355

11

11-1-62

7569-0134

Figure 2. Variation of Converter-Radiator Weight and Area With Temperature for a Ge-Si Converter

UNCLASSIFIED

~~SECRET~~

5-10-62

7561-0162

Figure 3. Variation of Converter-Radiator Weight With Power
for a Ge-Si Converter

(*Shaded areas reflect possible variations in pellet design)

III. SYSTEM ANALYSIS

A. SYSTEM SELECTION

1. Possible Configurations

Two general categories of nuclear-thermoelectric systems may be identified: conduction systems and convection systems. Both concepts have been considered in the SNAP 10 program.

The SNAP 10 power plant as originally conceived (Reference 2) was a completely static device in which heat was transferred from the reactor core by conduction to thermoelectric elements placed around the outside surface of the reactor. Although this system concept is simple and conducive to high reliability, power output is limited by the size of the radiator area available to cool the thermoelement cold junctions. Maximum electrical power for this system is about 200 watts at a reactor surface temperature of 1200°F or about 900 watts at a temperature of 1700°F (Reference 3). System specific weights (unshielded) range from 1500 lb/kw at the lower temperature to 500 lb/kw at the upper limit.

To achieve greater flexibility and increased power capability, the present SNAP 10A system makes use of a forced convection coolant loop for transferring heat from the reactor to the thermoelectric converter. In this manner, the radiator area restrictions implicit in the conduction system design are eliminated. Since the present report is concerned with the possibilities for still higher-powered systems, the convection design is of prime interest.

Three possible system configurations are shown schematically in Figure 4. The basic components of these systems are the reactor heat source, the heat transfer system, the thermoelectric converter, and a radiator for rejecting cycle waste heat to space.

In the first configuration of Figure 4, a single coolant loop is used to transfer heat from the reactor to the thermoelectric element hot junctions. Waste heat is rejected by radiator fins attached directly to the element cold junctions. The second configuration shown is similar to the first, except that a second coolant loop has been added between the converter and radiator, allowing somewhat greater flexibility in the design of these components. The third

UNCLASSIFIED

(a) "ONE-LOOP" SYSTEM

(b) "TWO-LOOP" SYSTEM

(c) "REGENERATIVE" SINGLE LOOP SYSTEM

Figure 4. Possible System Configurations

5-10-62

7561-0163

UNCLASSIFIED

DECLASSIFIED

SECRET

configuration of Figure 4 represents a "regenerative" type system in which the heat transfer fluid, after supplying heat to the converter hot leg, is cooled in the radiator and then used to remove heat at the cold leg.

2. Radiator Area Comparison

The criterion for selection of a particular space power plant configuration is minimum total system weight. One basis of comparison often used in evaluating various designs is radiator area requirement. Actually, area is only important as it ultimately affects system weight; but, since the radiator is usually an important weight item, the minimum area condition often corresponds closely to the minimum weight point. Furthermore, area requirements are relatively easy to determine as compared with the calculation of total system weights.

It may be shown (Appendix A) that minimum area for the one-loop and two-loop systems (Figures 4a and 4b) is obtained when^{*}

$$\frac{\Delta T_c}{T_H} = \frac{5}{8\eta_D} \left(1 - \sqrt{1 - \frac{16\eta_D}{25}} \right), \quad \dots(1)$$

where

ΔT_c = converter temperature drop, hot junction to cold junction,

T_H = average hot junction temperature,

η_D = total device efficiency = $\frac{\text{conversion efficiency}}{\text{Carnot efficiency}}$.

For the "regenerative" system (Figure 4c), minimum area (Appendix A) occurs at

$$\frac{\Delta T_L}{T_{HM}} = \frac{\frac{5}{4} - \frac{1}{4} \sqrt{17 - 8\eta_D + 4(1 + \eta_D)\Delta T_c/T_{HM}}}{1 + \eta_D}, \quad \dots(2)$$

where

ΔT_L = coolant temperature drop (hot leg), converter inlet to converter outlet;

T_{HM} = maximum hot junction temperature.

*For complete nomenclature, see table at end of report.

~~SECRET~~

Equations (1) and (2) are based on the following assumptions:

- 1) thermoelectric conversion efficiency is a fixed fraction of Carnot efficiency, independent of converter temperature conditions,
- 2) for the one-loop and two-loop systems, there is negligible difference between cold junction and heat rejection temperatures,
- 3) for the regenerative system, the temperature drops from coolant to hot junction and from cold junction to coolant are negligible,
- 4) space temperature is 0°R .

These assumptions delineate systems which are idealized but useful for comparison purposes.

Radiator area as a function of reactor ΔT , based on the optimized conditions of Equations (1) and (2), is plotted in Figure 5a for a device achieving 10% of Carnot efficiency at a maximum hot junction temperature of 1200°F . It can be seen that, for low reactor ΔT , the regenerative system gives minimum area, whereas for high reactor ΔT , the one-loop (or two-loop) system gives the minimum. The cross-over occurs at $\Delta T_R \cong \Delta T_L$ for the regenerative system, at which point the radiator power and temperature conditions are (very closely) the same for both systems.

An evaluation on the basis of Figure 5a alone would be somewhat misleading, since reactor ΔT affects the two systems in different manners. For the one-loop system, a low reactor ΔT simply results in a high pumping power requirement. For the regenerative system, a small reactor ΔT means a small converter ΔT as well and thus results in a low-efficiency, high-weight converter. An area comparison on an equitable basis for the two systems is given in Figure 5b. The reactor ΔT for the one-loop configuration was fixed at 200°F , a value which usually results in reasonable pumping requirements. For the regenerative system, the converter ΔT was chosen so as to give the same Carnot efficiency as was used for the one-loop system [optimized by Equation (1)] and thus a converter of approximately equal weight.

As shown in Figure 5b, the radiator area requirement for the regenerative system is somewhat greater than that for the one-loop (or two-loop) system. In addition, if the converter is limited by a maximum allowable hot junction temperature, the regenerative system will be more adversely affected than the

(a) Radiator Area vs Reactor ΔT

(b) Radiator Area vs Maximum Hot Junction Temperature

Figure 5. Comparison of Radiator Area Requirements for Two System Configurations

5-10-62

7561-0164

NAA-SR-7355

~~SECRET~~

one-loop system by thermal resistances in the hot and cold straps. For example, consider the systems defined by Figure 5b at a maximum hot junction temperature of 1200°F. If it is assumed that the hot and cold strap temperature drops (i. e., ΔT between coolant and thermoelectric hot junction or between cold junction and radiator) are each 30°F, then the area increase for the regenerative system is about 20%, and the increase for the one-loop (or two-loop) system is about 10%. Under these conditions, the regenerative radiator would be about 25% larger than the one- or two-loop radiators.

3. System Weight Considerations

The foregoing comparison on the basis of radiator area cannot be considered as a final evaluation of the possible system configurations. Under certain circumstances, area requirements for the three systems of Figure 4 may not be too different. Final system selection must include a consideration of several other factors, of which the most important are

- 1) the variations in converter design implied by the various system configurations, and the effect of these variations on converter performance and structural integrity,
- 2) system piping weights and pumping power requirements,
- 3) system structural design,
- 4) the vulnerability of the radiator tubing to meteoritic puncture.

For high-power thermoelectric systems, the last of these considerations is a key factor in the selection of a system configuration. In general, the armor required for meteorite protection of large radiators represents a serious weight penalty for high power level systems. For example, the MEPOS mercury condensing radiator (Reference 4, p. 91), at an area of 1000 to 1600 ft², is penalized by about a factor of 2 in achieving a meteorite nonpuncture probability of 90%. At a nonpuncture probability of 99%, the penalty would be a factor of about 4. Smaller and/or sensible heat radiators at reduced tubing sizes will be less drastically but still seriously affected. The meteorite protection effect is discussed further in Section IV of this report.

An attractive feature of thermoelectric systems is the dual use which may be made of the thermoelectric material, both as the electrical generating component of the system and as meteorite protection for the coolant tubing.

~~SECRET~~

DECLASSIFIED

SECRET

To accomplish this effect, use of the direct radiating one-loop system is indicated, since in this configuration the thermoelectric elements are attached directly to the vulnerable tubing. In fact, on the basis of meteorite armor requirements the one-loop configuration has a distinct advantage over the others for high power systems.

It may be noted here that use could also be made of the two-loop system in conjunction with redundant radiator loops to reduce tubing armor requirements. However, to avoid an excessive area (and weight) penalty for this system, a fairly large number of independent loops would be required. The resulting complex of piping systems, involving many individual pumps, with instruments for sensing meteorite punctures, and with provision for phasing in a new loop when a failure occurs, would tend to impair the concept of the thermoelectric system as being a very simple, highly reliable space power plant. For this reason, attention is directed toward only the one-loop system in the remaining sections of this report.

B. DESIGN POINT

For a space power plant in which waste heat must be rejected to space, it is desirable to operate at as high a temperature level as possible, to minimize the size of the radiator required. Upper system temperatures are usually set either by reactor limitations or from converter material considerations. Once this temperature limitation is established, the major system variables which affect the design of the conversion system are converter ΔT and radiator fin efficiency. Additional variables in the overall system design are reactor ΔT and the power allotment for coolant pumping. With these latter conditions fixed, the piping system can be sized.

In a final system analysis, the minimum weight design point would be determined by considering trade-offs among the above variables. However, for purposes within the scope of the present study, a reasonable design point may be established by considering each variable individually.

1. Converter ΔT

The criterion of minimum radiator area, as given by Equation 1, will be used to establish the temperature difference between thermoelectric hot and cold junctions. Actually, the minimum weight condition often occurs at a

03115507030

SECRET

converter ΔT somewhat higher than that given by the minimum area condition. To illustrate this fact, Figure 6 shows the minimum area and minimum weight points for a converter-radiator assembly operating at an average hot junction temperature of 1600°F and a conversion efficiency of 12.5% of Carnot. The weight variations are based on the converter model described in Section IV, with the pellet spacing optimized for each value of Carnot efficiency.

The parameter d_c in Figure 6 is the pellet area density, which is pellet weight divided by pellet heat transfer area. It is apparent that for many designs there is a significant weight advantage in operating above the minimum area Carnot efficiency. For a very light design ($d_c \sim 4 \text{ lb/ft}^2$) the radiator is the most important weight item and minimum weight occurs close to the minimum area point. With fairly heavy pellets ($d_c \sim 12 \text{ to } 16 \text{ lb/ft}^2$) it may be seen that minimum weight is obtained with a Carnot efficiency in the range of 30 to 35%. Optimum Carnot is also a function of power and temperature levels. The effect of increased temperature is to reduce the importance of the radiator and thus to shift the optimum to a higher efficiency. Increased power should decrease slightly the optimum Carnot efficiency.

2. Radiator Fin Efficiency

Radiator calculations in this report are based on the analysis of Reference 5 and in particular on the curve of fin efficiency versus dimensionless radiation modulus (see Section IV) presented in that report. From this curve it may be determined that radiator fin weight decreases with decreasing fin efficiency down to rather low values of efficiency. However, the increased radiator area required at low values of fin efficiency will cause additional problems in vehicle integration and in radiation shielding because the radiator represents a source of scattered neutrons to the payload. These latter effects will not be evaluated here. For the calculations in this report, a fin efficiency of 0.8 will arbitrarily be assumed as the basis for a set of consistent converter-radiator estimates. There would be only a minor reduction in weight by going to a lower value.

3. Reactor ΔT

Thermoelectric systems, as compared with turbogenerator systems, are characterized by relatively low efficiencies and consequent high thermal power requirements. As a result, the optimum reactor ΔT is likely to be higher for

03115507030

SECRET

5-10-62

Figure 6. Comparison of the Minimum Area and Minimum Weight Conditions for a 30-kw Converter-Radiator

SECRET

03115087030

the thermoelectric system; alternatively, there is strong incentive for using a coolant with a very high heat capacity. In the design presented in Section VI, the use of lithium as the heat transfer fluid is postulated, on which basis a reactor ΔT of 200°F is found to be reasonable.

4. Pumping Power

In the converter-radiator estimates of Section V, allowance is made for 10% of the converter output power to be used for pumping. This allotment is reasonably compatible with system requirements for most systems. For the design presented in Section VI, the 10% pumping allotment is found to be adequate in conjunction with the use of lithium as coolant and a reactor ΔT of 200°F. Under these conditions, the system piping is sized at 1.5 inches and the converter piping at half-sections (238) of quarter-inch tubing 9.2 feet long. If a coolant having a lower specific heat were used, higher pumping power and/or a higher reactor ΔT would be required.

03112087030

SECRET

DECLASSIFIED

IV. CONVERTER ANALYSIS

A. CONVERTER DESIGN

1. Pellet Design

A thermoelectric element configuration similar to that used in the SNAP 10A system is shown in Figure 7. Heat is supplied to the pellet hot junction by the reactor coolant, and heat is rejected to space by the radiator fin brazed to the cold junction. The temperature difference thus established creates an emf between junctions when thermoelectric pellets of the N and P types are connected alternately in series. Alternate connections between radiator fins provide the cold junction current path. Thus, the current flow is from hot face to cold face through the P-type pellet, from P-type to N-type pellet through the radiator fin, through the N-type pellet to the hot face, then from N to P through the hot strap, etc. A thin layer of alumina is used to insulate the elements from the coolant tubing.

The thermoelectric material in SNAP 10A is an alloy of 70 at. % silicon, with 30 at. % germanium, doped with arsenic (N-type) and boron (P-type), and produced by RCA. The tungsten and molybdenum shoes and pads shown in Figure 7 are required for material compatibility and thermal stress relief. The latter requirement is due to the relatively low thermal expansion coefficient of the germanium-silicon alloy in comparison with the thermal expansion coefficients for useful radiator and strap materials.

Sizing of the tungsten and molybdenum discs is largely empirical. Converter designs to date suffer severe weight penalties due to these components, as is illustrated by the typical pellet configuration itemized in Table I. This configuration is similar to (but does not agree in exact detail with) the current SNAP 10A design.

It can be seen that close to 70% of the total pellet weight is accounted for by the tungsten and molybdenum components. Despite this weight disadvantage, the high temperature capability of the germanium-silicon alloy makes this material of prime interest for a high power system.

2. Module Configurations

A converter module arrangement and two possible variations are shown conceptually in Figure 8. The first configuration corresponds to the current

DECLASSIFIED

Figure 7. Thermoelectric Element Configuration
5-10-62 7561-0165

5-10-62

Figure 8. Possible Module Designs

7561-0166

NAA-SR-7355

03115587030

TABLE I
TYPICAL Ge-Si PELLET DESIGN

Component	Thickness (mils)	% of Total Weight
Tungsten pad, radiator surface	20	15
Tungsten shoe, cold face	20	15
Ge-Si TE material	200	28
Tungsten shoe and pad, hot face	40	31
Molybdenum pad, strap side	10	4
Alumina	20	3
Molybdenum pad, tube side	<u>10</u>	<u>4</u>
Total	320	100

SNAP 10A converter. In the second arrangement, the pellets are of rectangular cross-section and are closely spaced to completely cover the coolant tube. In the third arrangement, the pellets have been encapsulated to provide structural strength and to inhibit sublimation of the thermoelectric material at elevated temperatures.

The converter assembly consists of a number of modules arranged in parallel. Although various arrangements are possible, the cylindrical or conical geometries (see Frontispiece) are often most practical because they are structurally simple and easily integrable into a vehicle package. Where very large radiator areas are required, it may be necessary to use flat plate assemblies which fold up into a cylindrical or quasi-cylindrical package for launch and then unfold to radiate from both sides during system operation. For the present study, use of the cylindrical (or conical) geometry is assumed.

Optimum spacing of the thermoelectric pellets along the coolant tubes is determined from a trade-off between tubing and radiator weights. Increased spacing results in a spreading of the radiator heat source and a shortening of the radiator fins. Total radiator area remains constant but fin thickness decreases, causing a decrease in radiator weight. With increased spacing, however, the tubing area vulnerable to meteorite puncture increases. The increase in tubing thickness required for meteorite protection and the increase in length result in higher tubing weights for widely spaced designs.

03172291030

SECRET

DECLASSIFIED

SECRET

Shown in Figure 9 are converter-radiator specific weights as a function of hot junction temperature for closely spaced and optimally spaced pellets. These curves are based on the rectangular pellet design, sized according to Table I. The fins are beryllium and the hot straps are copper. Tubing is 1/4 in.-ID, 20-mils thick (where no armor is required), and half-sectioned as shown in Figure 8. The converter ΔT is optimized on the basis of minimum radiator area. Computational methods are described in the next section.

The following assumptions were made concerning meteorite protection:

- a) Required nonpuncture probability in one year is 99%.
- b) Portions of the tubing covered by the thermoelectric pellets are completely protected from meteorites. For practical reasons, however, wall thickness was taken to be constant along the flat tube surface.
- c) The inside (rounded) portion of the tubing is protected by the "bumper" effect of the radiator; that is, it is assumed that meteorites penetrating the radiator tend to split and scatter, thus reducing the danger to tubing located some distance away.

Assumption (b) is considered to be conservative, based on the thickness of dense material shown in Table I plus the thicknesses of radiator fin, hot strap, and minimum tube wall required in the design. The validity of assumption (c) is less certain but consistent with the design philosophy used on SNAP systems. In a final system design, the radiator bumper effect is likely to be further augmented by a conical or cylindrical converter support structure, such as is used on SNAP 10A, placed inside the coolant tubing and concentric to the radiator.

As may be seen from Figure 9, converters designed for minimum area and operating at hot junction temperatures of 1400°F or above will be closely packed configurations. Converter estimates based on a closely packed design will in fact be valid down to about 1200°F. At lower temperatures, spacing of the elements is required because of the larger radiators involved. This conclusion, however, is subject to adjustment on changes in the pellet geometry. Increasing the thermoelectric length (and thus the area, at constant l/A) or decreasing the width will have the effect of lengthening the radiator heat source. With a longer heat source, optimum spacing is decreased and close-packing becomes feasible at a lower temperature. The reverse effect is true for shorter and/or wider pellets.

SECRET

DECLASSIFIED

Figure 9. Comparison of Converter-Radiator Weights for Close-Spaced and Optimally Spaced Pellet Arrangements

5-10-62

7561-0167

NAA-SR-7355

The effect of device efficiency on optimum spacing is small: lower efficiency involves a larger radiator but also more thermoelectric material and thus a larger heat source. Optimum spacing is slightly less for the lower efficiency device because of the greater vulnerable tubing area involved. The same effect accounts for the variation with power in optimum spacing and specific weight for spaced designs.

Close spacing of the thermoelectric pellets implies the module design of either Figure 8b or 8c. With germanium-silicon alloy thermoelectric elements, the configuration shown in Figure 8c is likely to be troublesome because of the low thermal expansion coefficient of germanium-silicon. Thus, the module design of Figure 8b is of primary interest.

In addition to the high reliability against tubing puncture which is obtained with a close packed pellet arrangement, there should be no problem in achieving high reliability in the generator itself. In the design of a high power system, the use of multiple parallel circuits, each operating at relatively high voltage and low current, is required in order to minimize the strap weights. Under these conditions, loss of a thermoelectric element simply results in a percentage reduction in power output rather than a catastrophic system failure. Reliability can be further increased to any desired extent by the use of cross-connections between the parallel circuits.

3. SNAP 10A Comparison

It is of interest to locate the SNAP 10A converter on Figure 9.* At an average hot junction temperature of 900°F and a conversion efficiency of ~9.4% of Carnot, the current SNAP 10A converter weighs 250 lb/kw. The corresponding weight given by Figure 9 would be about 120 lb/kw (i. e., about 6% higher than for $\eta_D = 10\%$). The basis for this variance in specific weights may be understood by examining the following weight breakdown by component:

Component	Specific Weight at $T_H = 900^\circ\text{F}$,	$\eta_D = 9.4\%$
	Converter of Figure 9	SNAP 10A Converter
Radiator	30	60
Tubing	28	58
Converter	56	108
Straps	6	24
Total	120 lb/kw	250 lb/kw

*The SNAP 10A converter referred to here and elsewhere within this report corresponds to the SNAP 10A design as of March 1, 1962.

~~SECRET~~

Of the 30-lb/kw discrepancy in radiator weights, 10 lb/kw is due to an emissive coating weight included in the SNAP 10A estimates but not in those of the present study. This omission represents a slight factor of optimism in the estimates of Figure 9 (less for higher temperature, lower area systems). The remaining discrepancy of 20 lb/kw can be partly attributed to the higher fin efficiency of the SNAP 10A radiator (86% vs 80%), which accounts for ~12 lb/kw, and partly to other factors, such as the use of different radiator materials (aluminum on SNAP 10A vs beryllium for the present study) and fin geometries.

The variance in tubing weights shown above simply reflects a bulkier tubing design on SNAP 10A, necessitated in part by the larger pellets (~0.45-in. diam) used. This variance is despite the fact that the SNAP 10A estimate does not include meteorite armor.

The 52-lb/kw difference in converter weights is almost wholly due to the greater length of the SNAP 10A pellet. At 323 mils (as compared with 200 mils), there is a 17% increase in pellet area density (see next section) and a 61% increase in total thermoelectric heat transfer area. These two factors account for an increased weight of 49 lb/kw. The remaining difference can be attributed to further design variations of a relatively minor nature.

The copper hot straps for the converter estimates of Figure 9 were sized at 1/4-in. wide by 10-mils thick. This sizing is arbitrary and will set a limitation on the module current output at a given strap I^2R loss. The higher strap weight in the SNAP 10A design reflects a higher current output per series circuit (thus a smaller pellet length to area ratio) plus a longer current path.

B. EQUATIONS FOR WEIGHT AND AREA

Equations useful for estimating radiator area requirements and converter-radiator assembly weights are presented here. A more complete discussion is given in the Appendix.

1. Radiator Area

Minimum radiator area for the direct-radiating one-loop system occurs at

$$\frac{\Delta T_c}{T_H} = \frac{5}{8\eta_D} \left[1 - \sqrt{1 - \frac{16\eta_D}{25} \left(1 - \frac{\Delta T}{T_H} \right)} \right], \quad \dots(3)$$

~~SECRET~~

where ΔT = difference (positive) between converter cold junction and heat rejection temperatures.

Radiator area is given by

$$A_R = \frac{P_o \left(\frac{1}{\eta_C \eta_D} - 1 \right)}{\sigma \epsilon \eta_f (T_B^4 - T_S^4)} , \quad \dots(4)$$

where

A_R = radiator area,

P_o = converter output power, design,

η_C = Carnot efficiency = $\frac{\Delta T_C}{T_H}$,

σ = Stefan-Boltzmann constant = 0.1713×10^{-8} Btu/ft²-hr-°R⁴,

ϵ = radiator surface emissivity,

η_f = radiator fin efficiency,

T_B = fin base temperature,

T_S = effective background temperature of space.

2. Radiator Weight

With the radiator area given by Equation (4), it remains to determine the fin thickness required to give the value of fin efficiency used. Plotted in Figure 10 is the curve of fin efficiency vs dimensionless radiation modulus, taken from Reference 5. In terms of the radiation modulus, the fin thickness becomes

$$t = \frac{B^2 \sigma \epsilon T_B^3}{k_R M_R} , \quad \dots(5)$$

where

t = fin thickness,

B = twice the fin length = spacing between parallel tubes,

k_R = conductivity of radiator material,

M_R = dimensionless radiation modulus.

Figure 10 is based on radiation from one side of the fin surface (e.g., a cylindrical radiator geometry), an assumed space temperature of 0°R, and a line

Figure 10. Fin Efficiency vs Radiation Modulus

5-10-62

7561-0168

source of heat. This last condition is closely approximated by a closely packed pellet design. As pellet spacing is increased, however, the line source approximation becomes less valid.

3. Pellet Weight

It can be shown that the pellet weight is given by

$$W_c = \frac{d_c \ell P_L}{2k_c} \times \frac{T_H + T_c}{(T_H - T_c)^2} \times \frac{2 - \eta_m \left(3 - \frac{T_c}{T_H}\right) + \eta_m^2 \left(1 - \frac{T_c}{T_H}\right)}{\eta_m \left(1 + \frac{T_c}{T_H}\right) + \eta_m^2 \left(\frac{T_c}{T_H} + \frac{T_c^2}{T_H^2}\right)}, \dots (6)$$

where

W_c = converter pellet weight,

d_c = pellet area density = $\frac{\text{total pellet weight}}{\text{pellet heat transfer area}}$

= 13.1 lb/ft² for design of Table I,

ℓ = thermoelectric length (e.g., 200 mils in Table I),

P_L = converter output power, start of life,

= $P_o/0.9$ for assumptions in next section,

k_c = conductivity of thermoelectric material,

T_H = thermoelectric hot face temperature,

T_c = thermoelectric cold face temperature,

η_m = materials efficiency (including strap and contact losses),

= $\eta_D/0.85$ for assumptions of Section V.

For conditions of interest to the present study (i.e., $\eta_D = 0.1$ to 0.2 , $\Delta T/T_H \sim 0.01$), optimum Carnot efficiency is close to 20%, for which Equation (6) reduces to

$$W_c = \left(\frac{25 d_c \ell P_L}{k_c \eta_m T_H} \right) \left(\frac{1 - 1.1 \eta_m + 0.1 \eta_m^2}{1 + 0.8 \eta_m} \right). \dots (7)$$

It can be shown that the first factor in Equation (7) represents the pellet weight which would be obtained if heat transfer through the thermoelectric material were

031507030

~~SECRET~~

by Fourier conduction alone. The second factor accounts for the reduction in thermoelectric area due to the Peltier and I^2R effects.

4. Strap Weight

The hot straps must be sized to meet an allowable I^2R loss. Sizing is thus dependent on the current output of the circuit, which may be decreased to any desired level (at constant power) by increasing the number of pellets. Total pellet weight is not affected, since the total heat transfer area must remain constant, nor is the converter output affected, since the number of parallel generator circuits may be selected to meet any desired voltage and current characteristics. The effect of increasing the number of pellets is simply to increase converter cost and complexity.

For preliminary estimating purposes, it will be sufficient to simply set an arbitrary strap thickness. For the close-packed converter design, strap weight will then be proportional to the total thermoelectric area, which is given by

$$A_c = \frac{W_c}{d_c} \dots (8)$$

5. Tube Weight

Estimates of converter tubing weight are based on the geometry shown in Figure 8, a tube diameter of 1/4 in. and a tube wall of 20 mils of steel. With respect to pressure drop considerations, the 1/4-in. diameter will be shown to be adequate when the coolant is lithium (c.f. Section VI) but may be questionable for a lower specific heat coolant, depending on the power level and converter geometry. Pressure drop limitations can always be met by increasing the number of parallel coolant tubes, although this may add somewhat to the overall piping system complexity.

Weight estimates will not be affected appreciably by the use of a refractory metal, such as niobium, in place of steel as the tube material.

6. Meteoroid Armor

Some form of shielding is required to prevent puncture of the coolant tubes by micrometeorites. Calculation of the tubing armor requirement is based

03170201030

~~SECRET~~

DECLASSIFIED

~~SECRET~~

on the analysis of Bjork (Reference 9), which is believed to be conservative, and the procedure given in Reference 5. Shown in Figure 11 are the thicknesses of steel needed to provide one-year nonpuncture probabilities ranging from 90 to 99%. To estimate the protection afforded by other materials, it is assumed that required thickness varies inversely with the square root of material density. An evaluation on this basis of various materials which are of interest for converter designs is given below:

<u>Material</u>	<u>Ratio of Steel to Material Thickness for Equal Nonpuncture Probability</u>
Tungsten	1.57
Molybdenum	1.14
Copper	1.07
Steel	1.00
Al ₂ O ₃	0.71
Ge-Si	0.66
Beryllium	0.48

Using these values for armor worth, it is found that the pellet design of Table I provides meteorite protection of the covered tube surface equal to that which would be provided by a steel thickness of 295 mils. Adding 20 mils of tube wall, 10 mils of copper hot strap, and a typical radiator thickness of 50 mils of beryllium, the tubing is protected by a total armor equivalent of about 350 mils of steel. As may be seen from Figure 11, this protection is sufficient to establish high reliability against puncture except where extremely large tubing surface areas are involved.

In a cylindrical or conical converter design, the inner (rounded) portions of converter tubing are shielded by the radiator fins on the opposite side of the assembly and probably also by an internal cylindrical (or conical) converter support structure. These shields act as meteoroid "bumper" shields; their effect is to split and scatter the penetrating particles. Current estimates of the bumper effect, based on rather meager experimental data, are summarized in Reference 10. It appears that the bumper shield may be as thin as possible consistent with structural and fabrication requirements. The reduction in penetration depth into the vulnerable surface is a function of the number of particles into which the original meteoroid is split. It is estimated that, on the average, the effect of a

~~SECRET~~

DECLASSIFIED

Figure 11. Material Thickness vs Vulnerable Area (Steel)

5-10-62

7561-0169

DECLASSIFIED

single bumper shield is to reduce the required armor thickness by a factor of 3, assuming that there is sufficient spacing between shield and vulnerable surface. The spacing must be equal to or greater than

$$s \cong 2 t_v \sqrt{\frac{t_v}{t_b \rho_b}}, \quad \dots (9)$$

where

- s = spacing required between shield and vulnerable surface for full bumper effect,
- t_v = thickness of vulnerable surface, assumed equal to 1/3 the thickness required without bumper,
- t_b = thickness of bumper,
- ρ_b = density of bumper material in g/cm³.

Meteoroids will encounter two bumpers (fin plus converter structure) and must penetrate the converter structure a second time prior to reaching the inward surface of the coolant tubing. Thus a thickness of 20 mils for the inner tubing surface should be adequate for high reliability against puncture.

For converter designs in which the thermoelectric elements are spaced, as considered in Section IV-A, the external tubing surface not covered by the pellets is protected by the radiator fins. It is found from Equation (9) that the approximate 300-mil separation between tube and fin (see Table I) is sufficient in most cases to establish at least a partial bumper effect. Additional armor is still required, however, except where very small vulnerable areas are involved. For the calculations, the nonpuncture probability is set at 99%. Vulnerable area is equal to the total area of flattened tube surface less the total pellet area.

C. CONVERTER MATERIALS

In the design of a high temperature system, limitations are encountered due to the problem of material sublimation in the vacuum of space. The alloy of germanium and silicon used as the SNAP 10A thermoelectric material is known to have significant capability at elevated temperatures. Pellets heated to 900°C in vacuum have not suffered serious weight loss. However, there is not sufficient data presently available to the writer to set a definite temperature limitation for this material.

SECRET

DECLASSIFIED

0314507030
~~SECRET~~

Sublimation rates of various other materials which are of interest for converter-radiator designs are shown in Figure 12. Aluminum, beryllium, and copper are potential radiator materials. Possible hot strap materials include aluminum, copper, iron, and molybdenum (molybdenum does not appear in Figure 12 because of its extremely low vapor pressure in the temperature range of interest).

Aluminum is the best radiator material, in terms of conductivity to density ratio, but is restricted to low temperature systems because of its low melting point. Beryllium is the next best radiator material and may be used to at least 1350°F, which corresponds to a hot junction of about 1800°F. For somewhat higher temperatures, use could be made of copper, with a conductivity-to-density ratio about 20% less than that of beryllium at high temperature.

Copper may be used as the hot strap material to about 1400°F. Above 1400°F, iron or molybdenum could be used, although it may be preferable to extend the range of copper by plating it with a suitable low pressure material. For example, nickel plate could be used to about 1750°F. Above this, the use of molybdenum as strap material would incur a strap weight penalty of about a factor of 4 in comparison with copper.

Sublimation of the tungsten and molybdenum components will be negligible for temperatures below 2000°F.

It may be concluded that it will be possible to operate a converter consisting of beryllium fins, germanium-silicon thermoelectric pellets, and copper hot straps at a hot junction temperature of 1600°F without serious material loss by sublimation. Development of a high temperature emissive coating for the radiator must be assumed. Operation at 1750°F may also be possible but cannot be substantiated at the present time due to lack of information on the germanium-silicon alloy. Of course, additional capability is always a possibility assuming the development of a suitable encapsulation material.

D. ELECTRICAL CIRCUITRY (References 11 and 12)

Most thermoelectric converter designs will utilize series-parallel wiring in order to minimize the effect of element failures on converter output. A generalized converter circuit diagram is shown in Figure 13; it consists of a number of primary current paths connected in parallel plus a number of interconnections to

0317201030

~~SECRET~~

Figure 12. Sublimation Rates of Materials in Space

5-10-62

7561-0170

NAA-SR-7355

5-10-62

7561-0171

Figure 13. Schematic Representation of Converter Electrical Circuitry

UNCLASSIFIED

NAA-SR-7355
40

UNCLASSIFIED

UNCLASSIFIED

provide alternate current paths when open-circuit element failures occur. In determining the optimum wiring configuration, it is convenient to consider separately two effects which may occur as the result of individual element open circuits: (a) catastrophic failure, i.e., complete loss of power, and (b) converter degradation, or partial loss of power.

The catastrophic failure probability for the converter of Figure 13 is given by

$$p_c = 1 - \left\{ 1 - \left[1 - (1 - p)^m \right]^n \right\}^{\frac{N^*}{m}} \quad \dots(10)$$

where

- p = thermoelement open-circuit failure probability,
- m = number of elements per module, i.e., the number of elements between current path interconnectors,
- n = number of primary current paths,
- N^* = number of elements per primary current path,
- p_c = probability of complete converter failure.

Equation (10) is based on the following assumptions:

- 1) the least level of independent failure is a single thermoelectric element,
- 2) the failure probability of all elements in the converter is the same,
- 3) the failure probability of all interconnectors is zero,
- 4) the failure of one element does not affect the failure probability of adjacent elements.

An approximate form of Equation (10) is

$$p_c \cong N^* m^{n-1} p^n, \quad \dots(11)$$

which is sufficiently accurate when $mp \leq 0.1$ and $p_c \leq 0.1$.

0315587030

~~SECRET~~

For converters consisting of a large number of thermoelectric pellets, considerable flexibility usually exists in selecting the wiring configuration, and a low failure probability is easily achieved. A more important consideration in converter designs is the effect of element open circuits in degrading the output. Expected power loss as a function of element failure rate, p , and elements per module, m , is given in Reference 11 for converters of 2, 3, and 4 primary current paths. A completely general expression for probable power loss in a converter of n primary current paths is not derived; but an approximate expression, when the loss in power is less than 10%, is

$$\frac{\Delta P}{P} \cong \frac{n}{n-1} mp . \quad \dots(12)$$

In this equation ΔP is the probable power loss when complete failure does not occur. It can be seen that for large converters the degradation is approximately equal to the product of the element failure probability and the number of elements between interconnections. Thus, for example, if the predetermined element failure rate were one per thousand, a reasonable design would incorporate at least one interconnector every tenth element, with a resultant power loss of only 1%.

03170291030

~~SECRET~~

V. CONVERTER - RADIATOR ESTIMATES

A. BASIS OF ESTIMATES

In this section, weight and area estimates are made for thermoelectric converter assemblies operating at average hot junction temperatures between 1200 and 2000°F. It is believed that this temperature range will be the range of primary interest for thermoelectric systems of this decade. At 1200°F, the system could be completely comprised of current development items, e.g., the germanium-silicon thermoelectric material used in SNAP 10A and a zirconium hydride power source, such as SNAP 8. The upper limit of 2000°F represents an extrapolation beyond the capability of present-day thermoelectric materials and would require the development of a fast reactor as the power source. For intermediate temperatures, the germanium-silicon alloy shows promise of considerable capability. The power source at intermediate temperatures could be either a fast reactor or an yttrium hydride thermal reactor.

From the analyses given in the preceding sections, the basic converter design features conducive to low weight and area and high reliability can be established. The system is one-loop, direct radiating, with the thermoelectric pellets closely spaced along the converter tubing. The converter Carnot efficiency, based on minimum radiator area, is about 20%.

Estimates are based on the use of beryllium as the radiator material and copper for the hot straps. Tubing and strap configurations are as discussed in the preceding section. A strap thickness of 10 mils is assumed. Further design assumptions include a fin efficiency of 0.8, a radiator emissivity of 0.9, and a space temperature of 0°F.

The estimates make allowance for 10% of the output power to be used for pumping; that is, specific weights and areas are based on a power delivered to the payload equal to 90% of the total converter power output.

B. WEIGHT

1. Ge-Si Converter

Because of its high temperature capability, the germanium-silicon alloy is of considerable interest as a possible thermoelectric material. An estimate of materials efficiency as a function of hot junction temperature for this alloy is

SECRET

shown in Figure 14.* The estimate is based on expected materials properties for Ge-Si (see Appendix C) which are slightly superior to properties currently being measured. The improved performance may be achieved by a variation in the material composition from the present 30% germanium, 70% silicon.

The materials efficiency of Figure 14 includes an estimate of electrical losses at the contacts and in the connecting straps. The contact losses were based on objective resistance values of $40\mu\Omega\text{-cm}^2$ per junction for the P-type pellets and $75\mu\Omega\text{-cm}^2$ per junction for the N-type pellets and a thermoelectric length of 200 mils. These resistances may be compared with currently measured values of about 60 and $140\mu\Omega\text{-cm}^2$, respectively, for the P- and N-type pellets. Strap losses were based on a total strap resistance (both hot and cold sides) equal to 10% of the pellet resistance.

Allowing for 10% degradation in performance over the operating lifetime and about 5% shunt heat loss, the device efficiency is estimated at 85% of the materials efficiency.

Specific weights for Ge-Si converter assemblies, based on the pellet design of Table I ($d_c = 13.1\text{ lb/ft}^2$), are shown in Figure 15. The converter is penalized rather severely by the inclusion of large amounts of tungsten and molybdenum in the thermoelectric pellets. Assembly weights which would be possible without the tungsten and molybdenum components are shown by the broken line in Figure 15.

It may be observed that an increase in average hot junction temperature from 1200 to 1600°F causes a reduction in assembly specific weight from about 83 to about 40 lb/kw and that this reduction is due largely to the variation in radiator weight with temperature. Since, at 1600°F, the radiator has become a relatively low weight item, it is obvious that a further increase in temperature should be accompanied by an increase in the design Carnot efficiency and a resultant decrease in pellet weight. The minimum weight Carnot, however, will vary depending on pellet design, hot junction temperature, and power level. For a light pellet design ($d_c \sim 4\text{ lb/ft}^2$) at 1600°F, the minimum area condition is essentially the minimum weight point (cf. Figure 6). With heavier pellets, there

*A value of $T_c/T_H = 0.8$ was used to calculate the efficiency. Small deviations from a Carnot efficiency of 20%, however, would have negligible effect on the referred efficiency for this material.

SECRET

UNCLASSIFIED

NAA-SR-7355

45

Figure 14. Variation of Referred Efficiency With Temperature for a Ge-Si Converter

5-10-62

7561-0172

UNCLASSIFIED

Figure 15. Variation of Converter-Radiator Weight With Temperature for a Ge-Si Converter

5-10-62

7561-0173

DECLASSIFIED

SECRET

is a trade-off between weight and area. In some designs a significant reduction in weight may be achieved by operating above the minimum area Carnot efficiency.

For a high temperature Ge-Si converter, there is also a strong incentive to eliminate as much of the tungsten and molybdenum as possible from the pellet design. It might be optimistic to assume that the weight variation given by the dashed line in Figure 15 will ever be achieved, but some weight reduction is possible due to experience to be gained from SNAP 10A. The difference between dashed and solid lines in Figure 15 may thus be considered to be a band of optimism in estimates of ultimate converter capability.

2. General

Estimates of converter-radiator specific weights, at thermoelectric device efficiencies of 0.1, 0.15, and 0.2, are shown in Figure 16. The shaded areas represent an uncertainty in the thermoelectric element weights, necessitated by the fact that the thermoelectric material and pellet design are unspecified.

It was found to be convenient to use the germanium-silicon design in estimating the converter weights, however, because the germanium-silicon converter represents a heavy design with the tungsten and molybdenum discs and a very light design without these components. Thus, the upper lines in Figure 16 correspond to a pellet area density of 13.1 lb/ft^2 and the lower lines to an area density of 4.0 lb/ft^2 . Weights for most converters of interest are expected to be somewhere between these limits.

C. RADIATOR AREA

The radiator area requirements for converters achieving device efficiencies of 10, 15, and 20% are shown as a function of hot junction temperature in Figure 17. The curve for germanium-silicon is based on the efficiency variation given by Figure 14. For comparison purposes, area requirements for several other space power systems are shown along the right side of the graph. It may be seen, for example, that by going to a hot junction temperature of 1600°F , radiator area for the Ge-Si system becomes approximately equal to the SNAP 8 area.

D. NUMBER OF ELEMENTS

A consideration in the evaluation of thermoelectric systems, and a relative disadvantage by comparison with other space systems, is the large number of

DECLASSIFIED

SECRET

UNCLASSIFIED

Figure 16. Variation of Converter-Radiator Weight With Temperature for a Device Efficiency of 0.1, 0.15, and 0.2

5-10-62

7561-0174

NAA-SR-7355

UNCLASSIFIED

Figure 17. Variation of Radiator Area With Temperature for Converters of Various Efficiencies

5-10-62

NAA-SR-7355

7561-0075

03115087030

~~SECRET~~

thermoelectric couples required for significant power production and the resultant high cost and complexity of the converter assembly. A decrease in the number of couples will be accompanied by an increased current output per couple and thus an increase in the strap size required at constant strap loss factor.

The trade-off between strap thickness and number of couples is illustrated in Figure 18 for germanium-silicon thermoelectric material and copper hot straps. The curves are based on the close-packed module configuration, as described previously, and a strap resistance equal to 5% of the element resistance. If the losses through the fin connections on the cold side were equal to those in the hot straps, the total strap loss factor would be 10%, a value which has been assumed in other sections of this report.

A design based on minimum weight, but with consideration given to the number of individual pellets required, can best be fulfilled at the knee of the thickness vs couple number curve. As may be seen from Figure 18, this implies a strap thickness in the range of 10 to 20 mils and a couple requirement of the order of 1500 couples per kilowatt for the temperature range of interest.

03172201030

SECRET

Figure 18. Copper Hot Strap Requirement for 5% Hot Strap Factor in a Ge-Si Converter

5-10-62

7561-0176

NAA-SR-7355

0315047030

~~SECRET~~

VI. 30 KW THERMOELECTRIC SYSTEM

In the preliminary design stage, thermoelectric system weights are relatively easy to calculate and, once calculated, easy to scale. The preliminary design of a 30 kwe system is presented here. Other power levels of interest (at least in the range of 10 to 100 kw) may be estimated from this design with reasonable accuracy by assuming that the nuclear system remains unchanged and the conversion system scales directly with power.

The reactor concept chosen is that of a UC-ZrC fast reactor (see, for example, Reference 6). Use of an yttrium-hydride thermal reactor represents an alternate possibility. The coolant is lithium (lithium-7 should be used if reactor is thermal), which is especially suitable for a low efficiency thermoelectric system because of its high heat capacity. The system is one-loop, with heat supplied to the converter hot side by the lithium coolant and heat rejected to space by radiator fins brazed to the element cold junctions.

The converter-radiator geometry is cylindrical. To avoid an excessive pressure drop in the converter tubing, the cylinder is split into halves, with hot lithium from the reactor being fed to the center of the assembly, where the flow splits between the two sections. The cooled lithium is collected in headers at opposite ends of the converter, recombined, and returned to the reactor.

A detailed design point and weight summary for this system is given in Table II. The unshielded system weight is 2000 lb, corresponding to a specific weight of 67 lb/kw.

In lieu of quoting a shield weight, it will simply be noted that the cylindrical radiator geometry, which was assumed in order to facilitate the calculations, is likely to lead to a heavy shielding configuration. In a final design, the use of a conical or conical/cylindrical geometry is indicated in order to reduce the radiator profile as seen from the reactor. For example, the required radiator area of 575 ft² could be obtained with a 10-ft cylinder, 10 ft in diameter, plus a 12-ft truncated cone with end diameters of 4 ft and 10 ft. Assuming a suitable converter-radiator geometry, it is expected that the shield will weigh in the order of 700 lb, resulting in a total system weight of about 2700 lb, or 90 lb/kw.

03712201030

~~SECRET~~

TABLE II
30 kw SYSTEM DESIGN

1. Reactor	
Type	UC-ZrC, fast
Thermal power	900 kw
Inlet temperature	1575° F
Exit temperature	1775° F
2. Heat Transfer System	
Coolant	Lithium
Flowrate	4.3 lb/sec
Piping	Niobium
ID (for full flow)	1.5 in.
Coolant pressure drop	11 psi
Reactor	4 psi
Piping	6 psi
Converter tubes	1 psi
Pump	a-c electromagnetic
Input power	3.3 kw
Efficiency	10%
3. Converter-Radiator	
Geometry	2 cylinders
Length (each cylinder)	9.2 ft
Diameter	10 ft
Total radiator area	575 ft ²
Number of modules	238
Number of parallel circuits	10
Output power (end of life)	33.3 kw
Output power (start of life)	37.0 kw
Output voltage (start of life)	198 volts dc
Thermal power	890 kw
Efficiency	3.75%
Carnot, hot to cold junctions	30.0%
Device	12.5%
Coolant inlet temperature	1775° F
Coolant exit temperature	1575° F

~~SECRET~~

0315087030

TABLE II (Continued)

3. Converter-Radiator (Continued)

Average hot junction	1600°F
Average cold junction	980°F
Average fin base temperature	970°F
Tubes	Niobium
Number	238
Spacing	3.2 in.
Profile	semicircular
ID	0.25 in.
Hot straps	Copper
Thickness	0.02 in.
Width	0.25 in.
Pellets	Ge-Si, Table I
Number	32,200
Number per module	135
Thermoelectric length	0.200 in.
Width	0.250 in.
Height (direction of tubing)	0.500 in.
Fins	Beryllium
Thickness	0.069 in.
Fin efficiency	0.80
Thermal emmissivity	0.90

4. Weight Summary

Reactor	450
Converter-radiator	980
Tubing	200
Straps	40
Pellets	365
Fins	375
Pump	60
Piping and coolant	150
Structure	360
System weight, unshielded	2000 lb
System specific weight	67 lb/kw

03172281030

~~SECRET~~

DECLASSIFIED

Compared with an advanced turbogenerator system operating at the same temperature level, it must be concluded that the nuclear-thermoelectric system is a relatively heavy and bulky item. However, if the comparison is in terms of pounds per kw-hr, based on mean time to system failure, the conclusion is likely to be significantly altered. Once the operating characteristics and temperature limitations of the converter have been firmly established, the thermoelectric system should be capable of highly reliable operation for periods considerably in excess of one year.

NAA-SR-7355

SECRET

DECLASSIFIED

~~SECRET~~

VII. APPLICATIONS FOR THERMOELECTRIC SYSTEMS

An overall evaluation of a space power system must be based on several criteria, of which the most important are usually weight, reliability, and life-time. The relative importance of each of these factors in determining total system desirability will depend to a large extent on the particular application for which the system is being considered. For electrical propulsion applications, for example, the prime requirement on the power source is low weight. Reliability is also important, but only for systems which meet the weight requirement. In general, power plants for propulsion which weigh more than about 50 lb/kw have little value for interplanetary missions and only limited usefulness in orbital applications.

On the other hand, for certain auxiliary power requirements such as communications, a definite assessment of importance among weight, reliability, and lifetime can be established. The disadvantage of high weight is offset by increased reliability. Consider, for example, a slightly idealized case in which the cost per pound of payload placed in orbit is a constant. Then the launch cost associated with space auxiliary power will be a function of power plant specific weight in terms of lb/kw-hr, based on mean system lifetime, assuming that power plant lifetime does not exceed the lifetime of the electronic equipment. Mean system lifetime here will be a function of both design lifetime and reliability.

Further applications can be identified in which reliability and lifetime are still higher in priority and weight is of decreased relative importance. These would include manned exploration and certain military missions.

The preceding sections of this report have dealt primarily with system weight estimates and designs for achieving low weight. From the results of Sections V and VI, it must be concluded that, on a weight basis alone, thermoelectric systems are not competitive with turbogenerator systems operating at similar temperature conditions. It should be noted, however, that the thermoelectric converter design based on minimum weight also resulted in high reliability. Based on current estimates of meteoroid effects in space, the pellet design of Table I should provide more than adequate protection of the outer coolant tube surfaces; and, in a cylindrical converter-radiator design, the inner tube walls will be protected by the radiator fins on the opposite side and probably

~~SECRET~~

DECLASSIFIED

SECRET

also by an internal cone or cylinder required for structure. Additional thin "bumper" type shields could be placed within the converter-radiator assembly at a relatively low weight penalty.

The generator itself is protected against catastrophic failure by the parallel circuit design and cross-connections between circuits. Random element failures, due to meteorite puncture or other causes, will thus produce only fractional decreases in generator output. In addition, the generator is inherently reliable because of the completely static nature of the thermal/electrical energy conversion. Use of an EM pump will provide comparable reliability in the heat transfer system.

This potential for high reliability should be fully exploited in future thermoelectric system designs. It is not envisaged that the nuclear-thermoelectric system will be competitive for high performance applications such as electric propulsion, since competition in this area would require overall efficiencies in the order of 10%, or device efficiencies around 50%. However, the thermoelectric system could become an item of value in meeting requirements for highly reliable, long-term auxiliary power.

It is believed that reliable, high temperature, thermoelectric systems similar to the design of Section VI will be achieved, although major development effort will be required to solve some of the problems which afflict current systems (e.g., materials compatability for long term operation and structural soundness of the thermoelectric pellets under shock and thermal loading). Temperature capability for germanium-silicon or other thermoelectric materials must be established, and consideration should be given to methods for assembling converters consisting of a very large number of individual pellets.

It may be expected, however, that reliable operation will be established at an earlier date for nuclear-thermoelectric systems than for turbogenerator systems at equal temperature levels. Thus it may be expected that there will be a requirement for thermoelectric systems in space applications.

SECRET

DECLASSIFIED

VIII. APPENDIX

A. RADIATOR AREA

The radiator area requirement is given by

$$A_R = \frac{P_R}{\sigma \epsilon \eta_f (T_B^4 - T_S^4)} \quad , \quad \dots(13)$$

where

P_R = radiated power.

1. One-Loop System

For the "one-loop" system of Figure 4a, the minimum area condition is obtained by differentiating A_R with respect to ΔT_c and setting the result equal to zero, which gives

$$T_B \frac{\partial P_R}{\partial \Delta T_c} = 4 P_R \frac{\partial T_B}{\partial \Delta T_c} \quad , \quad \dots(14)$$

where fin efficiency has been assumed constant and space temperature is taken to be absolute zero. Radiator power is given by

$$P_R = P_o \left(\frac{1}{\eta_D \eta_c} - 1 \right) \quad . \quad \dots(15)$$

Carnot efficiency is

$$\eta_c = \frac{\Delta T_c}{T_H} \quad , \quad \dots(16)$$

so that

$$P_R = P_o \left(\frac{T_H}{\eta_D \Delta T_c} - 1 \right) \quad . \quad \dots(17)$$

It will be assumed that the device efficiency is a constant, independent of the Carnot efficiency. The fin base temperature is given by

$$T_B = T_H - \Delta T_c - \Delta T \quad . \quad \dots(18)$$

Performing the indicated operations on radiator power and fin base temperature and combining with Equation (14), the formula for minimum area is obtained:

$$\frac{\Delta T_c}{T_H} = \frac{5}{8\eta_D} \left[1 - \sqrt{1 - \frac{16\eta_D}{25} \left(1 - \frac{\Delta T}{T_H} \right)} \right] \quad \dots(19)$$

If the temperature drop between cold junction and fin base is assumed to be zero, Equation (19) becomes

$$\frac{\Delta T_c}{T_H} = \frac{5}{8\eta_D} \left(1 - \sqrt{1 - \frac{16\eta_D}{25}} \right) \quad \dots(20)$$

It may be noted that, for a device efficiency of $\eta_D = 1$, Equation (20) reduces to the "3/4 law," i. e., a fin base temperature equal to 3/4 the hot junction temperature.

2. Regenerative System

For the "regenerative" system (Figure 4c), radiator area decreases monotonically with decreasing ΔT_c but minimizes on an optimum ΔT_L . Thus, minimum area occurs at

$$T_B \frac{\partial P_R}{\partial \Delta T_L} = 4P_R \frac{\partial T_B}{\partial \Delta T_L} \quad \dots(21)$$

ΔT_L is given by

$$\Delta T_L = \frac{P_T}{wC_P} \quad , \quad \dots(22)$$

where

P_T = thermal power into converter,

w = coolant flow rate,

C_P = specific heat of coolant.

The coolant temperature rise on the converter cold side is given by

$$\Delta T_{LC} = \frac{P_T - P_o}{wC_P} \quad , \quad \dots(23)$$

~~SECRET~~

0310507030

where

ΔT_{LC} = coolant temperature rise (cold leg), converter inlet to converter outlet.

The radiated power is

$$P_R = w C_P \left(\Delta T_c - \frac{\Delta T_L}{2} + \frac{\Delta T_{LC}}{2} \right) , \quad \dots (24)$$

where

ΔT_c = average converter temperature drop, hot junction to cold junction.

It has been assumed here that the temperature drops in the hot and cold straps (i. e., between junctions and coolant) are negligible. Combining Equations (22), (23), and (24), the expression for radiator power becomes

$$P_R = w C_P \left(\Delta T_c - \frac{P_o}{2w C_P} \right) . \quad \dots (25)$$

The output power is equal to the thermal power times the efficiency, or

$$P_o = P_T \eta_D \frac{\Delta T_c}{T_{HM} - \frac{\Delta T_L}{2}} , \quad \dots (26)$$

where

T_{HM} = maximum hot junction temperature.

Combining Equations (22), (25) and (26) to eliminate $w C_P$ and P_T , the final equation for radiated power is

$$P_R = P_o \left(\frac{T_{HM}}{\Delta T_L \eta_D} - \frac{1}{2\eta_D} - \frac{1}{2} \right) . \quad \dots (27)$$

The average fin base temperature is

$$T_B = T_{HM} - \Delta T_L - \frac{1}{2} \frac{P_R}{w C_P} . \quad \dots (28)$$

0310507030

~~SECRET~~

DECLASSIFIED

SECRET

Combining Equations (22) and (26), substituting the resulting expression for $P_o / w C_P$ into Equation (25), and then combining with Equation (28), the following formula for fin base temperature is obtained:

$$T_B = T_{HM} - \Delta T_L - \frac{1}{2} \Delta T_c + \frac{1}{4} \frac{\Delta T_L \Delta T_c \eta_D}{T_H - \frac{\Delta T_L}{2}} \quad \dots(29)$$

The last term in Equation (29) is small and becomes very small for small η_D . To simplify the algebra, this term will be omitted in the optimization of ΔT_L , leaving

$$T_B = T_{HM} - \Delta T_L - \frac{1}{2} \Delta T_c \quad \dots(30)$$

Differentiating Equations (27) and (30) and combining with Equation (21), the following condition for minimum area in the regenerative system is obtained:

$$\frac{\Delta T_L}{T_{HM}} = \frac{\frac{5}{4} - \frac{1}{4} \sqrt{17 - 8\eta_D + 4(1 + \eta_D) \Delta T_c / T_{HM}}}{1 + \eta_D} \quad \dots(31)$$

For $\eta_D = 1$ and $\Delta T_c = 0$, this equation also reduces to the 3/4 law for optimum radiator temperature.

B. CONVERTER WEIGHT

An expression for thermoelectric pellet weight in terms of converter materials efficiency will be derived. It is assumed, for simplicity, that the magnitudes of Seebeck coefficient, electrical resistivity, and thermal conductivity are the same for the P and N-type pellets. On this basis, Equations (32) through (41) are used to describe the converter (Reference 8):

$$\frac{A_P}{\ell} = \frac{\bar{\rho}}{r} \quad \dots(32)$$

where

A_P = pellet cross-sectional (heat transfer) area,

$\bar{\rho}$ = effective pellet resistivity (including strap and contact resistances),

r = converter internal resistance (per pellet).

NAA-SR-7355

61

DECLASSIFIED

SECRET

~~SECRET~~

$$r = \frac{R}{N} , \quad \dots(33)$$

where

R = converter internal resistance,

N = number of pellets.

$$M = \frac{R_L}{R} , \quad \dots(34)$$

where

M = ratio of load resistance to generator internal resistance,

R_L = load resistance.

$$R_L = \frac{V_L^2}{P_L} , \quad \dots(35)$$

where

V_L = load voltage,

P_L = power to load.

$$\eta_m = \frac{M - 1}{M + \frac{T_c}{T_H}} . \quad \dots(36)$$

$$M = \sqrt{1 + \bar{Z} \frac{(T_H + T_c)}{2}} , \quad \dots(37)$$

where

M = the ratio of load resistance to internal resistance which maximizes

η_m .

$$\bar{Z} = \frac{\alpha^2}{k_c \bar{\rho}} , \quad \dots(38)$$

where

$\bar{Z}$ = effective figure of merit,

α = Seebeck coefficient.

$$E = \frac{M + 1}{M} V_L , \quad \dots(39)$$

where

E = emf of generator.

~~SECRET~~

DECLASSIFIED

SECRET

$$N = \frac{E}{e} , \quad \dots (40)$$

where

$e = \text{emf per pellet.}$

$$e = a(T_H - T_C) . \quad \dots (41)$$

The total pellet weight is given by

$$W_c = d_c N A_p . \quad \dots (42)$$

Substituting from Equations (32), (33), and (34) for A_p and Equations (39) and (40) for N , the weight is

$$W_c = d_c \ell \times \frac{\bar{\rho} V_L^2}{e^2 R_L} \times \frac{(M+1)^2}{M} . \quad \dots (43)$$

Substituting from Equations (35), (38), and (41), this becomes

$$W_c = d_c \ell P_L \frac{(M+1)^2}{k_c \bar{Z} (T_H - T_C)^2 M} . \quad \dots (44)$$

Using Equation (37) to eliminate $\bar{Z}$,

$$W_c = \frac{d_c \ell P_L}{2k_c} \times \frac{T_H + T_C}{(T_H - T_C)^2} \times \frac{(M+1)}{M(M-1)} . \quad \dots (45)$$

Finally, combining Equations (36) and (45), the following general formula for pellet weight is obtained:

$$W_c = \frac{d_c \ell P_L}{2k_c} \times \frac{T_H + T_C}{(T_H - T_C)^2} \times \frac{2 - \eta_m \left(3 - \frac{T_C}{T_H}\right) + \eta_m^2 \left(1 - \frac{T_C}{T_H}\right)}{\eta_m \left(1 + \frac{T_C}{T_H}\right) + \eta_m^2 \left(\frac{T_C}{T_H} + \frac{T_C^2}{T_H^2}\right)} . \quad \dots (46)$$

NAA-SR-7355

63.

DECLASSIFIED

SECRET

~~SECRET~~

From Equation (19) or (20) it will be found that T_c/T_H is very close to 0.8 for the values of η_D of interest here. For $(T_c/T_H) = 0.8$ ($\eta_c = 0.2$), the converter pellet weight is

$$W_c = \frac{25d_c \ell P_L}{k_c \eta_m T_H} \times \frac{1 - 1.1\eta_m + 0.1\eta_m^2}{1 + 0.8\eta_m} \quad \dots(47)$$

C. GERMANIUM-SILICON DATA

Estimates for Ge-Si converters are based on RCA expected materials properties as of January 1962. Seebeck coefficient, electrical resistivity, and thermal conductivity are shown in Figures 19, 20, and 21. Contact resistivities of $40\mu\Omega\text{-cm}^2$ per junction (P-type) and $75\mu\Omega\text{-cm}^2$ per junction (N-type) and a strap resistance equal to 10% of the Ge-Si resistance were assumed. Thus,

$$\bar{\rho}_N = 1.1 \rho_N + \frac{1}{\ell} \times 150 \times 10^{-6} \Omega\text{-cm}, \quad \dots(48)$$

$$\bar{\rho}_P = 1.1 \rho_P + \frac{1}{\ell} \times 80 \times 10^{-6} \Omega\text{-cm}, \quad \dots(49)$$

where

ρ_N = resistivity of N-type Ge-Si, $\Omega\text{-cm}$,

ρ_P = resistivity of P-type Ge-Si, $\Omega\text{-cm}$.

An element length, ℓ , of 200 mils = 0.508 cm was used. The figure of merit is given by (Reference 8)

$$\bar{Z} = \left[\frac{|a_P| + |a_N|}{\sqrt{k_P \bar{\rho}_P} + \sqrt{k_N \bar{\rho}_N}} \right]^2 \quad \dots(50)$$

The figure of merit is plotted as a function of temperature in Figure 22. Using Figure 22 and Equations (36) and (37), assuming $(T_c/T_H) = 0.8$, the variation of materials efficiency with average hot junction temperature is as shown in Figure 14.

~~SECRET~~

Figure 19. Variation of Seebeck Coefficient With Temperature for Ge-Si

5-10-62

7561-0177

NAA-SR-7355

~~CONFIDENTIAL~~

Figure 20. Variation of Electrical Resistivity With Temperature for Ge-Si

5-10-62

7561-0178

NAA-SR-7355

66

~~CONFIDENTIAL~~

DECLASSIFIED

CONFIDENTIAL

Figure 21. Variation of Thermal Conductivity With Temperature for Ge-Si

5-10-62

7561-0179

NAA-SR-7355

CONFIDENTIAL

67

DECLASSIFIED

Figure 22. Variation of Figure of Merit With Temperature for a Ge-Si Couple

5-10-62

7561-0180

UNCLASSIFIED
NAA-SR-7355
68

UNCLASSIFIED

DECLASSIFIED

SECRET

UNCLASSIFIED NOMENCLATURE

A = area; subscript c refers to total thermoelectric (heat transfer) area, P to thermoelectric area per pellet, R to radiator area.

B = tube spacing, equals twice the fin length.

C_p = coolant specific heat.

d_c = pellet area density (weight per unit area).

e = emf of element.

E = emf of generator.

k = thermal conductivity; subscript c refers to thermoelectric material, N to N -type thermoelectric material, P to P -type thermoelectric material, R to radiator material.

ℓ = thermoelectric length, direction of heat transfer.

m = number of thermoelectric elements between interconnectors.

M = ratio of load resistance to generator internal resistance.

M_R = dimensionless radiation modulus, defined in Figure 10.

n = number of parallel electrical circuits (primary current paths) in converter.

N = number of elements.

N^* = number of elements per primary current path.

p = element open-circuit failure probability.

p_c = probability of complete converter failure.

P = power; P_L is converter output, start of life; P_R is radiator power; P_T is thermal power into converter; P_O is converter output, end of life.

r = internal electrical resistance of converter per element.

R = electrical resistance; subscript L refers to load; without subscript, generator internal resistance.

s = spacing required between meteoroid shield and vulnerable surface for "bumper" effect.

SECRET

DECLASSIFIED

~~SECRET~~
UNCLASSIFIED

t = thickness; subscript b refers to meteoroid bumper, v to vulnerable surface; without subscript, radiator fin thickness.

T = temperature; subscript B refers to fin base, c to converter cold junction or average converter cold junction, H to converter hot junction or average converter hot junction, HM to maximum converter hot junction, S to space.

ΔT = temperature difference; ΔT_C is between thermoelectric hot and cold junctions, ΔT_L is between coolant inlet and coolant outlet on converter hot leg, ΔT_{LC} is between coolant inlet and coolant outlet on converter cold leg, ΔT_R is between coolant inlet and coolant outlet in radiator; without subscript, temperature drop from converter cold junction to fin base.

V_L = load voltage.

w = coolant flow rate.

W_c = converter pellet weight.

$\bar{Z}$ = effective figure of merit for thermoelectric element.

α = Seebeck coefficient; subscript N refers to N-type thermoelectric material, P to P-type thermoelectric material.

ϵ = thermal emissivity.

η = efficiency; η_C is Carnot efficiency based on converter hot junction and cold junction temperatures; η_D is device efficiency, equals conversion efficiency divided by Carnot efficiency; η_f is radiator fin efficiency; η_m is converter materials efficiency including strap and contact factors.

ρ = electrical resistivity; subscript N refers to N-type thermoelectric material, P to P-type thermoelectric material; $\bar{\rho}$, $\bar{\rho}_N$, and $\bar{\rho}_P$ are effective resistivities which include strap and contact resistances.

ρ_b = density of meteoroid bumper material in g/cm^3 .

σ = Stefan-Boltzmann constant = $0.1713 \times 10^{-8} \text{ Btu/ft}^2\text{-hr-}^\circ\text{R}^4$.

UNCLASSIFIED

NAA-SR-7355

037228.030 70

~~SECRET~~

DECLASSIFIED

UNCLASSIFIED

REFERENCES

1. J. L. Johnson, ed., "Preliminary Design Study of the SNAP 10A Direct Conversion Nuclear Auxiliary Power Unit," NAA-SR-6263, June 20, 1961 (Secret).
2. A. W. Thiele, "Feasibility Study and Preliminary Design of a Low Power Direct Conversion Nuclear Auxiliary Power Unit," NAA-SR-3473, November 1, 1959 (Secret).
3. C. J. Morse, "High Temperature Thermoelectric Conduction Systems," NAA-SR-TDR-7220, March 14, 1962.
4. "The Preliminary Design of a 150 kw SNAP System," NAA-SR-6735, January 22, 1962 (Secret).
5. M. G. Coombs, R. A. Stone, and T. Kapus, "The SNAP 2 Radiative Condenser Analysis," NAA-SR-5317, 1960.
6. "Proposal for a 300 kwe Nuclear-Mechanical Power System," AI-4880, January 30, 1960 (Secret).
7. C. K. Smith, J. W. Holland, and R. Hirsch, "Design Study of a Thermionic Reactor Power Plant for Space Applications," NAA-SR-6077, May 1, 1961 (Secret).
8. J. C. Cooper, "Power Thermocouple Design," NAA-SR-TDR-6362, April 28, 1961.
9. R. L. Bjork, "Meteoroids vs Space Vehicles," Semi-Annual Meeting, American Rocket Society, Los Angeles, May 9-12, 1960.
10. L. D. Jaffe and J. B. Rittenhouse, "Behavior of Materials in Space Environments," Technical Report No. 32-150, Jet Propulsion Laboratory, Pasadena, November 1, 1961.
11. R. P. Johnston, "The Effect of Series-Parallel Electrical Circuitry on the SNAP 10A T/E Converter Electrical Performance Characteristics," NAA-SR-TDR-7689, September 5, 1962.
12. R. P. Johnston, Private Communication, October 1962.

NAA-SR-7355

SECRET

UNCLASSIFIED

DECLASSIFIED