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LARGE MILLIWATT RADIOISOTOPE THERMOELECTRIC GENERATOR PROGRAM

PARAMETRIC STUDY DATA

Volume II. Appendixes

By

Carl Carney	Donald Toomb
Ivan Lamb	Hal Whittum
Don Rockwell	George Sonnenschein
William Ruehle	Hans R. Strop
Donald L. Zanders	

April 1966

Aerojet-General Nucleonics
San Ramon, California

Monsanto Research Corporation
Dayton, Ohio

AEC Research and Development Report

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LARGE MILLIWATT RADIOISOTOPE THERMOELECTRIC GENERATOR PROGRAM

PARAMETRIC STUDY DATA

VOLUME II

APPENDIXES

Contract AT(30-1)-3628

April 1966

SPECIAL REREVIEW FINAL DETERMINATION	Reviewers	Class.	Date
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PREFACE

The work in the parametric study under Contract AT(30-1)-3628 was performed by personnel from Aerojet-General Nucleonics and Monsanto Research Corporation. The report was prepared by the following individuals from AGN:

Carl Carney
Ivan Lamb
Don Rockwell
William Ruehle
Donald Toomb
Hal Whittum

and the following from MRC:

George Sonnenschein
Hans R. Strop
Donald L. Zanders

The work was performed under the supervision of Paul E. Underhill, program manager (AGN); R. A. Cooley, Manager, Systems and Devices (MRC); and Harold Jaffe, Manager, Applied Science Division, AGN.

This report is printed in two volumes for the convenience of the reader: Volume I: General Characteristics of an Advanced, Large Milliwatt RTG; and Volume II: Appendixes.

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APPENDIX I-A

TEHE: AN IBM-7094 FORTRAN IV PROGRAM
FOR THERMOELECTRIC HEATER EVALUATION

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APPENDIX I-ATEHE: An IBM-7094 Fortran IV Program for ThermoelectricHeater Evaluation

An IBM-7094 Fortran IV program (TEHE) was written for use in evaluating thermoelectric heaters. Basically, TEHE optimizes the generator system for maximum efficiency at any given diameter, and establishes the minimum diameter that will satisfy system specifications. The program output includes system performance as a function of hot junction temperature for each overall diameter of interest. The program evaluates a cylindrical radioisotope-heated thermoelectric generator system where the cylindrical radioisotope fuel to be encapsulated by a specified cladding material is enclosed by a shield, thermal insulation, and an external shell. The thermal insulation is assumed to be of uniform thickness; the shield is also of uniform thickness except at the corners which are rounded to reduce weight. A typical configuration, with the thermal insulation outside of the shield, is shown in Figure A-1.

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FIGURE A-1. TYPICAL HEATER CONFIGURATION WITH EXTERNAL THERMAL INSULATION

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1. Description of TEHE Program

The data required for the program (input) includes the net electrical power, mission time, capsule L/D ratio, material designations, overall diameter limits, hot junction temperature limits, clearances, clad drawing thickness and thermoelectric module conversion efficiency/temperature function.

Output includes system performance as a function of hot junction temperature for each overall diameter of interest; that is, beginning and end of life net thermal efficiency, heater and thermoelectric efficiency, total heat generation, total heat loss (including structural losses) and insulation loss. Generator dimensions are calculated for each hot junction temperature, based on desired capsule L/D ratio; dimensions include fuel diameter and length, cladding thickness, shield thickness and insulation thickness. Weights of individual material and total system weight are also calculated. The output is in the form of three tables for each overall diameter, i.e. system performance, generator dimensions, and component weights are each tabulated versus hot junction temperature (Figure A-2).

1.1 Basic Assumptions

The TEHE program is based on the following assumptions:

- For the case of external insulation, the hot junction temperature is assumed to be uniform over the exterior surface of the shield, and the temperature drop across the outer shell is assumed to be negligible.
- Structural heat losses are calculated by an equation of the form

$$q = C_m (T_{hj} - T_{cj}) D_{max}^E$$

where C_m and E are constants based on data available for similar systems. These normalized constants are subject to change as better data are developed by the conceptual design effort.

1.000 WATTS NET SRTIO3 5.0YR MIN-K-1301 HALF SHIELD L/D=1.2 Z=0.90

1.000	5.000	1.200	3	1	1	1	1	-0
7.000	0.500	300.	100.	1600.	170.			
0.000	0.100	0.050	0.075	0.050	0.500	-0.000		
-0.1864E-01	0.1121E-03	-0.1446E-07	-0.0000E-38	-0.0000E-38				

OVERALL DIA. = 7.0000 IN.

THJ	BOLEFF	EOLEFF	EFF	EFF	HEAT GEN	HEAT LOSS	HEAT INS
DEG F	NET	NET	HTR	TE	BTU/HR	BTU/HR	BTU/HR
300.	0.0107	0.0121	0.8867	0.0137	0.28116E 03	0.31853E 02	0.25104E 02
400.	0.0161	0.0182	0.7614	0.0239	0.18763E 03	0.44767E 02	0.34092E 02
500.	0.0187	0.0212	0.6269	0.0338	0.16107E 03	0.60094E 02	0.45410E 02
600.	0.0192	0.0217	0.5002	0.0434	0.15709E 03	0.78508E 02	0.59505E 02
700.	0.0182	0.0206	0.3900	0.0527	0.16579E 03	0.10113E 03	0.77358E 02

THJ	DIA.	LENGTH	CLEAR	CLEAR	THICK	THICK	THICK	THICK	THICK
DEG F	FUEL	FUEL	DIA.	AXIAL	CLAD	ENDCLAD	SHIELD	INSUL	SHELL
	IN	IN	IN	IN	IN	IN	IN	IN	IN
300.	1.9708	2.2350	0.0000	0.1000	0.0500	0.0750	1.4899	0.9247	0.0500
400.	1.7272	1.9426	0.0000	0.1000	0.0500	0.0750	1.4213	1.1151	0.0500
500.	1.6435	1.8422	0.0000	0.1000	0.0500	0.0750	1.3955	1.1828	0.0500
600.	1.6301	1.8262	0.0000	0.1000	0.0500	0.0750	1.3912	1.1937	0.0500
700.	1.6590	1.8608	0.0000	0.1000	0.0500	0.0750	1.4004	1.1702	0.0500

THJ	WEIGHT	WEIGHT	WEIGHT	WEIGHT	WEIGHT	WEIGHT
DEG F	TOTAL	FUEL	CLAD	SHIELD	INSUL	SHELL
	LB	LB	LB	LB	LB	LB
300.	65.71	0.94	0.40	59.13	1.90	3.34
400.	53.11	0.63	0.31	46.71	2.15	3.32
500.	49.10	0.54	0.28	42.73	2.22	3.32
600.	48.47	0.53	0.28	42.11	2.24	3.32
700.	49.83	0.56	0.29	43.46	2.21	3.32

FIGURE A-2. SAMPLE TEHE PRINTOUT FORMAT

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- Mean thermal conductivity of the insulation is correlated as a function of hot junction temperature by

$$k_m = B_1 e^{\text{superscript } B_2 T_{hj}}$$

where B_1 and B_2 are correlating constants based on published data for thermal conductivity.

- Shield thickness is calculated by an equation of the form

$$x_{\text{shield}} = F \left[\frac{\ln(q/\alpha)}{\phi} \right]^{SE}$$

where F is an arbitrary input factor to calculated partial shield thickness (i.e., half shield, quarter shield, etc.); and SE , α and ϕ are correlating constants based on the specified permissible exterior dose rate and the attenuation properties of the materials.

- A special subroutine is required for the calculation of capsule dimensions when using plutonium, due to the pressure build-up therein caused by alpha decay. The stress equations used to calculate the required wall thickness of the cladding are based on $L/D = 1.2$, and must be modified for other L/D ratios. For problems using any other fuel than plutonium, L/D is a simple program input variable. The calculated plutonium capsule dimensions give minimum weight and near minimum volume.

1.2 TEHE Constants

Fuel data is generated in code as follows:

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<u>Fuel</u>	<u>Density, lb/in.³</u>	<u>Power Density, Btu/in.³</u>	<u>Packing Factor</u>	<u>Lamda, yr⁻¹</u>	<u>Depleted Uranium Shield Constants</u>		
					<u>SE</u>	<u>Ø</u>	<u>α</u>
PuO ₂	0.414	249.8	0.75	0.00773	1.	1.	1.(no shield)
SrTiO ₃	0.185	62.54	0.75	0.0250	1.	2.95	0.04849
Pm ₂ O ₃	0.264	110.6	0.9	0.2645	3.106	9.36	0.06147

Note: In the above table, SE, Ø and α are based on an isotope heat source strength expressed in Btu/hr.

Insulation data is generated as:

<u>Insulation</u>	<u>Conductivity Constants</u>		<u>Density, lb/in.³</u>
	<u>B₁</u>	<u>B₂</u>	
Min-K-1301	1.0667x10 ⁻³	2.07x10 ⁻⁴	0.01157
Linde Super	3.4x10 ⁻⁶	2.25x10 ⁻³	0.01157

Other material densities are:

	<u>Density, lb/in.³</u>
Capsule cladding (Hastelloy C)	0.323
Shell (304-Stainless steel)	0.282
Shield (depleted uranium)	0.672

The assumed mission times for the parametric study used to calculate initial fuel loading requirements are:

<u>Fuel</u>	<u>Mission Time, yr</u>
PuO ₂	10
SrTiO ₃	5
Pm ₂ O ₃	1.5

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Capsule requirements are specified as:

	SrTiO_3	Pm_2O_3
Fuel-capsule diametral clearance, in.	0	0.030
Fuel-capsule axial clearance, in.	0.100	0.090
Capsule wall thickness, in.	0.050	0.050
Capsule end cap thickness, in.	0.075	0.075

1.3 TEHE Flow Diagram

A flow diagram of the TEHE computer program (Figure A-3) illustrates the calculational sequences, iterative loops, convergence requirements, and incrementing capabilities. The initial heat balance (i.e. specification of adequate volume of fuel to supply thermal power for the thermoelectric module Q_{te} and insulation and structural heat losses Q_{loss}) is an iterative procedure. The convergence criterion is

$$\frac{Q_{htr}(n) - Q_{htr}(n-1)}{Q_{htr}(n-1)} = 0.001$$

where

$$Q_{htr} = Q_{te} + Q_{loss}$$

The thermoelectric hot junction temperature is incremented through given temperature intervals from an initial temperature to indicated maximum temperature, or is stopped at one increment past the temperature of maximum overall system efficiency. Overall system diameter is also incremented from an initial maximum diameter to smaller diameters through specified dimensional intervals until it is no longer possible to obtain a solution at the specified net power output.

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FIGURE A-3. TEHE FLOW DIAGRAM

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2. Symbols

A	Logarithmic shielding constant, Btu/hr
B1	Coefficient of conductivity vs T_{hj} function, Btu/hr-in- $^{\circ}$ F
B2	Exponent of conductivity vs T_{hj} function, $^{\circ}$ F
BRIDGE	Subroutine name for calculating ETASYS
CAPSUL	Subroutine name for calculating capsule dimensions
CLEAR	Diametral clearance fuel to clad, in.
CLEARA	Axial clearance fuel to clad, in. (subscripted)
CLRA	Axial clearance fuel to clad, in. (nonsubscripted)
GM	Coefficient for structural heat loss function
CONV	Convergence error
DELTAD	External heater diameter increment, in.
DF	Fuel diameter, in.
DII	Inside insulation diameter, in.
DMAX	External heater diameter, in.
DTH	Hot junction temperature increment, $^{\circ}$ F
E1-E5	Coefficients for five-term polynomial function of η_{te} vs T_{hj}
EL	Exponent for structural heat loss function
ETA	Net plant efficiency for previous (M-1) calculation, nd
ETAB	Net plant efficiency(beginning of life)for the Lth calculation, nd
ETAE	Net plant efficiency(end of life)for the Lth calculation, nd
ETAQ	Thermal efficiency of heater (end of life), nd
ETASYS	Thermoelectric unit efficiency, nd

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I	Print and storage index
IL	Logic control variable in M loop
IM	Logic control variable in M loop
J	Cost calculation option
KICK	Logic control variable in M loop for exit
L	Index variable for diameter loop
LAMDA	Fuel decay constant, year ⁻¹
LD	Capsule external L/D ratio, nd
LF	Fuel length, in.
LII	Inside insulation length, in.
LIM	Calculated L loop iteration limit after XINS<0.
IMAX	Overall heater length, in.
LP	Error trace for maximum iterations in L loop
LX	Maximum index value for L loop
M	Index variable for T _{hj} loop
MAX	Last converged value of M index with XINS >0.
MB	First value of M loop to be printed
MC	Clad identification number, nd
MF	Fuel identification number, nd
MI	Insulation identification number, nd
MP	Error trace for maximum iterations in M loop
MS	Shield identification number, nd
MSH	Shell identification number, nd
MX	Maximum index value for M loop
N	Index variable for thermal power convergence loop
NP	Error trace for maximum iterations in N loop

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PACK	Fuel packing factor, nd
PHI	Shielding coefficient, in. ⁻¹
PI	π
PSYST	Net system power, watts
QDEN	Fuel power density, Btu/hr-in. ³
QINS	Heat loss through insulation, Btu/hr
QLOS	Subroutine name for calculating QLOSS
QLOSS	Heat loss through insulation and support, Btu/hr
QTE	Thermoelectric unit heat requirement, Btu/hr
QT1	Preceding value of end of life heater thermal power, Btu/hr
QT1B	Preceding value of beginning of life heater thermal power, Btu/hr
QT2	Present value of end of life heater thermal power, Btu/hr
RC	Cladding density, lb/in. ³
RF	Fuel density, lb/in. ³
RI	Insulation density, lb/in. ³
RS	Shield density, lb/in. ³
RSH	Shell density, lb/in. ³
SE	Shield material correlating exponent, nd
SF	Stress safety factor (plutonium capsule calculation), nd
SHELDX	Shield thickness factor (half shield, quarter shield, etc.),nd
SHELDX	Subroutine name for calculating shield thickness
TC	Reference external temperature, °F
TH	Hot junction temperature, °F
THI	Initial hot junction temperature, °F
THMAX	Maximum hot junction temperature, °F
TIME	Mission time, years
TITLE	Problem identification

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VOLF	Fuel volume, in. ³
WSH	Shell weight, lb
WTC	Cladding weight, lb
WTF	Fuel weight, lb
WTI	Insulation weight, lb
WTS	Shield weight, lb
WTT	Total weight, lb
XACLAD	Cladding end thickness, in. (subscripted)
XACLD	Cladding end thickness, in. (nonsubscripted)
XCLAD	Cladding radial thickness, in. (subscripted)
XCLD	Cladding radial thickness, in. (nonsubscripted)
XINS	Insulation thickness, in.
XM	Floating point M
XMIN	Minimum permissible cladding thickness with plutonium fuel, in.
XSHELD	Shield thickness, in.
XSHELL	Shell thickness, in.

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3. TEHE Equations3.1 Main Program(η = ETA in glossary).

Thermal power to thermoelectric unit, Btu/hr

$$Q_{te} = 3.415 P_{syst} / \eta_{sys}$$

Heater thermal power (end of life), Btu/hr

$$Q_{tl} = Q_{te} + Q_{loss}$$

Heater thermal power (beginning of life), Btu/hr

$$Q_{tlb} = Q_{tl} \text{ Lamda} \cdot \text{Time}$$

Fuel volume, in. ³

$$\text{Vol}_f = Q_{tlb} / (Q_{den} \times \text{Pack})$$

Inside insulation diameter, in.

$$D_{ii} = D_f + \text{Clear}_d + 2(X_{clad} + X_{shield})$$

Inside insulation length, in.

$$L_{ii} = L_f + \text{Clear}_a + 2(X_{aclad} + X_{shield})$$

Overall heater length, in.

$$L_{max} = L_{ii} + 2 (X_{ins} + X_{shell})$$

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Convergence criteria, nd.

$$\text{Conv} = \left| \frac{Q_{t2} - Q_{t1}}{Q_{t1}} \right| = .001$$

Heater efficiency, nd.

$$\eta_q = 1 - Q_{\text{loss}}/Q_{t1}$$

Net electrical efficiency (end of life), nd.

$$\eta_b = 3.415 P_{\text{syst}}/Q_{t1b}$$

3.2 Subroutines

Thermoelectric system efficiency, nd.

$$\eta_{\text{sys}} = E_1 + E_2 T_h + E_3 T_h^2 + E_4 T_h^3 + E_5 T_h^4 \quad (\text{from Bridging Curves})$$

Capsule dimensions, in.

Given: Vol_f , L/D , X_{clad} , X_{aclad} , Clear , Clear_a

Refer to Figure I-A-4 and page I-A-14 for description of dimensions.

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$$\text{Vol}_f = \frac{\pi}{4} D_f^2 L_f = \frac{\pi}{4} D_f^3 (L/D)_f$$

$$L/D = \frac{L_f + \text{Clear}_a + 2X_{\text{aclad}}}{D_f + \text{Clear} + 2X_{\text{clad}}}$$

$$(L/D)_f = (L/D) \left(1 + \frac{\text{Clear}}{D_f} + \frac{2X_{\text{clad}}}{D_f} - \frac{\text{Clear}_a}{D_f} - \frac{2X_{\text{aclad}}}{D_f} \right)$$

$$\text{Vol}_f = \frac{\pi}{4} D_f^3 \left[(L/D) \left(1 + \frac{\text{Clear}}{D_f} + \frac{2X_{\text{clad}}}{D_f} \right) - \frac{\text{Clear}_a}{D_f} - \frac{2X_{\text{aclad}}}{D_f} \right]$$

$$\frac{4}{\pi} \text{Vol}_f = D_f^3 (L/D) + D_f^2 \left[(L/D) (\text{Clear} + 2X_{\text{clad}}) - \text{Clear}_a - 2X_{\text{aclad}} \right]$$

$$\text{i.e., } AD_f^3 + BD_f^2 + CD_f + D + E = 0$$

where

$$A = L/D, B = (L/D) (\text{Clear} + 2X_{\text{clad}}) - \text{Clear}_a - 2X_{\text{aclad}}$$

$$C = 0, E = - \frac{4 \text{Vol}_f}{\pi}$$

$$\text{or } D_f^3 + bD_f^2 + cD_f + d = 0$$

where $b = B/A$

$$c = 0$$

$$d = E/A$$

Solution to cubic:

$$D_d = y - b/3 \text{ where } y = \alpha + \beta$$

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where
$$\alpha = \left[\frac{-q + \sqrt{q^2 + \frac{4p^3}{27}}}{2} \right]^{1/3}$$

$$\beta = \left[\frac{-q - \sqrt{q^2 + \frac{4p^3}{27}}}{2} \right]^{1/3}$$

where
$$p = c - \frac{b^2}{3} = -\frac{b^2}{3}$$

$$q = d - \frac{bc}{3} + \frac{2b^3}{27} = d + \frac{2b^3}{27}$$

Shield thickness, in.

$$Q_{tlb} = A e^{\Phi(X_{\text{shield}})^{1/SE}}$$

$$\ln(Q_{tlb}/A) = \Phi(X_{\text{shield}})^{1/SE}$$

$$\left[\frac{\ln(Q_{tlb}/A)}{\Phi} \right]^{SE} = X_{\text{shield}}$$

For partial shields (half shields, quarter shields, etc.)

$$X_{\text{shield}} = F_{\text{shield}} \left[\frac{\ln(Q_{tlb}/A)}{\Phi} \right]^{SE}$$

Mean insulation area to inside area ratio

Curve fit of Figure 2-2, McAdam's Heat Transmission* gives:

$$\frac{A_m}{A_i} = \frac{2\pi X_{\text{ins}} (L_{ii} + .9 X_{\text{ins}})}{\ln\left(\frac{d_o}{d_i}\right)} + \frac{\pi}{2} D_{ii}^2$$

* W. H. McAdams, Heat Transmission, 3rd Edition, McGraw-Hill Book Company, Inc., N.Y. 1954, p. 14.

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Inside insulation area:

$$A_1 = \pi D_{ii} L_{ii} + \frac{\pi}{2} D_{ii}^2$$

Area ratio:

$$AMAI = \bar{A}_m / A_1 = \frac{D_{ii}}{2L_{ii} + D_{ii}} \left[\frac{4X_{ins}(L_{ii} + .9X_{ins})}{D_{ii}^2 \ln(1 + \frac{2X_{ins}}{D_{ii}})} + 1 \right]$$

See Figure A-4 for plot of correlation. The above is valid for $X_{ins}/D_{ii} \leq 2.0$.

For $X_{ins}/D_{ii} > 2.0$, use concentric sphere approximation.

Assuming the spheres have the same area as the cylinders they replace:

$$A_{cyl 1} = \pi D_{ii} L_{ii} + \frac{\pi}{2} D_{ii}^2$$

$$A_{cyl 2} = \pi (D_{ii} + 2X_{ins})(L_{ii} + 2X_{ins}) + \frac{\pi}{2} (D_{ii} + 2X_{ins})^2$$

$$\text{For spheres } \bar{A}_m = \sqrt{A_1 A_2}$$

$$\therefore AMA1 = \bar{A}_m / A_1 = \frac{\sqrt{A_1 A_2}}{A_1}$$

$$AMA1 = \left[\frac{2(D_{ii} + 2X_{ins})(L_{ii} + 2X_{ins}) + (D_{ii} + 2X_{ins})^2}{2D_{ii}L_{ii} + D_{ii}^2} \right]^{1/2}$$

$$AMA1 = \left[1 + \frac{4X_{ins}(L_{ii} + 2D_{ii} + 3X_{ins})}{2D_{ii}L_{ii} + D_{ii}^2} \right]$$

See Figure A-4; above good for $X_{ins}/D_{ii} > 2.0$

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FIGURE A-4. CORRELATION: A_m/A_1 VERSUS X/D

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Mean thermal conductivity, Btu/hr-in- $^{\circ}\text{F}$

$$\bar{k}_m = B_1 e^{B_2 T_h}$$

B_1 and B_2 are correlating constants.

Heater structural loss, Btu/hr

From correlation of typical heater losses:

$$Q_s = C_m (T_h - T_c) (D_{\max})^{EL}$$

Total heater loss, Btu/hr

$$Q_{\text{loss}} = \bar{k}_m \cdot \bar{A}_m (T_h - T_c) / X_{\text{ins}} + Q_s$$

where

$$\bar{A}_m = A_1 \cdot AMA1$$

Volume between concentric right cylinders, in.³

$$V = \frac{\pi}{4} (D_2^2 L_2 - D_1^2 (L_2 - 2X))$$

where
$$X = \frac{L_2 - L_1}{2}$$

Volume between rounded external cylinder and right internal cylinder, in.³

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$$V_s = Vol_1 - V_2 - (Vol_3 - Vol_4)$$

where

Vol_1 = circumscribed volume right cylinder

Vol_2 = inscribed volume right cylinder

Vol_3 = square corner area $\times D_{c.g.}$

Vol_4 = semicircular corner area $\times D_{c.g.}$

$$Vol_1 = \frac{\pi}{4} (D_i + 2X_{shield})^2 (L_i + 2X_{shield})$$

$$Vol_2 = \frac{\pi}{4} D_i^2 L_i$$

$$Vol_3 = 2X_{shield}^2 \pi (D_i + X_{shield})$$

$$Vol_4 = \frac{\pi X_{shield}^2}{2} \pi (D_i + \frac{8X_{shield}}{3\pi})$$

$$V_s = \frac{\pi}{4} \left[D_2^2 L_1 - D_1^2 (L_1 - 2X_{shield}) \right] + \frac{\pi^2 X_{shield}^2}{2} (D_1 + \frac{8X_{shield}}{3\pi})$$

Material weight, lb

$$Wt = \rho_m \cdot Vol_m$$

where Vol_m is material volume determined by appropriate volume equation from above.

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4. Plutonium Capsule Design Subroutine

The capsule design for any alpha emitter must provide volume to accommodate the helium generation and consequent pressure buildup. For the general case, the capsule will ultimately fail due to stress rupture resulting from the helium buildup; however the stress and temperature of the capsule are time-dependent so that the normal constant temperature/constant stress experimental data cannot be applied. The time to stress rupture is quite dependent on material temperature. A method has been developed in which the capsule is so designed that the stress is low during the high temperature period and so that the temperature is relatively low during the period of high pressure so that an extremely long containment time is obtained (greater than ten half-lives). The calculational technique optimizes the capsule for minimum weight and near minimum volume within the confines of long-term capsule integrity, while accounting for the temperature-dependent stress rupture properties of the capsule material .

4.1 Summary of Calculational Procedure

The plutonium capsule is assumed to fail by stress rupture. A Larson-Miller parameter curve based on stress rupture data for Hastelloy C was reported by R. Baciarelli* in the following parametric form:

$$LM = (T+460) (\log_{10} t + (15.435))$$

where T = temperature, $^{\circ}F$
 t = time, hr

The technique for developing the stress rupture equation using the Larson-Miller parameter was derived by Forrest** for tungsten. Similarly, the following equation was developed for stress rupture of Hastelloy-C using the Larson-Miller plot of Baciarelli (*ibid*).

* Internal communication: R. Baciarelli, "Larson-Miller Parameter for Hastelloy-C", AGN Memo AN-Met-359, 5 January 1966.

** Internal communication: D. Forrest, "Design of a Long Containment Life Pu-238 Radioisotope Capsule for Isotope Intermittent Space Thrusters", AGN Memo SD-292, 5 January 1966.

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$$2.72 \times 10^{15} \left(\frac{\sigma}{10^{10.45}} \right)^{\frac{10470}{T}} t_f = 1 \quad \text{For } \sigma < 10^5 \text{ psi}$$

This equation may be rewritten in integral form as follows:

$$\int_0^{t_f} 2.72 \left(\frac{\sigma}{10^{10.45}} \right)^{\frac{10470}{T}} dt = 1$$

where σ = stress, psi t = time, hours

t_f = time to rupture, hr

T = temperature, $^{\circ}\text{R}$

The capsule environmental factor b is defined as:

$$b = \frac{1}{\sigma} (1 - e^{-\lambda t}) T$$

where

σ = stress

λ = decay constant

t = time

$T = e^{-\lambda t} T_0$

T_0 = initial temperature

For $T_0 \leq 1600^{\circ}\text{R}$ the minimum permissible environmental factor is defined as:

$$b_{\min} > \left[\frac{(1 - e^{-\lambda t}) T}{\sigma_{\max}} \right]_{\max}$$

$$\left[(1 - e^{-\lambda t}) T \right]_{\max} = 1/4 T_0$$

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$$\sigma_{\max} \approx 10^5 \text{ psi}$$

$$b_{\min} = f \frac{T_o}{4 \times 10^5}$$

where

f = safety factor

For $T_o > 1600^\circ\text{R}$, numerical integration of equation 1 gives the following results for a long life capsule (greater than 10-half lives).

<u>T</u>	<u>b_{min}</u>
1600 ^o R	0.004
1700 ^o R	0.0056
1800 ^o R	0.0090
2000 ^o R	0.0200

This can be fitted to the equation

$$b = \frac{1}{4 \times 10^5} \left\{ T_o + 1.4 (T_o - 1600) + 0.042 - (T_o - 1600)^2 \right\} - 2 \times 10^{-5} (T_o - 1600)$$

For PuO_2 (from D. Forrest*)

$$\sigma = \frac{\frac{x^2+1}{x^2-1} \cdot \frac{23.3}{\frac{k_2}{x^2-1}}}{x^2} (1 - e^{-\lambda t}) T$$

$$\text{or } k_2 = \left[23.3b \frac{\frac{x^2-1}{x^2+1}}{\frac{x^2-1}{x^2+1}} + 1 \right] x^2 \quad \text{where } x = \frac{D_s}{D_i}$$

$$\text{or } k_2 = \left[b_o \frac{\frac{x^2-1}{x^2+1}}{\frac{x^2-1}{x^2+1}} + 1 \right] x^2 \quad (2)$$

* Internal communication: D. Forrest, "The Design of a Pu-238 Capsule for an Intermittent Thruster", AGN Memo SD-291, 30 December 1965.

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$$\text{also } k_2 = \frac{\pi D_s^2 L_s}{0.0524 P_o}$$

where

L_s = capsule length (less end caps), in.

D_s = capsule OD, in.

D_i = capsule ID, in.

P_o = capsule initial power, watts

$b_o = Bb$

B = material constant (23.3 for PuO_2)

$$\text{Similarly, } \sigma_e = \frac{k_2 D_i^2}{4 t_e^2} P_i$$

where

$k = 1.245$ (conservative from end cap stress equation for simply supported case)

t_e = end cap thickness

σ_e = stress, end cap

For $\sigma_e = \sigma$

$$\frac{\frac{x^2+1}{2} - 1}{x^2 - 1} = \frac{k D_s^2}{4 x^2 t_e^2}$$

Let $L_o = L_s + 2t_e$ = capsule length

Assume

$$\frac{L_o}{D} = 1.2$$

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$$\frac{V}{P_o} = \frac{\pi}{4} \frac{D_s^2 L_o}{P_o} = \frac{\pi D_s^2 L_s}{0.0524 P_o} \frac{0.0524}{4} \frac{L_o}{L_s}$$

where

V = total capsule volume

from above, $L_s = L_o - 2 t_e$

$$\frac{V}{P_o} = 0.0131 K_2 \frac{1}{1 - 2 \frac{t_e}{L_o}} = .0131 K_2 \frac{1}{1 - 2 \frac{t_e}{D_s} \frac{1}{(L_o/D_s)}}$$

$$\frac{2 t_e}{D_s} = \sqrt{\frac{k}{x^2} \left(\frac{x^2 - 1}{x^2 + 1} \right)}$$

therefore

$$\frac{V}{P_o} = \frac{.0131 \left[b_o \frac{x^2 - 1}{x^2 + 1} + \right] x^2}{1 - \frac{1.116}{1.2} \sqrt{\frac{x^2 + 1}{x^2 (x^2 - 1)}}} = \frac{.0131 \left[b_o \frac{x^2 - 1}{x^2 + 1} + \right] x^2}{1 - .930 \sqrt{\frac{x^2 - 1}{x^2 (x^2 - 1)}}}$$

Relating clad weight to total volume,

$$\begin{aligned} \frac{wt}{\rho} &= \frac{\pi}{4} D_s^2 L_o - \frac{\pi}{4} D_i^2 L_s \\ &= V \left[1 - \frac{D_i^2 L_s}{D_s^2 L_o} \right] \end{aligned}$$

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$$\begin{aligned}
 &= V \left[1 - \frac{1}{x^2} \left(1 - \frac{2 t_e}{L_o} \right) \right] \\
 &= V \left[1 - \frac{1}{x^2} \left(1 - .930 \sqrt{\frac{x^2+1}{x^2(x^2-1)}} \right) \right] \\
 &= \frac{V}{x^2} \left[(x^2-1) + .930 \sqrt{\frac{x^2+1}{x^2(x^2-1)}} \right]
 \end{aligned}$$

Now desirable for V to be near minimal

$\therefore K_2 \approx \min$ (where K_2 is the capsule volume (less end caps) divided by crystalline fuel volume)

From equation 2, the value of x^2 for $K_2 = \min$ is

$$x^2 = \sqrt{\frac{2 b_o}{1+b_o}} + 1$$

Over the range of interest K_2 does not vary significantly over the range of

$$0.8 \left(\frac{2 b_o}{1+b_o} + 1 \right) < x^2 < \sqrt{\frac{2 b_o}{1+b_o}} + 1$$

but weight decreases as x^2 decreases (from Forrest*)

$$\text{therefore } x^2 \approx .8 \left[\sqrt{\frac{2 b_o}{1+b_o}} + 1 \right]$$

for minimum weight and near minimum volume.

* Internal communication: D. Forrest, "The Design of a Pu-238 Capsule for an Intermittent Thruster", AGN Memo SD-291, 30 December 1965.

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Finally,

$$\frac{V}{D_s} = \frac{\pi}{4} D_s^2 L_o = 1.2 \frac{\pi}{4} D_s^3$$

$$D_s = \left(\frac{4}{1.2\pi} V \right)^{1/3}$$

4.2 Method For Calculating Source Weight and Size (TEHE Equations)

Given P_o, T_o, t wall min

$$\frac{L_o}{D_s} = 1.2$$

determine b

For

$$T_o \leq 1600^\circ R$$

$$b = \frac{f T_o}{4 \times 10^5}$$

T_o = initial temperature

f = safety factor

For $T_o > 1600^\circ R$

$$b = \frac{f}{4 \times 10^5} \left[T_o + 1.4 (T_o - 1600) + .042 (T_o - 1600)^2 + 2 \times 10^{-5} (T_o - 1600)^3 \right]$$

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determine b_o

$$b_o = B_b$$

PuO_2

$$b_o = 23.3b$$

$$b_o = 40.0b$$

Pu metal

determine x_o^2

$$x_o^2 = .8 \left(1 + \sqrt{\frac{2 b_o}{1 + b_o}} \right)$$

determine D_s

$$D_s = \left[\frac{4}{\pi 1.2} \frac{.0157 \left[b_o \frac{x_o^{2+1}}{x_o^{2-1}} + 1 \right] x_o}{1.2 - 1.116 \sqrt{\frac{x^2-1}{x^2+1}} \frac{1}{x^2}} \right] P_o^{1/3}$$

let

$$\frac{x_o^{2-1}}{x_o^{2+1}} \frac{1}{x_o^2} = C_o = \frac{1}{\emptyset} \frac{1}{x_o^2}$$

$$D_s = \left[\frac{K_o \left[\frac{b_o}{C_o} + x_o^2 \right]}{1 - .930 C_o^{1/2}} \right]^{1/3} P_o^{1/3}$$

where

$$K_o = .01315 \quad \text{PuO}_2$$

$$K_o = .00735 \quad \text{Pu metal}$$

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determine x^2

$$x^2 = \left(1 - \frac{2 t_m}{D_s}\right)^{-2}$$

where

t_m = minimum side wall thickness

determine wt

$$wt = 1.2 \frac{\pi}{4} D_x^3 \left[(x_1^2 - 1) + .930 C^{\frac{1}{2}} \right] \rho$$

where

$$C = \frac{x^2 - 1}{x^2 + 1} \frac{1}{x^2} \quad \left. \vphantom{\frac{x^2 - 1}{x^2 + 1}} \right\} \text{ if } \left(\frac{x}{x_o}\right)^2 > 1$$

$$x_1^2 = x^2$$

$$c = c_o$$

$$\left. \vphantom{c = c_o} \right\} \text{ if } \left(\frac{x}{x_2}\right)^2 < 1$$

$$x_1^2 = x_o^2$$

determine thickness

$$t_e = .558 C^{\frac{1}{2}} D_s$$

$$t_s = \frac{D_s}{2} \left(\frac{x_1 - 1}{x_1} \right)$$

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5. TEHE Program Statement and Input Format

The input card formats are described on the next page: A typical TEHE program statement is included on the following pages.

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Input Cards

	<u>Columns</u>	<u>Data</u>	<u>Format</u>
<u>Card 1</u>	1-72	Any alphanumeric problem identification	A
<u>Card 2</u>	1-8	Net electric power output, watts	F
	9-16	Mission life, yr	F
	17-24	Length/diameter ratio, nd	F
	25-28	Fuel material designation number, nd	I
	29-32	Clad material designation number, nd	I
	33-36	Shield material designation number, nd (input 1 if no shield)	I
	37-40	Insulation material designation number, nd	I
	41-44	Shell material designation number, nd	I
<u>Card 3</u>	1-8	Overall diameter initial value, in.	F
	9-16	Overall diameter increment, in.	F
	17-24	Hot junction temperature initial value, °F	F
	25-32	Hot junction temperature increment value, °F	F
	33-40	Hot junction temperature maximum value, °F	F
	41-48	Cold junction (environment) temperature, °F	F
<u>Card 4</u>	1-8	Diametral clearance fuel-to-clad, in. (can be blank for Pu)	F
	9-16	Axial clearance fuel-to-clad, in. (can be blank for Pu)	F
	17-24	Radial clad thickness, in. (minimum permissible clad for Pu)	F
	25-32	Axial clad thickness, in. (blank for Pu)	F
	33-40	External shell thickness, in.	F
	41-48	Shield factor = 1 for full shield, 0.5 for half shield, etc. (= 0. for Pu)	F
	49-56	Safety factor for Pu clad calculation (blank for other fuels)	F
<u>Card 5</u>	1-8	First term (A) of five term thermoelectric efficiency polynomial, nd. $\eta_{tc} = A + Bt + Ct^2 + Dt^3 + Et^4$ where t = hot junction temperature, °F	E

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9-16 Second term (B) of five term efficiency E
 polynomial

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"

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33-40 Fifth term (E) of five term efficiency polynomial E

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$JOB          TEHE      1/FEB/66      ROCKWELL      AGN
$EXECUTE      IBJOB
$IBJOB        MAP
$IBFTC TEHE
C  THERMELECTRIC HEATER EVALUATION - TEHE      ROCKWELL      1 FEB 66
C  MATERIAL DESIGNATION
C  FUEL 1 PU OXIDE      CLAD 1 HAST-C      INSUL 1 MIN-K
C  FUEL 2 PU METAL      INSUL 2 SUPER LINDE
C  FUEL 3 SR TIO3      SHIELD 1 U(DEPLETED)
C  FUEL 4 SR(SPECIAL)
C  FUEL 5 PM203      SHELL 1 304-SS
C *****
C  NOTE THAT SUBROUTINE PLUTO IS BASED ON HAST-C CLAD AND MUST BE
C  MODIFIED FOR OTHER CLAD MATLS.
C *****
C  DIMENSION TITLE(12),TH(100),DF(100),LF(100),XINS(100),DC(100),
C  1LC(100),WTT(100),WTF(100),WTC(100),WTS(100),WTI(100),WTSH(100),
C  2RF(10),RC(5),RS(5),RI(5),RSH(5),B1(5),B2(5),A(5),PHI(5),PACK(10),
C  3QDEN(10),SE(10),LAMDA(10),XSHELD(50),XCLAD(50),XACLAD(50),CLEARA
C  4(50)
C  REAL LF,LD,LII,LMAX,LC,LAMDA
C *****
C  LAMDA=0.693/HALF LIFE
C *****
C  PHI(3) AND A(3) ASSUME DEPLETED URANIUM SHIELD AND SPECIFIED DOSE
C  WHEN CALCULATING SHIELD THICKNESS.
C *****
C  DATA (RF(I),QDEN(I),PACK(I),LAMDA(I), SE(I),PHI(I),A(I),I=1,5)/
C  1.414,249.8,.75,.00773,1.  ,1.,1.,.578,412.2,1.,.00773,1.  ,1.,1.,
C  2.185,62.54,.75,.025,1.  ,2.95,.04849,.153,75.58,.9,.025,1.  ,1.000,
C  31.000,.264,110.6,.90,.2645,3.106,9.36,.06147/
C  DATA (B1(I),B2(I),RI(I),I=1,2)/.0010667,.000207,.01157,.0000034,
C  1.00225,.01157/
C  DATA RC(1),RSH(1),RS(1),PI/.323,.282,.672,3.141593/
C *****
C  STRUCTURAL GLOSS
C  DATA CM,EL/.005123,1.43/
C *****
C  LOOP DIAGNOSTICS
C  DATA LP,MP,NP/1HL,1HM,1HN/
C *****
C  100 READ (5,200) TITLE,PSYST,TIME,LD,MF,MC,MS,MI,MSH,DMAX,DELTAD,THI,
C  1DTH,THMAX,TC,CLEAR,CLRA,XCLD,XACL,D,XSHELL,SHELD,SF,E1,E2,E3,E4,E5
C  WRITE (6,300) TITLE
C  XMIN=XCLD
C  LX=50
C  MX=50
C  IM=2
C  IL=1
C  DO 103 I=1,50
C  CLEARA(I)=CLRA
C  XCLAD(I)=XCLD
C  103 XACLAD(I)=XACL,D
C  IF( DELTAD.EQ.0.) LX=1
C  IF(DTH.EQ.0.) MX=1
C *****
C  DO 140 L=1,LX

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      GO TO 107
105 WRITE (6,309)
      DMAX=DMAX+DELTAD
      DELTAD=DELTAD/10.
      IL=2
107 ETA=0.
      IF(L.EQ.1) DMAX=DMAX+DELTAD
      DMAX=DMAX-DELTAD
      WRITE (6,301) DMAX
      WRITE (6,302)
      MB=1
      KICK=2
C*****
      DO 130 M=1,MX
      XM=M
      TH(M)=THI+(XM-1.)*DTH
      CALL BRIDGE (ETASYS,TH(M),E1,E2,E3,E4,E5)
      QTE=PSYST/ETASYS*3.415
      QT1=QTE
C*****
      DO 110 N=1,50
      QT1B=QT1*EXP(LAMDA(MF)*TIME)
      VOLF=QT1B/QDEN(MF)/PACK(MF)
      CALL CAPSUL (DF(M),LF(M),PI,MF,VOLF,LD,CLEAR,CLEARA(M),XCLAD(M),
1XACLAD(M),QT1B,TH(M),XMIN,SF)
      CALL SHELDF (M,N,MS,PHI(MF),XSHELD(M),A(MF),QT1B,SHELD,SE(MF))
      XINS(M)=(DMAX-DF(M)-CLEAR)/2.-XCLAD(M)-XSHELD(M)-XSHELL
      IF(XINS(M).LE.0.) GO TO 125
      DII=DF(M)+CLEAR+(XCLAD(M)+XSHELD(M))*2.
      LII=LF(M)+CLEARA(M)+(XACLAD(M)+XSHELD(M))*2.
      LMAX=LII+(XINS(M)+XSHELL)*2.
      CALL QLOS (QLOSS,B1(M),B2(M),PI,DII,XINS(M),LII,TH(M),TC,EL,QINS
1,CM)
      QT2=QTE+QLOSS
      CONV=ABS(QT2-QT1)/QT1
      IF(CONV.LT..001) GO TO 12
      IF(N.EQ.50) WRITE (6,306) NP
110 QT1=QT2
C*****
120 ETAQ=1.-QLOSS/QT1
      ETAE=ETASYS*ETAQ
      ETAB=PSYST*3.415/QT1B
      MAX=M
      WRITE (6,303) TH(M),ETAB,ETAE,ETAQ,ETASYS,QT1,QLOSS,QINS
      CALL WEIGHT (PI,WTT(M),WTF(M),WTC(M),WTS(M),WTI(M),WTSH(M),RF(MF),
1RC(MC),RS(MS),RI(MI),RSH(MSH),XCLAD(M),XACLAD(M),XSHELD(M),
2XINS(M),XSHELL,MF,DMAX,LMAX,VOLF,PACK(MF))
      IF(ETAE.LT.ETA .OR. TH(M).GE.THMAX) GO TO 135
      IF(M.EQ.50) WRITE (6,306) MP
      ETA=ETAE
      KICK=1
      GO TO 130

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125 IF(IL.EQ.1) GO TO 105
    WRITE (6,305)
    IF (KICK.EQ.2) MB=M+1
    IF (TH(M).GE.THMAX) GO TO(139,138),IM
130 CONTINUE
C*****
135 WRITE (6,304) (TH(M),DF(M),LF(M),CLEAR,CLEARA(M),XCLAD(M),XACLAD(M),
    1,XSHELD(M),XINS(M),XSHELL,M=MB,MAX)
    WRITE (6,307) (TH(M),WTT(M),WTF(M),WTC(M),WTS(M),WTI(M),WTSH(M),M=M
    1B,MAX)
    IF (L.EQ.50) WRITE (6,306) LP
    GO TO 140
138 LIM=L+5
    IM=1
139 IF(KICK.EQ.2) GO TO 150
    IF(L.GE.LIM) GO TO 150
    GO TO 135
140 CONTINUE
C*****
    GO TO 100
150 WRITE (6,308)
    GO TO 100
C*****
200 FORMAT (12A6/3F8.0,5I4/6F8.0/7F8.0/5E8.4)
C*****
300 FORMAT (1H1,12A6)
301 FORMAT(/15H00OVERALL DIA. =,F8.4,4H IN.)
302 FORMAT(7H0 THJ,8H BOLEFF,8H EOLEFF,2(5X3HEFF),4X8HHEAT GEN,
    13X9HHEAT LOSS,4X8HHEAT INS,7H DEG F,2(5X3HNET),5X3HHTR,6X2HTE,3(6
    2X6HBTU/HR))
303 FORMAT(1H ,F6.0,4F8.4,3E12.5)
304 FORMAT(7H0 THJ, 4X4HDIA.,2X6HLENGTH ,2(3X5HCLEAR),5(3X5HTHICK)/
    17H DEG F,2(4X4HFUEL),4X4HDIA.,3X5HAXIAL,4X4HCLAD,8H ENDCLAD,2X6HS
    2HIELD,3X5HINSUL,3X5HSHELL/7X9(6X2HIN)/(F7.0,9F8.4))
305 FORMAT(76H INSUL THICK .LE. ZERO DUE TO SMALL OVERALL DIA. CONTIN
    1UE TO NEXT THJ VALUE)
306 FORMAT( 6H LOOP ,A1,55H REACHED MAXIMUM INDEX VALUE. POTENTIAL ER
    1ROR FOLLOWS.)
307 FORMAT(7H0 THJ,6(2X6HWEIGHT)/2X5HDEG F,3X5HTOTAL,4X4HFUEL,4X4HCL
    1AD,2X6HSHIELD,3X5HINSUL,3X5HSHELL/7X6(6X2HLB)/(F7.0,6F8.4))
308 FORMAT (77H INSUL THICK STILL .LE. ZERO AT SPECIFIED MAX THJ SO CO
    1NTINUE TO NEXT PROBLEM)
309 FORMAT(79H0INSUL THICK .LE. ZERO DUE TO SMALL OVERALL DIA. RESET
    1DELTAD TO 1/10TH DELTAD)
C*****
    END
$IBFTC BRDG
    SUBROUTINE BRIDGE (Y,X,A,B,C,D,E)
    Y=A+B*X+C*X**2+D*X**3+E*X**4
    RETURN
    END
$IBFTC CPSL
    SUBROUTINE CAPSUL (DF,LF,PI,MF,VF,LD,CD,CA,XR,XA,Q,T,XM,SF)

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REAL LD,LF
IF (MF.EQ.1) GO TO 5
IF (MF.EQ.2) GO TO 5
C3=0.-4.*VF/PI
C1=LD
C2=LD*(CD+2.*XR)-CA-2.*XA
DF=ROOT(C1,C2,C3)
LF=LD*(DF+CD+2.*XR)-CA-2.*XA
GO TO 10
5 CALL PLUTO (Q,T,XM,SF,LD,VF,MF,XA,XR,DF,LF,CD,CA)
10 RETURN
END
$IBFTC RT
REAL FUNCTION ROOT (C1,C2,C3)
B=C2/C1
D=C3/C1
P=0.-B**2/3.
Q=D+2.*B**3/27.
QN=0.-Q
RT=SQRT(Q**2+4.*P**3/27.)
ALPHA=((QN+RT)/2.)*.33333
BETA=((QN-RT)/2.)*.33333
Y=ALPHA+BETA
ROOT=Y-B/3.
RETURN
END
$IBFTC PLUT XR7,M94
SUBROUTINE PLUTO(PQ,TO,IM,F,ELOD,VF,NPF,TE,TS,DF,FL,CLR,CLRA)
REAL KO
C INPUT NPF=1 FOR PUO2 OR NPF=2 FOR PU METAL
C STRESS CALC BASED ON HASTELLOY-C STRESS RUPTURE DATA
PQ=PQ/3.413
GO TO (1,2),NPF
C CONSTANTS FOR PUO2
1 B1=23.3
KO=.01668
GO TO 3
C CONSTANTS FOR PU METAL
2 B1=40.
KO=.00882
3 TO=TO+460.
IF (TO.LE.1600.) GO TO 10
Z=TO-1600.
B=.25E-5*(TO+1.4*Z+.042*Z**2-2.E-5*Z**3)*F
GO TO 11
10 B=.25E-5*F*TO
11 BQ=B1*B
XO2=.8*(1.+SQRT(2.*BQ/(1.+BQ)))
PHI=(XO2+1.)/(XO2-1.)
TOP=PQ*KO*XO2*(BQ*PHI+1.)
BOT=ELOD-1.116*SQRT(1./PHI/XO2)
DS=(TOP/BOT)**.333333

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X2=1./((1.-2.*TM/DS)**2
XR=X2/X02
IF (XR.LE.1.) GO TO 20
C=(X2-1.)/(X2+1.)/X2
X12=X2
GO TO 22
20 C=1./PHI/X02
X12=X02
22 IE=.558*SQRT(C)*DS
X1=SQRT(X12)
TS=.5*DS*(1.-1./X1)
CLR=0.0
DF=DS/X1 -CLR
FL=1.27324*VF/DF**2
CLRA=DS*ELOD-2.*TE-FL
TO=TO-460.
PO=PO*3.413
RETURN
END
$IBFTC SHLD
SUBROUTINE SHELDX (M,N,MS,PHI,X,A,Q,SF,C)
IF (M.NE.1. OR.N.NE.1) GO TO 5
IF (MS.LT.0.OR.MS.GT.5) PRINT 10
5 X=0.
IF (MS.NE.0) X=SF*(ALOG(Q/A)/PHI)**C
10 FORMAT (49H0INCORRECT SHIELD DESIGNATION. XSHIELD SET TO 0. /)
RETURN
END
$IBFTC QL
SUBROUTINE QLOS (QL,B1,B2,PI,D,X,L,TH,TC,C,QI,A)
REAL L
A1=PI*D*(L+D/2.)
XD=X/D
IF (XD.LT.2.) GO TO 10
AM1=SQRT(4.*X*(L+3.*X+2.*D)/D/(2.*L+D)+1.)
GO TO 20
10 AM1=D/(2.*L+D)*(4.*X*(L+.9*X)/D**2/ALOG(1.+2.*X/D)+1.)
20 AM=AM1*A1
QI=COND(B1,B2,TH)*AM*(TH-TC)/X
QS=A*(TH-TC)*D**C
QL=QI+QS
RETURN
END
$IBFTC CON
REAL FUNCTION COND (B1,B2,TH)
COND=B1*EXP(B2*TH)
RETURN
END
$IBFTC WGHT
SUBROUTINE WEIGHT (PI,WT,F,C,S,I,SH,RF,RC,RS,RI,RSH,XC,XAC,XS,XI,
1XSH,MF,D5,L3,VF,PK)
REAL L1,L2,L3,I
D4=D5-XSH*2.

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D3=D4-XI*2.
D2=D3-XS*2.
D1=D2-XC*2.
L2=L3-2.*XSH
L1=L2-2.*XI-2.*XS
F=RF*VF*PK
C=RC*V(PI,D2,D1,L1,XAC)
S=RS*VS(PI,D3,D2,L1,XS)
I=RI*V(PI,D4,D3,L2,XI)
SH=RSH*V(PI,D5,D4,L3,XSH)
WT=F+C+S+I+SH
RETURN
END
$IBFTC VOL
REAL FUNCTION V(PI,D2,D1,Y,X)
V=PI/4.*(D2**2*Y-D1**2*(Y-2.*X))
RETURN
END
$IBFTC VOLS
REAL FUNCTION VS(PI,D2,D1,Y,X)
VS=PI/4.*(D2**2*Y-D1**2*(Y-2.*X))+(PI*X)**2/2.*(D1+8.*X/3./PI)
RETURN
END
$DATA
```

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APPENDIX I-B

OPTIMUM CAPSULE LENGTH-TO-DIAMETER RATIOS

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APPENDIX I-B

OPTIMUM CAPSULE LENGTH-to-DIAMETER RATIO

A parametric study was completed to determine the optimum capsule length-to-diameter (L/D) ratio for minimum system weight and maximum thermal efficiency. The effect of L/D variation is most pronounced with heavily shielded systems, i.e., the light plutonium systems are relatively insensitive to L/D for practical purposes. Accordingly, the effect of capsule L/D on the full shield strontium titanate and promethium oxide systems was investigated using the TEHE computer program. The results are summarized in Figures B-1 and B-2. The results show that minimum weight and maximum efficiency are about the same throughout an L/D range of 1.0 to 1.5. Accordingly, a capsule L/D of 1.2 was selected as optimum and used throughout the parametric study.

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FIGURE B-1. EFFECT OF L/D ON SrTiO_3 SYSTEM

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FIGURE B-2. EFFECT OF L/D ON Pm_2O_3 SYSTEM

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APPENDIX I-C

SELECTION OF COLD JUNCTION TEMPERA-
TURE FOR THE PARAMETRIC STUDY

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SELECTION OF COLD JUNCTION TEMPERATURE
FOR THE PARAMETRIC STUDY

Heat is transferred by natural convection and radiation from a hot surface surrounded by still air. Radiation is an important factor in the loss of heat from surfaces where the gas movement is due to natural convection, except in the case of small wires. Heat transfer may be expressed as

$$q = (h_c + h_r) A_s (T_s - T_a)$$

where:

q	=	heat transfer rate
h_c	=	natural convection heat transfer coefficient
h_r	=	radiation heat transfer coefficient
A_s	=	surface area
T_s	=	surface temperature
T_r	=	temperature of surroundings

Values of $h_c + h_r$ for horizontal bare or insulated standard steel pipe of various sizes in a room at 80°F are shown below*:

* W.H. McAdams, Heat Transmission, 3rd Ed., McGraw-Hill Book Co., Inc., N.Y., 1954, p. 179

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Nominal Pipe
Diam. (in.)

	$T_s - T_a (^{\circ}\text{F})$	$h_c + h_r \text{ (Btu/hr-ft}^2 \text{ - } ^{\circ}\text{F)}$						
		<u>50</u>	<u>100</u>	<u>150</u>	<u>200</u>	<u>250</u>	<u>300</u>	<u>400</u>
1/2		2.12	2.48	2.76	3.10	3.41	3.75	4.47
1		2.03	2.38	2.65	2.98	3.29	3.62	4.33
2		1.93	2.27	2.52	2.85	3.14	3.47	4.18
4		1.84	2.16	2.41	2.72	3.01	3.33	4.02
8		1.76	2.06	2.29	2.60	2.89	3.20	3.88
12		1.71	2.01	2.24	2.54	2.82	3.13	3.83

These values were used to calculate the surface temperature of a cylindrical generator surface of an assumed 6-in.-length, surrounded by still air at 70°F. Heat transfer from the ends was neglected and it is assumed that the surface temperature is approximately equal to the thermoelectric module cold junction temperature. Based on the results shown in Figure C-1 an average cold junction temperature of 170°F was used throughout the TEHE parametric study.

Generator performance is significantly improved at the lower cold junction temperatures that can be achieved in marine applications. Figure C-2 shows the effect of cold junction temperature throughout a range of 50°F to 170°F for the 1-w, full shield, SrTiO₃ system.

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FIGURE C-1. THERMOELECTRIC GENERATOR SURFACE TEMPERATURE

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FIGURE C-2. EFFECT OF COLD JUNCTION TEMPERATURE ON GENERATOR PERFORMANCE

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APPENDIX I-D

RESULTS OF TEHE PARAMETRIC STUDY

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APPENDIX I-DRESULTS OF TEHE PARAMETRIC STUDY

The results of the TEHE parameter study, (see Section I and Appendix I-A) are summarized in Figures D-1 through D-40. Optimized hot junction temperature conditions for maximum efficiency were used in plotting these curves. The optimum temperature exceeds the maximum temperature capabilities of bismuth telluride ($Z_E = 0.90 \times 10^{-3}/^{\circ}\text{C}$) in some cases. The curves for $Z_E = 0.9$ therefore are considered as representative of advanced technology for thermoelectric materials.

Plots of the results are listed below.

<u>Figure</u>	<u>Title</u>			
D-1	PuO_2	Min-K-1301	150 mw	
D-2	PuO_2	Min-K-1301	300 mw	
D-3	PuO_2	Min-K-1301	600 mw	
D-4	PuO_2	Min-K-1301	1w	
D-5	PuO_2	Super Linde	150 mw	
D-6	PuO_2	Super Linde	300 mw	
D-7	PuO_2	Super Linde	600 mw	
D-8	PuO_2	Super Linde	1w	
D-9	Pm_2O_3	Full Shield	MIN-K-1301	150 mw
D-10	Pm_2O_3	Full Shield	MIN-K-1301	300 mw
D-11	Pm_2O_3	Full Shield	MIN-K-1301	600 mw
D-12	Pm_2O_3	Full Shield	MIN-K-1301	1w
D-13	Pm_2O_3	Full Shield	Super Linde	150 mw
D-14	Pm_2O_3	Full Shield	Super Linde	300 mw
D-15	Pm_2O_3	Full Shield	Super Linde	600 mw
D-16	Pm_2O_3	Full Shield	Super Linde	1w
D-17	SrTiO_3	No Shield	MIN-K-1301	150 mw
D-18	SrTiO_3	No Shield	MIN-K-1301	300 mw

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<u>Figure</u>	<u>Title</u>
D-19	SrTiO ₃ No Shield MIN-K-1301 600 mw
D-20	SrTiO ₃ No Shield MIN-K-1301 lw
D-21	SrTiO ₃ No Shield Super Linde 150 mw
D-22	SrTiO ₃ No Shield Super Linde 300 mw
D-23	SrTiO ₃ No Shield Super Linde 600 mw
D-24	SrTiO ₃ No Shield Super Linde lw
D-25	SrTiO ₃ Half Shield MIN-K-1301 150 mw
D-26	SrTiO ₃ Half Shield MIN-K-1301 300 mw
D-27	SrTiO ₃ Half Shield MIN-K-1301 600 mw
D-28	SrTiO ₃ Half Shield MIN-K-1301 lw
D-29	SrTiO ₃ Half Shield Super Linde 150 mw
D-30	SrTiO ₃ Half Shield Super Linde 300 mw
D-31	SrTiO ₃ Half Shield Super Linde 600 mw
D-32	SrTiO ₃ Half Shield Super Linde lw
D-33	SrTiO ₃ Full Shield MIN-K-1301 150 mw
D-34	SrTiO ₃ Full Shield MIN-K-1301 300 mw
D-35	SrTiO ₃ Full Shield MIN-K-1301 600 mw
D-36	SrTiO ₃ Full Shield MIN-K-1301 lw
D-37	SrTiO ₃ Full Shield Super Linde 150 mw
D-38	SrTiO ₃ Full Shield Super Linde 300 mw
D-39	SrTiO ₃ Full Shield Super Linde 600 mw
D-40	SrTiO ₃ Full Shield Super Linde lw
D-41	MIN-K-1301 TH 400 Bi ₂ Te ₃
D-42	Super Linde Insulation TH 400 Bi ₂ Te ₃
D-43	SrTi ₃ - No Shield - MIN-K-1301 - TH 400 Bi ₂ Te ₃
D-44	SrTiO ₃ - No Shield - Super Linde - TH 400 Bi ₂ Te ₃
D-45	SrTiO ₃ - Half Shield - TH 400 Bi ₂ Te ₃
D-46	SrTiO ₃ - Full Shield - MIN-K-1301 - TH 400 Bi ₂ Te ₃
D-47	SrTiO ₃ - Full Shield - Super Linde - TH 400 Bi ₂ Te ₃

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FIGURE D-1. PuO₂ MIN-K-1301 150mw

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FIGURE D-2. PuO₂ MIN-K-1301 300mw

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FIGURE D-3. PuO₂ MIN-K-1301 600mw

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FIGURE D-4. PuO_2 MIN-K-1301 1 w

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FIGURE D-5. PuO₂ SUPER LINDE 150mw

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FIGURE D-6. PuO_2 SUPER LINDE 300mw

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FIGURE D-7. PuO₂ SUPER LINDE 600mw

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FIGURE D-8. PuO_2 SUPER LINDE 1 w

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FIGURE D-9. Pm_2O_3 FULL SHIELD MIN-K-1301 150mw

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FIGURE D-10. Pm_2O_3 FULL SHIELD MIN-K-1301 300mw

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FIGURE D-11. Pm_2O_3 FULL SHIELD MIN-K-1301 600mw

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FIGURE D-12. Pm_2O_3 FULL SHIELD MIN-K-1301 1w

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FIGURE D-13. Pm_2O_3 FULL SHIELD SUPER LINDE 150mw

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FIGURE D-14. Pm_2O_3 FULL SHIELD SUPER LINDE 300mw

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FIGURE D-15. Pm_2O_3 FULL SHIELD SUPER LINDE 600mw

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FIGURE D-16. Pm_2O_3 FULL SHIELD SUPER LINDE 1w

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FIGURE D-17. SrTiO_3 NO SHIELD MIN-K-1301 150mw
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FIGURE D-18. SrTiO₃ NO SHIELD MIN-K-1301 300mw

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FIGURE D-19. SrTiO₃ NO SHIELD MIN-K-1301 600mw

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FIGURE D-20. SrTiO₃ NO SHIELD MIN-K-1301 1w

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FIGURE D-21. SrTiO_3 NO SHIELD SUPER LINDE 150mw

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FIGURE D-22. SrTiO_3 NO SHIELD SUPER LINDE 300mw

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FIGURE D-23. SrTiO₃ NO SHIELD SUPER LINDE 600mw

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FIGURE D-24. SrTiO₃ NO SHIELD SUPER LINDE 1 w

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FIGURE D-25. SrTiO_3 HALF SHIELD MIN-K-1301 150mw

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FIGURE D-26. SrTiO₃ HALF SHIELD MIN-K-1301 300mw

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FIGURE D-27. SrTiO_3 HALF SHIELD MIN-K-1301 600mw

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FIGURE D-28. SrTiO_3 HALF SHIELD MIN-K-1301 1 w

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FIGURE D-29. SrTiO_3 HALF SHIELD SUPER LINDE 150mw

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FIGURE D-30. SrTiO₃ HALF SHIELD SUPER LINDE 300mw

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FIGURE D-31. S-TiO₃ HALF SHIELD SUPER LINDE 600mw

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FIGURE D-32. SrTiO_3 HALF SHIELD SUPER LINDE 1 w

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FIGURE D-33. SrTiO_3 FULL SHIELD MIN-K-1301 150mw

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FIGURE D-34. SrTiO_3 FULL SHIELD MIN-K-1301 300mw

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FIGURE D-35. SrTiO_3 FULL SHIELD MIN-K-1301 600mw

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FIGURE D-36. SrTiO_3 FULL SHIELD MIN-K-1301 1w

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FIGURE D-37. SrTiO_3 FULL SHIELD SUPER LINDE 150mw

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FIGURE D-38. SrTiO_3 FULL SHIELD SUPER LINDE 300mw

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FIGURE D-39. SrTiO₃ FULL SHIELD SUPER LINDE 600mw

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FIGURE D-40. SrTiO_3 FULL SHIELD SUPER LINDE 1 w

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FIGURE D-41. MIN-K-1301 TH 400 Bi_2Te_3

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FIGURE D-42. SUPER LINDE INSULATION TH 400 Bi_2Te_3

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FIGURE D-43. SrTiO_3 - NO SHIELD - MIN-K-1301 - TH 400 Bi_2Te_3

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FIGURE D-44. S_7TiO_3 - NO SHIELD - SUPER LINDE - TH 400 Bi_2Te_3

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FIGURE D-45. SrTiO_3 - HALF SHIELD - TH 400 Bi_2Te_3

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FIGURE D-46. SrTiO_3 - FULL SHIELD - MIN-K-1301 - TH 400 Bi_2Te_3

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FIGURE D-47. SrTiO_3 - FULL SHIELD - SUPER LINDE - TH 400 Bi_2Te_3

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APPENDIX I-E

FUEL COST DATA

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APPENDIX I-E

FUEL COST DATA

The fuel cost data shown in Figures E-1 thru E-4 represent that cost for the most efficient operating temperature as previously discussed. The computer has been programmed to optimize the system efficiency against hot junction temperature. The thermoelectrics have finite temperature limitations (such as Bi_2Te_3 at 400 to 500°F) and therefore the Figures E-5, E-10, E-15 and E-20 represent advanced system concepts. Curves E-7, E-11, E-16, and E-21 have been included to accurately indicate the Bi_2Te_3 system fuel cost at 400°F.

The curves for fuel cost have been established from those costs shown in Table I-3 below:

Table I-3

<u>Fuel</u>	<u>Present Cost</u>	<u>Future Cost</u>
Pm-147	560 \$/w(t)	93 \$/w(t)
Sr-90	32 \$/w(t)	19 \$/w(t)
Pu-238	No cost available	560 \$/w(t)

A complete RTG system cost can be established from the following relationship

$$\text{Total Cost} = C_f + C_i + C_m + C_s + C_{pc} + C_{te}$$

where

- C_f = Cost of fuel (obtained from figures E-2 through E-45)
- C_i = Cost of insulation \$50.00/unit for Min-K-1301, \$1000.00/unit for Super Linde
- C_m = Cost of Manufacturing \$780.00/unit for shield units, \$450.00/unit for shieldless units
- C_s = Cost of shield. Shield weight is plotted on curves D-1 thru D-40 for each diameter system. Using the weight information and Figure E-1 a shield cost is established for the lot size anticipated

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Cpc = The cost of the power conditioning system is estimated
 \$1050.00 each for lots of 10
 \$ 940.00 each for lots of 100
 \$ 880.00 for lots of 500

Cte = The cost of the thermoelectric module can be estimated as
 \$200.00 for Bi_2Te_3 and
 \$700.00 for PbTe systems

Using the above relationship, the costs of any systems selected within the range of the data can be compared.

Plots of the results are listed below.

<u>Figure</u>	<u>Title</u>
E-1	Uranium Shield Weight Versus Cost in Dollars Per Pound
E-2	PuO_2 Min-K-1301 Z = 0.10
E-3	PuO_2 Min-K-1301 Z = 0.35
E-4	PuO_2 Min-K-1301 Z = 0.55
E-5	PuO_2 Min-K-1301 Z = 0.90
E-6	PuO_2 Min-K-1301 Z = 0.90 T = 400°F
E-7	PuO_2 Super Linde Z = 0.10
E-8	PuO_2 Super Linde Z = 0.35
E-9	PuO_2 Super Linde Z = 0.55
E-10	PuO_2 Super Linde Z = 0.90
E-11	PuO_2 Super Linde T = 400°F
E-12	Pm_2O_3 Full Shield Min-K-1301 Z = 0.10
E-13	Pm_2O_3 Full Shield Min-K-1301 Z = 0.35
E-14	Pm_2O_3 Full Shield Min-K-1301 Z = 0.55
E-15	Pm_2O_3 Full Shield Min-K-1301 Z = 0.90
E-16	Pm_2O_3 Full Shield Min-K-1301 Z = 0.90 T = 400°F
E-17	Pm_2O_3 Full Shield Super Linde Z = 0.10
E-18	Pm_2O_3 Full Shield Super Linde Z = 0.35

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<u>Figure</u>	<u>Title</u>			
E-19	Pm ₂ O ₃	Full Shield	Super Linde	Z = 0.55
E-20	Pm ₂ O ₃	Full Shield	Super Linde	Z = 0.90
E-21	Pm ₂ O ₃	Full Shield	Super Linde	Z = 0.90 T = 400°F
E-22	SrTiO ₃	No Shield	Min-K-1301	Z = 0.10
E-23	SrTiO ₃	No Shield	Min-K-1301	Z = 0.35
E-24	SrTiO ₃	No Shield	Min-K-1301	Z = 0.55
E-25	SrTiO ₃	No Shield	Min-K-1301	Z = 0.90
E-26	SrTiO ₃	No Shield	Super Linde	Z = 0.10
E-27	SrTiO ₃	No Shield	Super Linde	Z = 0.35
E-28	SrTiO ₃	No Shield	Super Linde	Z = 0.55
E-29	SrTiO ₃	No Shield	Super Linde	Z = 0.90
E-30	SrTiO ₃	Half Shield	Min-K-1301	Z = 0.10
E-31	SrTiO ₃	Half Shield	Min-K-1301	Z = 0.35
E-32	SrTiO ₃	Half Shield	Min-K-1301	Z = 0.55
E-33	SrTiO ₃	Half Shield	Min-K-1301	Z = 0.90
E-34	SrTiO ₃	Half Shield	Super Linde	Z = 0.10
E-35	SrTiO ₃	Half Shield	Super Linde	Z = 0.35
E-36	SrTiO ₃	Half Shield	Super Linde	Z = 0.55
E-37	SrTiO ₃	Half Shield	Super Linde	Z = 0.90
E-38	SrTiO ₃	Full Shield	Min-K-1301	Z = 0.10
E-39	SrTiO ₃	Full Shield	Min-K-1301	Z = 0.35
E-40	SrTiO ₃	Full Shield	Min-K-1301	Z = 0.55
E-41	SrTiO ₃	Full Shield	Min-K-1301	Z = 0.90
E-42	SrTiO ₃	Full Shield	Super Linde	Z = 0.10
E-43	SrTiO ₃	Full Shield	Super Linde	Z = 0.35
E-44	SrTiO ₃	Full Shield	Super Linde	Z = 0.55
E-45	SrTiO ₃	Full Shield	Super Linde	Z = 0.90

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FIGURE E-1. URANIUM SHIELD WEIGHT VERSUS COST IN DOLLARS PER POUND

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FIGURE E-2. PuO_2 MIN-K-1301 $Z = 0.10$
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FIGURE E-3. PuO_2 MIN-K-1301 $Z = 0.35$

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FIGURE E-4. PuO_2 MIN-K-1301 $Z = 0.55$

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49 40 66 - 692

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FIGURE E-5. PuO_2 MIN-K-1301 $Z = 0.90$

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FIGURE E-6. PuO_2 MIN-K-1301 $Z = 0.90$

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FIGURE E-7. PuO_2 SUPER LINDE $Z = 0.10$

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DECLASSIFIED

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0315087030

FIGURE E-8. PuO_2 SUPER LINDE $Z = 0.35$

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FIGURE E-9. PuO_2 SUPER LINDE $Z = 0.55$

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FIGURE E-10. PuO_2 SUPER LINDE $Z = 0.90$

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FIGURE E-11. PuO_2 SUPER LINDE $T = 400^\circ\text{F}$

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FIGURE E-12. Pm_2O_3 FULL SHIELD MIN-K-1301 $Z = 0.10$

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FIGURE E-13. Pm_2O_3 FULL SHIELD MIN-K-1301 $Z = 0.35$

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FIGURE E-14. Pm_2O_3 FULL SHIELD MIN-K-1301 $Z = 0.55$

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FIGURE E-15. Pm_2O_3 FULL SHIELD MIN-K-1301 $Z = 0.90$

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49-40-60-701

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FIGURE E-16. Pm_2O_3 FULL SHIELD MIN-K-1301 $Z = 0.90$

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CONFIDENTIAL

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FIGURE E-17. Pm_2O_3 FULL SHIELD SUPER LINDE $Z = 0.10$

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FIGURE E-18. Pm_2O_3 FULL SHIELD SUPER LINDE $Z = 0.35$

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FIGURE E-19. Pm_2O_3 FULL SHIELD SUPER LINDE $Z = 0.55$

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FIGURE E-20. Pm_2O_3 FULL SHIELD SUPER LINDE $Z = 0.90$

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FIGURE E-21. Pm_2O_3 FULL SHIELD SUPER LINDE $Z = 0.90$

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FIGURE E-22. SrTiO_3 NO SHIELD MIN-K-1301 $Z = 0.10$

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FIGURE E-23. SrTiO_3 NO SHIELD MIN-K-1301 $Z = 0.35$

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DECLASSIFIED

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CONFIDENTIAL

FIGURE E-24. SrTiO_3 NO SHIELD MIN-K-1301 $Z = 0.55$

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CONFIDENTIAL

49.40-66-547

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FIGURE E-25. SrTiO_3 NO SHIELD MIN-K-1301 $Z = 0.90$

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199-10-66-548

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FIGURE E-26. SrTiO_3 NO SHIELD SUPER LINDE $Z = 0.10$

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FIGURE E-27. SrTiO_3 NO SHIELD SUPER LINDE $Z = 0.35$

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FIGURE E-28. SrTiO_3 NO SHIELD SUPER LINDE $Z = 0.55$

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FIGURE E-29. SrTiO_3 NO SHIELD SUPER LINDE $Z = 0.90$

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FIGURE E-30. SrTiO_3 HALF SHIELD MIN-K-1301 $Z = 0.10$

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FIGURE E-31. SrTiO_3 HALF SHIELD MIN-K-1301 $Z = 0.35$

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FIGURE E-32. SrTiO_3 HALF SHIELD MIN-K-1301 $Z = 0.55$

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FIGURE E-33. SrTiO_3 HALF SHIELD MIN-K-1301 $Z = 0.90$

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FIGURE E-34. SrTiO_3 HALF SHIELD SUPER LINDE $Z = 0.10$

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FIGURE E-35. SrTiO_3 HALF SHIELD SUPER LINDE $Z = 0.35$

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FIGURE E-36. SrTiO_3 HALF SHIELD SUPER LINDE $Z = 0.55$

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FIGURE E-37. SrTiO_3 HALF SHIELD SUPER LINDE $Z = 0.90$

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FIGURE E-38. SrTiO_3 FULL SHIELD MIN-K-1301 $Z = 0.10$

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FIGURE E-39. SrTiO_3 FULL SHIELD MIN-K-1301 $Z = 0.35$

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FIGURE E-40. SrTiO_3 FULL SHIELD MIN-K-1301 $Z = 0.55$

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DECLASSIFIED

FIGURE E-41. SrTiO_3 FULL SHIELD MIN-K-1301 $Z = 0.90$

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FIGURE E-42. SrTiO_3 FULL SHIELD SUPER LINDE $Z = 0.10$

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FIGURE E-43. SrTiO_3 FULL SHIELD SUPER LINDE $Z = 0.35$

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DECLASSIFIED

CONFIDENTIAL

FIGURE E-44. SrTiO_3 FULL SHIELD SUPER LINDE $Z = 0.55$

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CONFIDENTIAL

49-40-66-567

DECLASSIFIED

FIGURE E-45. SrTiO_3 FULL SHIELD SUPER LINDE $Z = 0.90$

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APPENDIX II-A

DESIGN ANALYSIS AND COMPUTER CODE FOR
THERMOELECTRIC GENERATORS USING NON-
SEGMENTED THERMOELECTRIC ELEMENTS AT
MILLIWATT POWER LEVELS

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Appendix II-A - Design Analysis and Computer
Code for Thermoelectric Generators Utilizing
Non-Segmented Thermoelectric Elements at Milli-
Power Levels.

The analysis is made under the following assumptions.

1. The thermoelectric properties are constant averages over the design temperature range.
2. The Thomson power is neglected.
3. The element geometries are not dimensionally optimized. The lengths of the elements in the generator are equal.

Figure (A-1) shows a representative couple of a single stage circuit. Heat flowing in the manner indicated produces a steady state temperature difference $T_H - T_C$.

Figure A-1 Single-Stage Thermoelectric Converter Couple
The open circuit voltage generated by SERJ couples in series is

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$$V_{oc} = SERJ \cdot S \cdot (TH-TC) \quad (A-1)$$

where

SERJ = number of couples in series
 S = total Seebeck coefficient per couple
 TH, TC = hot, cold junction temperature respectively

Following Joffe (A-1), it is convenient to define a mismatch ratio between load resistance and total internal resistance

$$RMIS = \frac{R_L}{SERJ \cdot R_o} \quad (A-2)$$

where

R_L = load resistance
 R_o = $RHO \cdot ELAR$
 = internal resistance of a couple
 RHO = total resistivity of the couple
 ELAR = $ELGTH/ACRO$ ratio of the element
 ELGTH = length of the element
 ACRO = cross-sectional area of element

The current CURLD is

$$CURLD = \frac{SERJ \cdot S \cdot (TH-TC)}{R_L} \cdot \left(\frac{RMIS}{RMIS + 1} \right) \quad (A-3)$$

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The voltage across the load is therefore

$$VLD = SERJ \cdot S \cdot (TH-TC) \cdot \left(\frac{RMIS}{RMIS + 1} \right) \quad (A-4)$$

and the power dissipated in the load

$$PGENT = \frac{(SERJ \cdot S \cdot (TH-TC))^2}{R_L} \cdot \left(\frac{RMIS}{RMIS + 1} \right)^2 \quad (A-5)$$

The thermal power balance at the hot junctions of the generator is

$$\begin{aligned} QIN &= SERJ \cdot CURLD \cdot S \cdot TH + \\ &SERJ \cdot THCN \cdot (TH-TC)/ELAR \\ &- 0.5 \cdot (CURLD)^2 \cdot SERJ \cdot R_O \end{aligned} \quad (A-6)$$

where

$$THCN = \text{total thermal conductivity of a couple}$$

The thermodynamic efficiency of the generator is

$$ETA = \frac{PGENT}{QIN} \quad (A-7)$$

or upon substitution of equations (A-5) and (A-6)

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$$\text{ETA} = \frac{\text{TH}-\text{TC}}{\text{TH}} \cdot \frac{\left(\frac{\text{RMIS}}{\text{RMIS}+1}\right)}{1 + \frac{(\text{RMIS}+1)}{Z \cdot \text{TH}} - \frac{(\text{TH}-\text{TC})}{2 \cdot \text{TH}} \cdot \frac{1}{\text{RMIS}+1}} \quad (\text{A-8})$$

where

$$Z = S^2(\text{RHO} \cdot \text{THCN}) = \text{couple figure of merit}$$

For given temperature limits and thermoelectric properties, the efficiency is a function only of the dimensionless mismatch ratio RMIS. The maximum efficiency

$$\text{ETA} = \frac{\text{TH}-\text{TC}}{\text{TH}} \cdot \frac{\text{RMIS} - 1}{\text{RMIS} + \text{TC}/\text{TH}}$$

is obtained for

$$\text{RMIS} = \sqrt{1 + 0.5 \cdot Z \cdot (\text{TH} + \text{TC})}$$

The thermal flow at the hot junctions of the generator is

$$\text{QH} = \frac{\text{QIN}}{2 \cdot \text{SERJ} \cdot \text{ACRO}}$$

or on substitution of (A-7) and (A-5)

$$\text{QH} = \frac{(\text{S})^2 \cdot (\text{TH}-\text{TC})^2}{2 \cdot \text{ELGTH} \cdot \text{RHO} \cdot \text{ETA}} \cdot \left(\frac{\text{RMIS}}{(\text{RMIS}+1)^2}\right) \quad (\text{A-9})$$

The generator power to be generated, PGENT will have to be larger than the power level to compensate for internal ohmic losses, for losses in power conditioning equipment and finally for the time-dependent power degradation. It is convenient to account for these losses in the following manner.

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$$PGENT = \frac{PSYST}{ETAPC \cdot (1 - EMUC \cdot TIME) \cdot COLPA} \quad (A-10)$$

where

PSYST	=	systems power level specified
ETAPC	=	efficiency of the power conditioning equipment
EMUC	=	power degradation rate
TIME	=	mission length
COLPA	=	contact loss parameter

Another source of losses in a generator is the conduction of heat through the thermal insulation around the elements in the generator.

$$QLOS = THINS \cdot (TH - TC) \cdot 2 \cdot SERJ \cdot ACRO \cdot (1 - PADC) / PADC \cdot ELGTH \quad (A-11)$$

where	THINS	=	thermal conductivity of the thermal insulation material
	PADC	=	packing density of thermoelectric material in generator

Subsequently the basic design parameters can be determined in terms of heat flow density, temperatures, thermoelectric properties and load characteristics.

Number of couples:

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$$\text{SERJ} = \frac{\text{VLD}}{\text{S} \cdot (\text{TH}-\text{TC})} \cdot \frac{\text{RMIS} + 1}{\text{RMIS}}$$

Element length:

$$\text{ELGTH} = \frac{\text{S}^2 \cdot (\text{TH}-\text{TC})^2}{2 \cdot \text{QH} \cdot \text{RHO} \cdot \text{ETA}} \cdot \frac{\text{RMIS}}{(\text{RMIS} + 1)^2}$$

Element cross-section

$$\text{ACRO} = \frac{\text{ELGTH} \cdot \text{CURLD} \cdot (\text{RMIS} + 1) \cdot \text{RHO}}{\text{S} \cdot (\text{TH}-\text{TC})}$$

where

$$\text{CURLD} = \frac{\text{PSYST}}{\text{ETAPC} \cdot (1-\text{EMUC} \cdot \text{TIME}) \cdot \text{COLPA} \cdot \text{VLD}}$$

$$\text{ETASYS} = \frac{\text{PSYST}}{\text{QIN} + \text{QLOS}}$$

These formulas were coded in Fortran IV language. The next pages show a complete listing of the program for determining these basic parameters and examples of output print-outs. In addition to these basic parameters a number of other parameters useful to the generator designer can be determined with this code. These parameters are

volume of thermoelectric material
weight of thermoelectric material
cost on a per unit weight and per
unit couple basis
reliability of the generator circuit

The program has an option for determining the design parameters for generators with several circuits in parallel. PARC is a variable that denotes the number of parallel circuits in the generator. With respect to the reliability computations the code distinguishes between the series-parallel circuits in wire-type generators and the cross-connected series - parallel circuits common in semiconductor - type generators.

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FORTRAN SOURCE LIST

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ISN SOURCE STATEMENT

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0 $19FTC P722A LIST
CTGEX THERMOELECTRIC GENERATOR OPTIMIZATION - MRC - DAYTON
C LIST ALL COMMON AND DIMENSIONED VARIABLES
1 COMMON NIN1,NEXT1, KON1, SP,SN,S,RHOP,RHON,RHO,THCNP,THCNN,
1THC,PSYST,TH,TC,QH,SAINT,VLD,NAMTE,RMIS,PARC,COLPA,JM:TL,DP,
2DN,MMRAT,DELT,RMAT,Z,ETA,SERJ,PGENT,CURLD,ACRO,ELGTH,VOLT,D,
3WATES,COST,COSTE,TIME,FALRAT,NAMTEL,LLCAT,RECO,REMOD,REMODK,
4INTAPE,NTAPE,EMUC,PADC1,PADC2,THINS,T
2 COMMON QLOS,ETASYS,ETAPC,ELAR,RINT,RING
3 COMMON ICASE,IMAT
4 COMMON IA,IB,IC,IPAGE
5 COMMON QIN,PADC,DOLA,DOLS,EFT,TERMAT,RMOP,ETAMAX
6 DIMENSION T(20),SP(20),SN(20),RHOP(20),RHON(20),THCNP(20),
1THCNN(20)
7 DIMENSION NAMTE(2)
C DEFINE ALL CONSTANTS
10 INTAPE = 5
11 NTAPE = 6
12 EMUC = 0.005
13 TIME = 13.00
14 COLPA = 0.75
C INITIALIZE CONTROL INTEGERS
15 JK = 1
16 NEXT1 = 1
17 KM = 0
C READ IN NECESSARY INPUT DATA
20 5 READ(INTAPE,101) ICARD,IA,IB,IC,ICASE,IPAGE,KON1,IMAT
31 NIN1 = 1
32 KM = KM + 1
C DEFINE SEGMENTED AND NON-SEGMENTED CASES
33 GO TO (10,120),KON1
34 10 CALL ENPUT
35 20 CALL AVPROP
36 30 CALL TERMEY
37 40 CALL ANJS
40 50 CALL LOEL
41 60 CALL ACROS
42 70 CALL VOLTE
43 80 CALL WATE
C PERFORM RELIABILITY CALCULATIONS
44 85 CALL CATRE
45 90 SAINT = 2. * SERJ * ACRO * PARC/PADC
46 QLOS=THINS*DELT*((1.-PADC)/PADC)*2.*SERJ*ACRO*PARC/ELGTH
47 QIN = PGENT/ETA
50 ETASYS = PSYST/(QIN + QLOS)
51 100 CALL OUTPUT
52 IF(ICASE-JK) 107,107,105
53 105 NIN1 = 2
54 GO TO 115
55 107 IF(IMAT-KM) 112,112,110
56 110 GO TO 5
57 112 CALL EXIT
60 115 GO TO 10
61 120 CALL ENPUT
62 130 CALL AVPROP

```

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ISN SOURCE STATEMENT

```
63 140 CALL ENPUT  
C ESTIMATE LENGTHS OF LOWER TEMP SEGMENTS  
64 170 CALL ANJS  
65 175 CALL ACROS  
66 180 CALL VOLTE  
67 185 CALL WATE  
70 190 CALL ENPUT  
71 196 CALL OUTPUT  
72 101 FORMAT(14,413,312)  
73 END
```

```

ISN      SOURCE STATEMENT
-----
0 8IBFTC P722B LIST
CTGEN DATA INPUT SUBROUTINE - T.G. OPT PROG
1 SUBROUTINE ENPUT
2 COMMON NIN1,NEXT1, KON1, SP,SN,S,RHOP,RHON,RHO,THCNP,THCNN,
1THC,PSYST,TH,TC,QH,SAINT,VLD,NAMTE,RMIS,PARC,COLPA,JMATL,DP,
2DN,MHRAT,DELT,RMAT,Z,ETA,SERJ,PGENT,CURLD,ACRO,ELGTH,VOLT,D,
3WATES,COST,COSTE,TIME,FALRAT,NAHTEL,LLCAT,RECO,REMOD,REMODK,
4INTAPE,NTAPE,EMUC,PADC1,PADC2,THINS,T
3 COMMON QLOS,ETASYS,ETAPC,ELAR,RINT,RING
4 COMMON ICASE,IMAT
5 COMMON IA,IB,IC,IPAGE
6 COMMON QIN,PADC,DOLA,DOLS,EFT,TERMAT,RMOP,ETAMAX
7 DIMENSION T(20),SP(20),SN(20),RHOP(20),RHON(20),THCNP(20),
1THCNN(20)
10 DIMENSION NAMTE(2)
C SELECT OPTION ON LIBRARY READS
11 GO TO(10,20),NIN1
C READ IN LIBRARY OF THERMOELECTRIC PROPERTIES
12 10 READ(INTAPE,100) ICARD,N, (T(I), I = 1,N)
21 READ(INTAPE,100) ICARD,N, (SP(I), I = 1,N)
30 READ(INTAPE,100) ICARD,N, (SN(I), I = 1,N)
37 READ(INTAPE,100) ICARD,N, (RHOP(I), I = 1,N)
46 READ(INTAPE,100) ICARD,N, (RHON(I), I = 1,N)
55 READ(INTAPE,100) ICARD,N, (THCNP(I), I = 1,N)
64 READ(INTAPE,100) ICARD,N, (THCNN(I), I = 1,N)
C READ IN VARIABLES FOR SERIES JUNCTION CALCS
73 20 READ(INTAPE,102) ICARD,PSYST,TH,TC,QH,VLD,DOLS,DOLA,THINS,
1(NAMTE(I), I = 1,2)
101 READ(5,103) ICARD,MHRAT,LLCAT,NAHTEL,RMIS,PARC,DP,DN,FALRAT,PADC
106 GO TO 101
107 101 RETURN
110 100 FORMAT(I4,I3,8E8.2/9E8.2/3E8.2 )
111 102 FORMAT(I4,5F8.2,3F6.2,2A4)
112 103 FORMAT(I4,3I3,6F4.2 )
113 END

```

```

ISN      SOURCE STATEMENT
-----
0  SIBFTC P722C
   CTGAVP  AVERAGE T.E. PROPERTIES CALCULATIONS
1      SUBROUTINE AVPROP
2      COMMON NIN1,NEXT1, KON1, SP,SN,S,RHOP,RHON,RHO,THCNP,THCNN,
   1THC,PSYST,TH,TC,QH,SAINT,VLD,NAMTE,RMIS,PARC,COLPA,JMATL,DP,
   2DN,MMRAT,DELT,RMAT,Z,ETA,SERJ,PGENT,CURLD,ACRO,ELGTH,VOLT,D,
   3WATES,COST,COSTE,TIME,FALRAT,NAMTEL,LLCAT,RECO,REMOD,REMODK,
   4INTAPE,NTAPE,EMUC,PADC1,PADC2,THINS,T
3      COMMON QLOS,ETASYS,ETAPC,ELAR,RINT,RING
4      COMMON ICASE,IMAT
5      COMMON IA,IB,IC,IPAGE
6      COMMON QIN,PADC,DOLA,DOLS,EFT,TERMAT,RMOP,ETAMAX
7      DIMENSION T(20),SP(20),SN(20),RHOP(20),RHON(20),THCNP(20),
   1THCNN(20)
10     DIMENSION NAMTE(2)
11     DO 100 I = 1,20
12     IF(TC - T(I)) 50,50,100
13     50 K = I - 1
14     GO TO 110
15     100 CONTINUE
17     110 DO 200 I = 1,20
20     IF(TH - T(I)) 150,150,200
21     150 L = I - 1
22     GO TO 210
23     200 CONTINUE
25     210 M = L
26     SUMX1 = 0.
27     SUMX2 = 0.
30     SUMX3 = 0.
31     SUMX4 = 0.
32     SUMX5 = 0.
33     SUMX6 = 0.
34     DO 300 I = K,M
35     SUMX1 = SUMX1 + SP(I) + SP(I + 1)
36     SUMX2 = SUMX2 + SN(I) + SN(I+1)
37     SUMX3 = SUMX3 + RHOP(I) + RHOP(I+1)
40     SUMX4 = SUMX4 + RHON(I) + RHON(I+1)
41     SUMX5 = SUMX5 + THCNP(I) + THCNP(I+1)
42     SUMX6 = SUMX6 + THCNN(I) + THCNN(I+1)
43     300 CONTINUE
45     NUMPT = M - K + 1
46     SPA = SUMX1/(2.*FLOAT(NUMPT))
47     SNA = SUMX2/(2.*FLOAT(NUMPT))
50     S = SNA+ SPA
51     RHOPA = SUMX3/(2.*FLOAT(NUMPT))
52     RHONA = SUMX4/(2.*FLOAT(NUMPT))
53     RHO = RHOPA+ RHONA
54     THCNPA = SUMX5/(2.*FLOAT(NUMPT))
55     THCNNA = SUMX6/(2.*FLOAT(NUMPT))
56     THC = THCNPA+ THCNNA
57     400 RETURN
60     END

```


FORTRAN SOURCE LIST

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1SN      SOURCE STATEMENT
0 $1BFTC P722D  LIST
CTGTER  THERMODYNAMIC EFFICIENCY CALCULATIONS
1      SURROUTINE TERMEY
2      COMMON NIN1,NEXT1, KON1, SP,SN,S,RHOP,RHON,RHO,THCNP,THCNN,
1THC,PSYST,TH,TC,QH,SAINT,VLD,NAMTE,RMIS,PARC,COLPA,JMATL,DP,
2DN,MMRAT,DELT,RMAT,Z,ETA,SERJ,PGENT,CURLD,ACRO,ELGTH,VOLT,D,
3WATES,COST,COSTE,TIME,FALRAT,NAMTEL,LLCAT,REC0,REMOD,REMODK,
4INTAPE,NTAPE,EMUC,PADC1,PADC2,THINS,T
3      COMMON QLOS,ETASYS,ETAPC,ELAR,RINT,RING
4      COMMON ICASE,IMAT
5      COMMON IA,IB,IC,IPAGE
6      COMMON QIN,PADC,DOLA,DOLS,EFT,TERMAT,RMOP,ETAMAX
7      DIMENSION T(20),SP(20),SN(20),RHOP(20),RHON(20),THCNP(20),
1THCNN(20)
10     DIMENSION NAMTE(2)
11     GO TO (10,30),MMRAT
C      CALCULATE THE THERMODYNAMIC EFFICIENCY
12 10 DELT = TH - TC
13     EFT = DELT/TH
C      CALCULATE THE FIGURE OF MERIT
14     Z = S*2/(RHO * THC)
15 20 RMAT = RMIS + 1.
16     TERMAT = RMIS/RMAT
17     TERMAT = TERMAT/(1. + (RMAT/(Z * TH)) - (DELT/(2.*TH))*(1./RMAT))
20     ETA = EFT * TERMAT
21     GO TO 100
C      CALCULATE THE OPTIMUM MISMATCH RATIO
22 30 RMOP = SQRT(1. + 0.5 * Z * (TH + TC))
C      CALCULATE THE MAXIMUM THERMODYNAMIC EFFICIENCY
23 40 ETAMAX = EFT * ((RMOP - 1.)/(RMOP + (TC/TH)))
24     RMIS = RMOP
25     ETA = ETAMAX
26 100 RETURN
27     END

```

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ISN SOURCE STATEMENT

```

0 $IBFTC P722E LIST
  CTGANJ  CALCULATION OF SERIES JUNCTIONS
1      SUBROUTINE ANJS
2      COMMON NIN1,NEXT1, KON1, SP,SN,S,RHOP,RHON,RHO,THCNP,THCNN,
      1THC,PSYST,TH,TC,GH,SAINT,VLD,NAMTE,RMIS,PARC,COLPA,JMATL,DP,
      2DN,MHRAT,DELT,RMAT,Z,ETA,SERJ,PGENT,CURLD,ACRO,ELGTH,VOLT,D,
      3WATES,COST,COSTE,TIME,FALRAT,NAMTEL,LLCAT,RECO,REMOD,REMODK,
      4INTAPE,NTAPE,EMUC,PADC1,PADC2,THINS,T
3      COMMON QLOS,ETASYS,ETAPC,ELAR,RINT,RING
4      COMMON ICASE,IMAT
5      COMMON IA,IB,IC,IPAGE
6      COMMON QIN,PADC,DOLA,DOLS,EFT,TERMAT,RMOP,ETAMAX
7      DIMENSION T(20),SP(20),SN(20),RHOP(20),RHON(20),THCNP(20),
      1THCNN(20)
10     DIMENSION NAMTE(2)
  C      CALCULATE NUMBER OF SERIES JUNCTIONS
11     SERJ = (VLD/DELT) * (RMAT/(RMIS * S))
12     SERJ = IFIX(SERJ)
13     100 RETURN
14     END

```

FORTTRAN SOURCE LIST

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ISN SOURCE STATEMENT

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0 $IBFTC P/22F - LIST
CTGLOE ELEMENT LENGTH CALCULATIONS - T.G. OPT
1 SUBROUTINE LOEL
2 COMMON NIN1,NEXT1, KON1, SP,SN,S,RHOP,RHON,RHO,THCNP,THCNN,
1THC,PSYST,TH,TC,QH,SAINT,VLD,NAMTE,RMIS,PARC,COLPA,JMATL,DP,
2DN,MMRAT,DELT,RMAT,Z,ETA,SERJ,PGENT,CURLD,ACRO,ELGTH,VOLT,D,
3WATES,COST,COSTE,TIME,FALRAT,NAMTEL,LLCAT,RECO,REMOD,REMODK,
4INTAPE,NTAPE,EMUC,PADC1,PADC2,THINS,T
3 COMMON GLOS,ETASYS,ETAPC,ELAR,RINT,RING
4 COMMON ICASE,IMAT
5 COMMON IA,IB,IC,IPAGE
6 COMMON QIN,PADC,DOLA,DOLS,EFT,TERMAT,RMOP,ETAMAX
7 DIMENSION T(20),SP(20),SN(20),RHOP(20),RHON(20),THCNP(20),
1THCNN(20)
10 DIMENSION NAMTE(2)
C CALCULATE THE ELEMENT LENGTH
11 10 ELGTH = DELT**2/(2. * QH)
12 ELGTH = ELGTH*(RMIS*S**2)/(RMAT**2*ETA*RHO)
13 100 RETURN
14 END

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0 $IBFTC P722G LIST
  CTGACR CROSS SECTIONAL AREA CALCULATIONS - T.G. OPT
1  SUBROUTINE ACROS
2  COMMON NIN1,NEXT1, KON1, SP,SN,S,RHOP,RHON,RHO,THCNP,THCNN,
   1THC,PSYST,TH,TC,QH,SAINT,VLD,NAMTE,RHIS,PARC,COLPA,JMATL,DP,
   2DN,MHRAT,DELT,RMAT,Z,ETA,SERJ,PGENT,CURLD,ACRO,ELGTH,VOLT,D,
   3WATES,COST,COSTE,TIME,FALRAT,NAMTEL,LLCAT,RECO,REMOD,REMODK,
   4INTAPE,NTAPE,EMUC,PADC1,PADC2,THINS,T
3  COMMON QLOS,ETASYS,ETAPC,ELAR,RINT,RING
4  COMMON ICASE,IMAT
5  COMMON IA,IB,IC,IPAGE
6  COMMON QIN,PADC,DOLA,DOLS,EFT,TERMAT,RHOP,ETAMAX
7  DIMENSION T(20),SP(20),SN(20),RHOP(20),RHON(20),THCNP(20),
   1THCNN(20)
10  DIMENSION NAMTE(2)
11  ETAPC = EXP(-0.323*(1./VLD)**0.553)
12  PGENT = PSYST/(ETAPC*(1. -EMUC*TIME)*COLPA)
13  CURLD = PGENT/VLD
14  CURLD = CURLD/1000.
15  ACRO = CURLD*RMAT*RHO*ELGTH/(S*DELT*PARC)
16  RING = SERJ * RHO * ELGTH/(ACRO*PARC)
17  ELAR = ELGTH/ACRO
20  RINT = ELAR * RHO
21  GO TO 100
22 100 RETURN
23  END
  
```

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ISN	SOURCE STATEMENT
0	\$1BFTC P722H LIST
	CTGVLT THERMOELECTRIC MATERIAL VOLUME CALCULATIONS
1	SUBROUTINE VOLTE
2	COMMON NIN1, NEXT1, KON1, SP, SN, S, RHOP, RHON, RHO, THCNP, THCNN, 1THC, PSYST, TH, TC, QH, SAINT, VLD, NAMTE, RMIS, PARC, COLPA, JMATL, DP, 2DN, MMRAT, DELT, RMAT, Z, ETA, SERJ, PGENT, CURLD, ACRO, ELGTH, VOLT, D, 3WATES, COST, COSTE, TIME, FALRAT, NAMTEL, LLCAT, RECO, REMOD, REMODK, 4INTAPE, NTAPE, EMUC, PADC1, PADC2, THINS, T
3	COMMON QLOS, ETASYS, ETAPC, ELAR, RINT, RING
4	COMMON ICASE, IMAT
5	COMMON IA, IB, IC, IPAGE
6	COMMON QIN, PADC, DOLA, DOLS, EFT, TERMAT, RMOP, ETAMAX
7	DIMENSION T(20), SP(20), SN(20), RHOP(20), RHON(20), THCNP(20), 1THCNN(20)
10	DIMENSION NAMTE(2)
	C CALCULATE THE VOLUME OF THERMOELECTRIC MATERIAL REQUIRED
11	VOLT = 2. * SERJ * ELGTH * ACRO * PARC
12	100 RETURN
13	END

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ISN	SOURCE STATEMENT
0	\$18F1C P7221 LIST
	CTGWAT WEIGHT AND COST CALCULATIONS
1	SUBROUTINE WATE
2	COMMON NIN1,NEXT1, KON1, SP,SN,S,RHOP,RHON,RMO,THCNP,THCNN, 1THC,PSYST,TH,TC,QH,SAINT,VLD,NAMTE,RMIS,PARC,COLPA,JMATL,DP, 2DN,MMRAT,DELT,RMAT,Z,ETA,SERJ,PGENT,CURLD,ACRO,ELGTH,VOLT,D, 3WATES,COST,COSTE,TIME,FALRAT,NAMTEL,LLCAT,RECO,REMOD,REMODK, 4INTAPE,NTAPE,EMUC,PADC1,PADC2,THINS,T
3	COMMON QLOS,ETASYS,ETAPC,ELAR,RINT,RING
4	COMMON ICASE,IMAT
5	COMMON IA,IB,IC,IPAGE
6	COMMON QIN,PADC,DOLA,DOLS,EFT,TERMAT,RMOP,ETAMAX
7	DIMENSION T(20),SP(20),SN(20),RHOP(20),RHON(20),THCNP(20), 1THCNN(20)
10	DIMENSION NAMTE(2)
	C CALCULATE THE WEIGHT AND COST OF T.E. MATERIAL
11	D = (DN + DP)/2.
12	WATES = VOLT * D
13	COST = DOLS * WATES
14	COSTE = DOLA * SERJ * PARC
15	100 RETURN
16	END

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ISN      SOURCE STATEMENT
0 $I8FTC P722J LIST
CTGCAT  RELIABILITY CALCULATIONS
1  SUBROUTINE CATRE
2  COMMON NIN1,NEXT1, KON1, SP,SN,S,RHOP,RHON,RHO,THCNP,THCNN,
1THC,PSYST,TH,TC,GH,SAINT,VLD,NAMTE,RMIS,PARC,GOLPA,JMATL,DP,
2DN,MMRAT,DELT,RMAT,Z,ETA,SERJ,PGENT,CURLD,ACRO,ELGTH,VOLT,D,
3WATES,COST,COSTE,TIME,FALRAT,NAMTEL,LLCAT,RECO,REMOD,REMODK,
4INTAPE,NTAPE,EMUC,PADC1,PADC2,THINS,T
3  COMMON QLOS,ETASYS,ETAPC,ELAR,RINT,RING
4  COMMON ICASE,IMAT
5  COMMON IA,IB,IC,IPAGE
6  COMMON QIN,PADC,DOLA,DOLS,EFT,TERMAT,RMOP,ETAMAX
7  DIMENSION T(20),SP(20),SN(20),RHOP(20),RHON(20),THCNP(20),
1THCNN(20)
10  DIMENSION NAMTE(2)
11  TIME = TIME/1000.
12  RECO = EXP(-1.*FALRAT*TIME)
13  IF(NAMTEL) 20,20,30
14  20 REMOD = 1.-(1.-EXP(-1.*SERJ*FALRAT*TIME))*PARC
15  GO TO 90
16  25 REMOD = (1.-(1.-EXP(-1.*FALRAT*TIME))*PARC)**SERJ
17  30 REMODK = ((RECO)**SERJ)**PARC
20  NUM = PARC*SERJ
21  NEX = NUM - 1
22  ANUM = NUM
23  REMODK = REMODK + ANUM* RECO **NEX *(1.-RECO)
24  DO 50 I = 2,LLCAT
25  K = I
26  DO 40 M = 1,K
27  NEN = 1
30  NEN = NEN * M
31  NFACT = 1
32  NFACT = NFACT*(INT(SERJ)-K*M)
33  40 CONTINUE
35  NFACT = NFACT/NEN
36  REMODK=REMODK+(PARC**I)*FLOAT(NFACT)*(RECO**NEX)*((1.-RECO)**I)
37  50 CONTINUE
41  GO TO 90
42  90 RETURN
43  END

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0 \$IBF7C P722K LIST

CTGOUT OUTPUT AND FORMAT CONTROLS

1 SUBROUTINE OUTPUT

2 COMMON NIN1,NEXT1, KON1, SP,SN,S,RHOP,RHON,RHO,THCNP,THCNN,
 1THC,PSYST,TH,TC,QH,SAINT,VLD,NAMTE,RMIS,PARC,COLPA,JMATL,DP,
 2DN,MMRAT,DELT,RMAT,Z,ETA,SERJ,PGENT,CURLD,ACRO,ELGTH,VOLT,D,
 3WATES,COST,COSTE,TIME,FALRAT,NAMTEL,LLCAT,RECO,REMOD,REMODK,
 4NTAPE,NTAPE,EMUC,PADC1,PADC2,THINS,T

3 COMMON QLOS,ETASYS,ETAPC,ELAR,RINT,RING

4 COMMON ICASE,IMAT

5 COMMON IA,IB,IC,IPAGE

6 COMMON QIN,PADC,DOLA,DOLS,EFT,TERMAT,RMOP,ETAMAX

7 DIMENSION T(20),SP(20),SN(20),RHOP(20),RHON(20),THCNP(20),

1THCNN(20)

10 DIMENSION NAMTE(2)

11 10 WRITE(NTAPE,100) IA,IB,IC,IPAGE

12 GO TO (20,30),KON1

13 20 WRITE(NTAPE,101)

14 GO TO 40

15 30 WRITE(NTAPE,102)

16 40 WRITE(NTAPE,103) NAMTE,PSYST

17 WATES = WATES/454.

20 WRITE(NTAPE,104) VOLT,WATES

21 COST = COST/454.

22 WRITE(NTAPE,105) COSTE,COST

23 TH = TH - 273.

24 TC = TC - 273.

25 WRITE(NTAPE,106) TH,TC

26 TH = TH * 1.8 + 32.

27 TC = TC * 1.8 + 32.

30 WRITE(NTAPE,107) TH,TC

31 WRITE(NTAPE,107) VLD,RMIS

32 ELGTH = ELGTH/2.54

33 QLOS = QLOS * 1000.

34 WRITE(NTAPE,115) ELGTH,QLOS

35 ACRO = ACRO * 0.1550

36 WRITE(NTAPE,108) ACRO,CURLD

37 WRITE(NTAPE,109) PARC,ETASYS

40 TIME = TIME * 1000.

41 WRITE(NTAPE,110) Z,TIME

42 WRITE(NTAPE,111) ETA,SAINT

43 PGENT = PGENT/1000.

44 WRITE(NTAPE,112) SERJ,PGENT

45 WRITE(NTAPE,113) RECO,REMOD

46 WRITE(NTAPE,114) REMODK,LLCAT

47 WRITE(NTAPE,118) S,RHO

50 WRITE(NTAPE,119) THC,QH

51 WRITE(NTAPE,120) COLPA,ETAPC

52 WRITE(NTAPE,121) ELAR,RINT

53 WRITE(NTAPE,122) RING

54 IPAGE = IPAGE + 1

55 JK = JK + 1

56 150 RETURN

57 100 FORMAT(1H1,70HTHERMOELECTRIC GENERATOR OPTIMIZATION - MONSANTO RES
 1SEARCH CORPORATION .5X,4HDATE,3X,I2,1H/,I2,1H/,I2,10X,4HPAGE)


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        2 3X, 12, ///)
60      101 FORMAT(10X,21HNON - SEGMENTED CASE //)
61      102 FORMAT(10X,15HSEGMENTED CASE //)
62      103 FORMAT(10X,5X,23HTHERMOELECTRIC MATERIAL ,9X,2A4,20X,
        1 18HSYSTEM POWER LEVEL ,10X,E12.5,3X,11HMILLIWATTS //)
63      104 FORMAT(5X,26HVOL OF THERMOELECTRIC MATL ,4X,E12.5,2X,3HCM3 ,13X,
        1 23HWEIGHT OF T.E. MATERIAL ,6X,E12.5,3X,6HPOUNDS //)
64      105 FORMAT(5X,28HT.E. MATERIAL COST-COUPLES ,2X,E12.5,2X,7HDOLLARS
        1 10X,27HT.E. MATERIAL COST-POUNDS ,3X,E12.5,3X,7HDOLLARS //)
65      106 FORMAT(5X,24HHOT JUNCTION TEMPERATURE ,6X,E12.5,2X,5HDEG-C,14X,
        1 26HCOLD JUNCTION TEMPERATURE ,E12.5,2X,5HDEG-C )
66      107 FORMAT(5X,25HOUTPUT VOLTAGE FROM GEN ,5X,E12.5,2X,5HVOLTS,11X,
        1 14HMISMATCH RATIO , 15X, E12.5, //)
67      108 FORMAT(5X,28HELEMENT CROSS SECTIONAL AREA ,2X,E12.5,2X,5HSQ IN,
        1 11X, 22HGENERATOR LOAD CURRENT , 8X, E12.5, //)
70      109 FORMAT(5X,24HNO OF PARALLEL CIRCUITS ,6X,E12.5, 18X,
        1 20HGENERATOR EFFICIENCY , 10X,E12.5,2X,7HPERCENT //)
71      110 FORMAT(5X,24HFIGURE OF MERIT - COUPLE ,6X,E12.5,18X,
        1 12HMISSION TIME,18X, E12.5,2X,6HMH-HRS //)
72      111 FORMAT(5X,27HTHERMODYNAMIC EFF OF COUPLE ,3X,E12.5,18X,
        1 21HGENERATOR HEATED AREA , 9X,E12.5,2X,5HSQ CM //)
73      112 FORMAT(5X,23HNO OF COUPLES IN SERIES ,7X,E12.5, 18X,
        1 15HGENERATOR POWER , 15X, E12.5,5HWATTS //)
74      113 FORMAT(5X,17HREL OF IND COUPLE ,13X, E12.7, 18X,
        1 27HSERIES-PARALLEL RELIABILITY , 3X, E12.7, //)
75      114 FORMAT(5X,27HINTERCONNECTED SER-PARA REL , 3X, E12.7, 18X,
        1 29HALLOWABLE CAT COUPLE FAILURES ,2X,16, //)
76      115 FORMAT(5X,14HELEMENT LENGTH ,16X,E12.5,3X,2HIN,13X,
        1 28HHEAT LOSS BYPASSING ELEMENTS ,2X,E12.5, 12H MILLIWATTS //)
77      117 FORMAT(35X,E12.5,2X,5HDEG-F,40X,E12.5,5HDEG-F //)
100     118 FORMAT(5X,27HAVG SEEBECK COEF - TH TO TC , 3X,E12.5,2X,
        1 11HVOLTS-DEG C ,4X,30HAVG RESISTIVITY - N AND P MATL , 5X,
        2 E12.5, 3X, 6HOHM-CM //)
101     119 FORMAT(5X,29HAVG THERMAL CON-N AND P MATL ,2X,E12.5,2X,
        1 14HWATTS/CM-DEG-K ,2X,30HHEAT FLUX DENSITY AT INTERFACE ,
        2 2X, E12.5, 9HWATTS/CM2 , //)
102     120 FORMAT(5X,22HCONTACT LOSS PARAMETER , 8X, E12.5, 18X,
        1 31HEFF OF POWER CONDITIONING EQUIP ,2X,E12.5, //)
103     121 FORMAT(5X,9H/A RATIO , 21X, E12.5, 2X, 4HCM-1 , 12X,
        1 29HINTFRNL RESISTANCE OF COUPLE , 2X, E12.5, 2X, 4HOHMS //)
104     122 FORMAT(5X,29HINTERNAL RESISTANCE OF MODULE ,2X,E12.5,2X,
        15HOHMS //)
105     END

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NON - SEGMENTED CASE

THERMOELECTRIC MATERIAL	SI GE	SYSTEM POWER LEVEL	0.15000E 03 MILLIWATTS
VOL OF THERMOELECTRIC MATL	0.22594E 02 CM3	WEIGHT OF T.E. MATERIAL	0.16921E 00 POUNDS
T.E. MATERIAL COST-COUPLES	0.20000E 04 DOLLARS	T.E. MATERIAL COST-POUNDS	0.33842E 01 DOLLARS
HOT JUNCTION TEMPERATURE	0.92203E 03 DEG-C 0.16916E 04 DEG-F	COLD JUNCTION TEMPERATURE	0.77000E 02 DEG-C 0.17060E 03 DEG-F
OUTPUT VOLTAGE FROM GEN	0.50000E 00 VOLTS	MISMATCH RATIO	0.10000E 01
ELEMENT LENGTH	0.41744E 01 IN	HEAT LOSS BYPASSING ELEMENTS	0.33964E 03 MILLIWATTS
ELEMENT CROSS SECTIONAL AREA	0.41287E-01 SQ IN	GENERATOR LOAD CURRENT	0.68713E 00
NO OF PARALLEL CIRCUITS	0.20000E 01	GENERATOR EFFICIENCY	0.12472E-01 PERCENT
FIGURE OF MERIT - COUPLE	0.14487E-03	MISSION TIME	0.13000E 02 YR-HRS
THERMODYNAMIC EFF OF COUPLE	0.28568E-01	GENERATOR HEATED AREA	0.42619E 01 SQ CM
NO OF COUPLES IN SERIES	0.20000E 01	GENERATOR POWER	0.34358E 00 WATTS
REL OF IND COUPLE	0.99987E 00	SERIES-PARALLEL RELIABILITY	0.00000E-38
INTERCONNECTED SER-PARA REL	0.10000E 01	ALLOWABLE CAT COUPLE FAILURES	3
AVG SEEBECK COEF - TM TO TC	0.52422E-03 VOLTS-DEG C	AVG RESISTIVITY - N AND P MATL	0.16194E-01 OHM-CM
AVG THERMAL CON-N AND P MATL	0.11713E 00 WATTS/CM-DEG-K	HEAT FLUX DENSITY AT INTERFACE	0.50000E 01 WATTS/CM2
CONTACT LOSS PARAMETER	0.75000E 00	EFF OF POWER CONDITIONING EQUIP	0.62258E 00
L/A RATIO	0.39805E 02 CM-1	INTERNAL RESISTANCE OF COUPLE	0.64464E 00 OHMS
INTERNAL RESISTANCE OF MODULE	0.64464E 00 OHMS		

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SYMBOL TABLE - APPENDIX "A"

SP(I)	-	Seebeck coefficient of P-material at temperature T(I)
SP	-	Average Seebeck coefficient of P-material in range TH-TC
SN(I)	-	Seebeck coefficient of N-material at temperature T(I)
SN	-	Average Seebeck coefficient of N-material in range TH-TC
S	-	SN + SP, Average Seebeck coefficient of couple in range TH-TC
RHOP(I)	-	Electrical resistivity of P-material at temperature T(I)
RHOP	-	Average resistivity in range TH-TC
RHON(I)	-	Electrical resistivity of N-material at T(I)
RHON	-	Average resistivity of N-material in range TH-TC
RHO	-	Average resistivity of couple in range TH-TC
THCNP(I)	-	Thermal conductivity of P-material at T(I)
THCNP	-	Average thermal conductivity of P-material in range TH-TC
THCNN(I)	-	Thermal conductivity of N-material at T(I)
THCNN	-	Average thermal conductivity of N-material in range TH-TC
THC	-	Average thermal conductivity of couple in range TH-TC
TH	-	Hot junction temperature

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TC	- Cold junction temperature
RMIS	- Mismatch ratio - external/internal resistance
RMOP	- Optimum mismatch ratio
VLD	- Generator load voltage
SERJ	- Number of series junctions
QH	- Heat flux density at generator heated area
ETA	- Thermodynamic efficiency of couple
Z	- Figure of merit
PSYST	- System power level
PARC	- Number of parallel circuits
COLPA	- Contact loss parameter
SAINT	- Module heated area between generator and heat source
TERMAT	- Materials term in thermodynamic efficiency equation
ELGTH	- Element length
TEMAT	- Thermoelectric material
ICARD	- Card numbers for accounting and input data orientation
IA,IB,IC	- date
IPAGE	- Page number
KON1	- Option control - 1=non-segmented case, 2=segmented case
RMAT	- Mismatch ratio + 1
ETAMAX	- Maximum thermodynamic efficiency

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EMUC	-	Corrected average degradation rate for apportioned reliability requirement - fraction/1000 hrs.
TIME	-	Mission length in thousands of hours
PGENT	-	Gross electrical power generated
EFT	-	Carnot efficiency
ETAPC	-	Efficiency of the power conditioning unit
CURLD	-	The current load
ACRO	-	Cross sectional area of the elements
VOLT	-	Volume of thermoelectric material required
COST	-	Cost of T.E. materials based on dollars per couple
COSTE	-	Cost of T.E. materials based on dollars per lb.
THINS	-	Thermal conductivity of thermal insulation material in module
DELT	-	The hot junction temperature - the cold junction temperature
PADC	-	Packing density of T.E. material in module
QLOS	-	Heat loss bypassing the elements
FALRAT	-	Failure rate - number of failures per hour
LLCAT	-	Number of catastrophic failures without systems failure
RECO	-	Reliability of individual T.E. couples
REMOD	-	Reliability with parallel circuits
REMODK	-	Reliability of module if LLCAT couple failures are allowed without systems failure

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ETASYS - System efficiency
DP - Density of P-material
DN - Density of N-material
ELAR - L/A ratio
D - Average density of N- and P-material
WATES - Weight of T.E. material required
RINT - Internal resistance of couple
RING - Internal resistance of module
QIN - Heat input to module

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APPENDIX II-B

DESIGN ANALYSIS AND COMPUTER CODE FOR THERMOELECTRIC
GENERATOR UTILIZING SEGMENTED THERMOELECTRIC ELEMENTS
AT MILLIWATT POWER LEVELS

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Appendix II-B - Design Analysis and
Computer Code for Thermoelectric
Generator Utilizing Segmented Thermo-
electric Elements at Milliwatt Power
Levels.

The following assumptions were made in the analysis:

1. The thermoelectric properties are constant averages over the design temperature ranges.
2. The Thomson power is neglected.
3. The overall lengths of the N- and P-legs are equal. The cross section of the segments within the legs are equal.

The design procedure used for the internal geometrical optimization of the couple, *i.e.*, the determination of the lengths of the thermoelectric segments that yield maximum efficiency and for the determination of couple power output and couple efficiency, is in essence, the one developed by Swanson *et al* (Ref. B-1).

Figure B-1 shows a model of a segmented couple. Figure B-2 presents the flow diagram of the procedure for the calculation of the segmented couple and module performance parameters. The procedure evolves through the following steps:

First, the average thermoelectric properties for the segments in the couple are determined. The area below the thermoelectric property-temperature curve in the thermoelectric property-temperature plane is numerically integrated and subsequently, the average value is computed.

Second, the effective Seebeck coefficient for the temperature conditions of the couple is calculated

$$\begin{aligned} \text{SEEB} &= (\text{DELNH} \cdot \text{SUMXN1})/(\text{DELHC} \cdot 2) \\ &+ (\text{DELPH} \cdot \text{SUMXP1})/(\text{DELHC} \cdot 2) \end{aligned}$$

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Figure B-1 Model of a Segmented Couple

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Figure B-2 Logic Flow Diagram -
Calculation Procedure

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$$+ (\text{DELNC} \cdot \text{SUMXN4})/(\text{DELHC} \cdot 2)$$

$$+ (\text{DELPC} \cdot \text{SUMXP4})/(\text{DELHC} \cdot 2)$$

where

SEEB = effective Seebeck coefficient

SUMXN1/2 = average Seebeck coefficient of the high-temperature N-segment

SUMXP1/2 = average Seebeck coefficient of the high-temperature P-segment

SUMXN4/2 = average Seebeck coefficient of the low-temperature N-segment

SUMXP4/2 = average Seebeck coefficient of the low-temperature P-segment

DELHC = temperature difference across couple

DELNH, DELPH = temperature difference across the high-temperature N- and P-segments, respectively

DELNC, DELPC = temperature difference across the low-temperature N- and P-segments, respectively

Third, subsequently the lengths of the segments are determined by means of an iterative procedure. The technique will be demonstrated for the N-leg only since the same procedure holds for the P-leg.

An estimate is made lengths of the segments

$$\text{ELSTIN} = (\text{AL} \cdot \text{DELNH} \cdot \text{THCNN1})/(\text{DELNH} \cdot \text{THCNN1} + \text{DELNC} \cdot \text{THCNN2})$$

$$\text{ELST2N} = \text{A1} - \text{ELST1N}$$

where

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ELST1N,ELST2N = estimated lengths of the high- and low-temperature segment in the N-leg, respectively

AL = length of N-leg

THCNN1,THCNN2 = average thermal conductivities of the high- and low-temperature segment in the N-leg, respectively.

Next, the heat flow QH is used to determine the cross-sectional area AN of the N-leg

$$AN = (QH \cdot ELST2N) / (DELNC \cdot THCNN2)$$

Subsequently, the couple resistance RINT and the couple current, COCUR are computed

$$RINT = (ELST1N \cdot RHON1) / AN + (ELST2N \cdot RHON2) / AN \\ + (ELST1P \cdot RHOP1) / AP + (ELST2P \cdot RHOP2) / AP$$

$$COCUR = (SEEB \cdot DELHC) / (RMIS + 1) \cdot RINT$$

where

RHON1,RHON2,
RHOP1,RHOP2 = average resistivities of the high- and low-temperature N- and P-segments

AP = cross section of P-leg

RMIS = mismatch ratio external load to internal resistance

Next, a record estimate can be made of the lengths of the segments in the N-leg

$$ALONEN = (AL \cdot QTN1) / (QTN1 + QTN2 - (PELT \cdot QTN2) / QH)$$

$$ALTWON = AL - ALONEN$$

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with

$$QTN1 = QH \cdot THCNN1 \cdot DELHN$$

$$QTN2 = QH \cdot THCNN2 \cdot DELNC$$

$$PELT = SEEB \cdot TH \cdot COCUR$$

The next step is to compare the second estimates ALONEN and ALTWON with ELST1N and ELST2N, the first estimate. If the difference between the estimates is larger than a prescribed value, the process is repeated until $ELST1N \approx ALONEN$ and $ELST2N \approx ALTWON$.

Finally, RINT and COCUR can be computed using the correct values for the lengths of the segments.

Fourth, couple efficiency and couple power can now be computed

$$POWC = (COCUR)^2 \cdot RMIS \cdot RINT$$

$$POWC = \text{power output of couple}$$

$$ETAS = POWC/2 \cdot QH$$

$$ETAS = \text{couple efficiency}$$

Fifth, the gross electrical power to be generated PGENT and the series-parallel configuration (SRJSEG, PARCS) are subsequently calculated using the equation below:

$$PGENT = PSYST/(ETAPC \cdot COLPA \cdot (1-EMUC \cdot TIME))$$

$$SRJSEG = (VLD/DELHC) \cdot ((RMIS + 1)/(RMIS \cdot SEEB))$$

$$PARCS = PGENT/POWC \cdot SRJSEG$$

where

$$PSYST = \text{net electrical power output required}$$

$$ETAPC = \text{efficiency of power conditioning equipment}$$

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COLPA = contact loss parameter
 EMUC = power degradation rate
 TIME = mission length
 VLD = load voltage (input voltage to the power conditioning equipment)
 SRJSEG = number of segmented couples in series
 PARCS = number of parallel strings in the series - parallel configuration.

Sixth, finally the module efficiency ETAMOD is calculated

QINS = PGENT/ETAS

where

QINS = heat absorbed at the hot junctions of the segmented thermoelectric module

also

QLOSS = $TH1NS \cdot DELHC \cdot ((1-PADC)/PADC) \cdot SRJSEG \cdot (AN + AP) \cdot PARCS/AL$

where

QLOSS = conducted heat in the thermal insulation system around the thermoelectric elements

PADC = packing density of thermoelectric material in module

TH1NS = thermal conductivity of the thermal insulation material

ETAMOD = $PSYST/(Q1NS + QLOSS)$

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The formulas listed in this appendix were coded in FORTRAN IV language. The next pages show a complete listing of the program for determining these basic module parameters and examples of output print-out. In addition to these basic parameters, a number of other parameters useful to the module designer can be determined with this code. These parameters are:

- volume of thermoelectric material
- weight of thermoelectric material
- cost on a per unit weight and per unit couple basis
- reliability of the module circuit

REFERENCES

- B-1 Swanson *et al* "Optimization of a Sandwiched Thermoelectric Device," Journal of Heat Transfer, February 1961, pp. 77-82.

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FORTRAN SOURCE LIST		03/03/66
ISN	SOURCE STATEMENT	
0	STBFTC 722H LIST	
	CTGEX EXECUTIVE ROUTINE TO OPT - SEG CASE	
1	COMMON T, SNA1, SNA2, SPA1, SPA2, RHONA1, RHONA2, RHOPA1, RHOPA2, THCN1, 1 THCN2, THCP1, THCP2, KL, LM, ICASE, IMAT, NEN2, TH, TC, QH, RMIS, VLD, PSYST, 2 PAUC, COLPA, EMUC, TIME, DOLS, DOLA, THINS, GINS, THCNN1, THCNN2, THCNPI, 3 THCNP2, ALST2N, ALST2P, RINT , ETAPC, PGENT, RECO, REMOD, REMODK, 4 NMYTEL, SERJ, PALRAY, LLCAT, SAINTS	
2	COMMON SEEB, DELHC, DELNH, DELNC, DELPH, DELPC, ELST1N, ELST2N, ELST1P, 1 ELST2P, AN, AP, COCUR, PELY, QTN1, QTN2, ALONEN, ALTWON, QTP1, QTP2, ALONEP, 2 ALTWOP, DIFRN, DIFRP, POWC, HEATN2, HRATP2, ETAS, SRJSEG, ANUM, PARCS, 3 VOLYS, DEN, WAYSEG, QLOSS, GINS, ETAMOD, TN, TP, AL, DN1, DN2, DP1, DP2	
3	COMMON NAMTE	
4	DIMENSION T(20), SNA1(20), SNA2(20), SPA1(20), SPA2(20), RHONA1(20), 1 RHONA2(20), RHOPA1(20), RHOPA2(20), THCN1(20), THCN2(20), THCP1(20), 2 THCP2(20)	
5	DIMENSION NAMTE(2)	
6	LM = 0	
7	KL = 1	
10	5 READ(INYAPE,101) ICARD,IA,IB,IC,ICASE,IMAT	
17	NEN2 = 1	
20	LM = LM + 1	
21	120 CALL INPUT	
22	130 CALL AVPROQ	
23	140 CALL SEGEN	
24	150 CALL SEGEV	
25	160 CALL ANJSEG	
26	170 CALL VHSEG	
27	180 CALL GENEFS	
30	190 CALL CATRES	
31	200 CALL OUTPUT	
32	IF(ICASE=KL) 207,207,205	
33	205 NEN2 = 2	
34	GO TO 215	
35	207 IF(IMAT=LM) 212,212,210	
36	210 GO TO 5	
37	212 CALL EXIT	
40	215 GO TO 120	
41	101 FORMAT(14,313,214,12)	
42	END	

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ISN	SOURCE STATEMENT	FORTRAN SOURCE LIST	03/03/66
0	SUBFC 722H	LIST	
1	SUBROUTINE INPUT		
2	COMMON Y,SN1,SN2,SPA1,SPA2,RHON1,RHON2,RHOP1,RHOP2,THCN1, 1 THCN2,THCP1,THCP2,KL,LN,IGAB,IMAT,NEN2,TM,TC,OH,RMIS,VLD,PSYST, 2PADD,COLPA,SHUD,TIME,DOLS,DOLA,THIN,GIN,THCN1,THCN2,THCP1, 3THCN2,ALST2N,ALSTP,RINT,ETAPC,PGENT,RECO,REMOD,REMODK, 4NAMY,SRJ,PALEY,LLCAY,SAINTS COMMON SEER,DELHG,DELNH,DELNC,DELP,DELP,ELST1N,ELST2N,ELST1P, 5ELST2P,AN,AN,CORR,PULY,GTN1,GTN2,ALONEN,ALWON,GTW1,GTW2,ALONP, 2 ALWOP,DIFRN,DIFRD,PWC,HEATN2,HEATP2,ETAS,SRJSE0,ANUM,PARCE, 3 VOLYS,DEN,HAYSE0,QLQSS,GTNS,EYAMOD,VN,TP,AL,DN1,DN2,DP1,DP2 COMMON NAME 6 DIMENSION Y(20),SN1(20),SN2(20),SPA1(20),SPA2(20),RHON1(20), 7 RHON2(20),RHOP1(20),RHOP2(20),THCN1(20),THCN2(20),THCP1(20), 8 THCP2(20) 9 DIMENSION NAME(2) 10 GO TO (110,120),NEN2 110 READ(INTAP,100) ICARD,N,{Y(I),I=1,N) 12 READ(INTAP,100) ICARD,N,{SN1(I),I=1,N) 13 READ(INTAP,100) ICARD,N,{SN2(I),I=1,N) 14 READ(INTAP,100) ICARD,N,{SPA1(I),I=1,N) 15 READ(INTAP,100) ICARD,N,{SPA2(I),I=1,N) 16 READ(INTAP,100) ICARD,N,{RHON1(I),I=1,N) 17 READ(INTAP,100) ICARD,N,{RHON2(I),I=1,N) 18 READ(INTAP,100) ICARD,N,{RHOP1(I),I=1,N) 19 READ(INTAP,100) ICARD,N,{RHOP2(I),I=1,N) 20 READ(INTAP,100) ICARD,N,{THCN1(I),I=1,N) 21 READ(INTAP,100) ICARD,N,{THCN2(I),I=1,N) 22 READ(INTAP,100) ICARD,N,{THCP1(I),I=1,N) 23 READ(INTAP,100) ICARD,N,{THCP2(I),I=1,N) 24 GO TO 150 120 READ(INTAP,101) ICARD,NAME1,TM,TC,TN,TP,AL,OH,RMIS,VLD,PSYST, 2 PADD,PALEY 147 130 READ(INTAP,102) ICARD,COLPA,SHUD,TIME,DN1,DN2,DP1,DP2,DOLS,DOLA, 3 THIN,{NAME1},101,2),LLCAY 156 100 FORMAT(I4,I3,8E8,2/9E8,2/3E8,2) 157 101 FORMAT(2I4,4F8,E,8F4,E,8E,2) 160 102 FORMAT(I4,7F4,2,2F6,2,2F4,3,2A4, 13) 161 150 RETURN 162 END		

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SOURCE STATEMENT

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SOURCE STATEMENT

SOURCE STATEMENT

COMMON T, SNA2, SPA1, SPA2, RHONA1, RHONA2, RHOPA1, RHOPA2, THCN1,
 1 THCN2, THCP1, THCP2, KL, LM, ICASE, INAT, NEN2, TH, TC, OH, RMIS, VLD, PSYST,
 2 PADC, COLPA, EMUC, TIME, DOLS, DOLA, THINS, GINS, YHCNN1, YHCNN2, YHCNP1,
 3 YHCNP2, ALST2N, ALST2P, RINT, ETAPC, PGENT, RECO, REMOD, REMODK,
 4 NAME1, SERJ, FALRAT, LCCAT, SAINTS
 3 COMMON SEEB, DELHC, DELNH, DELNC, DELPH, DELPC, ELST1N, ELST2N, ELST1P,
 1 ELST2P, AN, AP, COCUR, PELT, QTN1, QTN2, ALONEN, ALTHON, QTP1, QTP2, ALONEP,
 2 ALTHOP, DIFRN, DIFRP, POWC, HEATN2, HEATP2, ETAS, SRJSEQ, ANUM, PARCS,
 3 VOLTS, DEN, WATSEG, QLOBS, GINS, ETAMOD, TN, TP, AL, DN1, DN2, DP1, DP2
 4 COMMON NAME
 5 DIMENSION Y(20), SNA1(20), SNA2(20), SPA1(20), SPA2(20), RHONA1(20),
 1 RHONA2(20), RHOPA1(20), RHOPA2(20), THCN1(20), THCN2(20), THCP1(20),
 2 THCP2(20)
 6 DIMENSION NAME(2)
 7 DO 100 I = 1, 40
 10 IF (TC - T(I)) 50, 90, 100
 11 50 K = I - 1
 12 GO TO 125
 13 100 CONTINUE
 15 125 DO 200 I = 1, 40
 16 IF (TH - T(I)) 150, 150, 200
 17 150 L = I - 1
 20 GO TO 205
 21 200 CONTINUE
 23 205 DO 220 I = 1, 40
 24 IF (TN - T(I)) 210, 210, 220
 25 210 M = I - 1
 26 GO TO 225
 27 220 CONTINUE
 31 225 DO 240 I = 1, 40
 32 IF (TP - T(I)) 230, 230, 240
 33 230 N = I - 1
 34 GO TO 245
 35 240 CONTINUE
 37 245 NA = L
 40 NB = M
 41 NC = N
 42 SUMXN1 = 0,
 43 SUMXN2 = 0,
 44 SUMXN3 = 0,
 45 SUMXN4 = 0,
 46 SUMXN5 = 0,
 47 SUMXN6 = 0,
 50 SUMXP1 = 0,
 51 SUMXP2 = 0,
 52 SUMXP3 = 0,
 53 SUMXP4 = 0,
 54 SUMXP5 = 0,
 55 SUMXP6 = 0,
 56 DO 250 I = M, NA
 57 SUMXN1 = SUMXN1 + (SNA1(I) + SNA1(I+1))
 60 SUMXN2 = SUMXN2 + (RHONA1(I) + RHONA1(I+1))
 61 SUMXN3 = SUMXN3 + (THCN1(I) + THCN1(I+1))

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ISN	SOURCE STATEMENT	FORTRAN SOURCE LIST	03/03/66
0	SIBFTC 722P LIST		
1	SUBROUTINE SEGEN		
2	COMMON Y, SNA1, SNA2, SPA1, SPA2, RHONA1, RHONA2, RHOPA1, RHOPA2, THCN1, 1 THCN2, THCP1, THCP2, KL, LM, ICASE, IMAT, NEN2, TH, TC, QH, RMIS, VLD, PSYST, 2 PADCC, COLPA, EMUC, TIME, DOLS, DOLA, THINS, GINS, THONN1, THCNN2, THCNP1, 3 THCNP2, ALST2N, ALST2P, RINT, ETAPC, PGENT, RECO, REMOD, REMODK,		
3	4 NAMEL, SERJ, PALCAT, LLEAT, SAINTS COMMON SEEB, DELHC, DELNH, DELNC, DELPH, DELPC, ELST1N, ELST2N, ELST1P, 1 ELST2P, AN, AP, COCUR, PELT, QTN1, QTN2, ALONEN, ALTWON, QTP1, QTP2, ALONEP, 2 ALTWOP, DIFRN, DIFRP, POWC, HEATN2, HEATP2, ETAS, SRJSEG, ANUM, PARCS, 3 VOLTS, DEN, WAYSEG, JLOSS, GINS, ETAMOD, TN, TP, AL, DN1, DN2, DP1, DP2		
4	COMMON NAME		
5	DIMENSION Y(20), SNA1(20), SNA2(20), SPA1(20), SPA2(20), RHONA1(20), 1 RHONA2(20), RHOPA1(20), RHOPA2(20), THCN1(20), THCN2(20), THCP1(20), 2 THCP2(20)		
6	DIMENSION NAME(2)		
7	ELST1N = ((DELNH*THCNN1)/(DELNH*THCNN1+DELNC*THCNN2)*AL)		
10	ELST2N = AL - ELST1N		
11	ELST1P = ((DELPH*THCNP1)/(DELPH*THCNP1+DELPC*THCNP2)*AL)		
12	ELST2P = AL - ELST1P		
13	10 AN = (QH*ELST2N)/(DELNC*THCNN2)		
14	20 AP = (QH*ELST2P)/(DELPC*THCNP2)		
15	RINT = (ALST1N*RHON1)/AN + (ALST2N*RHON2)/AN + (ALST1P*RHOP1)/AP + 1 (ALST2P*RHOP2)/AP		
16	COCUR = (SEEB*DELHC)/((RMIS + 1.) * RINT)		
17	PELT = SEEB * TH * COCUR		
20	QTN1 = QH*THCNN1*DELNH		
21	QTN2 = QH*THCNN2*DELNC		
22	ALONEN = (AL*QTN1)/(QTN1+QTN2 - (PELT*QTN2)/QH)		
23	ALTWON = AL - ALONEN		
24	QTP1 = QH*THCNP1*DELPH		
25	QTP2 = QH * THCNP2 * DELPC		
26	ALONEP = (AL*QTP1)/(QTP1+QTP2-(PELT*QTP2)/QH)		
27	ALTWOP = AL - ALONEP		
30	DIFRN = ALONEN - ELST1N		
31	DIFRP = ALONEP - ELST1P		
32	IF (ABS(DIFRN)-1.E-2) 25,25,30		
33	25 IF (ABS(DIFRP)-1.E-2) 30,30,30		
34	30 ELST1N = ALONEN		
35	ELST2N = ALTWON		
36	ELST1P = ALONEP		
37	ELST2P = ALTWOP		
40	GO TO 10		
41	50 RINT = (ALONEP*RHOP1)/AP + (ALTWOP*RHOP2)/AP + (ALONEN*RHON1)/AN + 1 (ALTWON*RHON2)/AN		
42	COCUR = (SEEB*DELHC)/((RMIS+1.) * RINT)		
43	RETURN		
44	END		

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ISN	SOURCE STATEMENT	FORTRAN SOURCE LIST	03/03/66
0	SIBFYC 7220	LIST	
1		SUBROUTINE SEGEY	
2		COMMON T, SNA1, SNA2, SPA1, SPA2, RHONA1, RHONA2, RHOPA1, RHOPA2, THCN1, 1 THCN2, THCP1, THCP2, KL, LM, ICASE, IMAT, NEN2, TH, TC, QH, RMIS, VLD, PSYST, 2 PADC, COLPA, EMUC, TIME, DOLS, DOLA, THINS, GINS, THCNN1, THCNN2, THCNF1, 3 THCNF2, ALST2N, ALST2P, RINT, ETAPC, PGENT, RECO, REMOD, REMODK, 4 NAME1, SERJ, PALRAT, LCCAT, SAINTS	
3		COMMON SEEB, DELHC, DELNH, DELNC, DELPH, DELPC, ELST1N, ELST2N, ELST1P, 1 ELST2P, AN, AP, COCUR, PELT, QTN1, QTN2, ALONEN, ALTWON, QTP1, QTP2, ALONEP, 2 ALTHOP, DIFRN, DIFRP, POWC, HEATN2, HEATP2, ETAS, SRJSEQ, ANUM, PARCS, 3 VOLTS, DEN, WAYSEQ, QLOSS, GINS, ETAMOD, YN, TP, AL, DN1, DN2, DP1, DP2	
4		COMMON NAME	
5		DIMENSION T(20), SNA1(20), SNA2(20), SPA1(20), SPA2(20), RHONA1(20), 1 RHONA2(20), RHOPA1(20), RHOPA2(20), THCN1(20), THCN2(20), THCP1(20), 2 THCP2(20)	
6		DIMENSION NAME(2)	
7		POWC = ((COCUR**2)*RMIS*RINT)	
10		HEATN2 = (QTN2*AN)/(QH*ALTWON)	
11		HEATP2 = (QTP2*AP)/(QH*ALTHOP)	
12		ETAS = POWC/(HEATN2 + HEATP2)	
13		RETURN	
14		END	

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ISN	SOURCE STATEMENT	FORTRAN SOURCE LIST	03/03/66
0	SIBFYC 722R LIST		
1	SUBROUTINE ANJSEG		
2	COMMON T, SNA1, SNA2, SPA1, SPA2, RHONA1, RHONA2, RHOPA1, RHOPA2, THCN1, 1 THCN2, THCP1, THCP2, KL, LM, ICASE, IMAT, NEN2, TH, TC, QH, RMIS, VLD, PSYST, 2PADC, COLPA, EMUC, TIME, DOLS, DOLA, THINS, GINS, THCNN1, THCNN2, THCNF1, 3THCNF2, ALST2N, ALST2P, RINT, ETAPC, PGENT, RECO, REMOD, REMODK, 4NAHYEL, SERJ, PALRAY, LLCAT, SAINTS		
3	COMMON SEEB, DELHC, DELNH, DELNC, DELPH, DELPC, ELST1N, ELST2N, ELST1P, 1ELST2P, AN, AP, COCUR, PELY, QYN1, QYN2, ALONEN, ALYRON, QTP1, QTP2, ALONEP, 2 ALTHOP, DIFRN, DIFRP, POWC, HEATN2, HEATP2, ETAS, SRJSEG, ANUM, PARCS, 3 VOLTS, DEN, WAYSEG, QLOSS, GINS, ETAMOD, TN, TP, AL, DN1, DN2, DP1, DP2		
4	COMMON NAME		
5	DIMENSION T(20), SNA1(20), SNA2(20), SPA1(20), SPA2(20), RHONA1(20), 1RHONA2(20), RHOPA1(20), RHOPA2(20), THCN1(20), THCN2(20), THCP1(20), 2THCP2(20)		
6	DIMENSION NAME(2)		
7	ETAPC = EXP(-0.323*(1./VLD)**0.553)		
10	PGENT = PSYST/(ETAPC*COLPA*(1.-EMUC*TIME))		
11	SRJSEG = (VLD/DELHC)*((RMIS*1.)/(RMIS*SEEB))		
12	SRJSEG = IFIX(SRJSEG)		
13	ANUM = PGENT/POWC		
14	PARCS = ANUM/SRJSEG		
15	PARCS = IFIX(PARCS)		
16	PGENT = SRJSEG * PARCS * POWC		
17	RETURN		
20	END		

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ISN		SOURCE STATEMENT	FORTRAN SOURCE LIST	03/03/66
0	STBPTC 7228	LIST		
1		SUBROUTINE VWSEG		
2		COMMON T, SNA1, SNA2, SPA1, SPA2, RHONA1, RHONA2, RHOPA1, RHOPA2, THCN1, 1 THCN2, THCP1, THCP2, KL, LM, ICASE, IMAT, NEN2, TH, TC, OH, RMIS, VLD, PSYST, 2 PADC, COLPA, EMUC, TIME, DOLS, DOLA, THINS, GINS, THCNN1, THCNN2, THCNP1, 3 THCNP2, ALST2N, ALST2P, RINT, ETAPC, PGENT, RECO, REMOD, REMODK, 4 NAMEL, SERJ, FACRAT, LLOCAT, SAINTS		
3		COMMON SEEB, DELHC, DELNH, DELNC, DELPH, DELPC, ELST1N, ELST2N, ELST1P, 1 ELST2P, AN, AP, COCUR, PELT, QTN1, QTN2, ALONEN, ALTWON, QTP1, QTP2, ALONEP, 2 ALTWOP, DIFRN, DIFRP, POWC, HEATN2, HEATP2, ETAS, SRJSEG, ANUM, PARCS, 3 VOLTS, DEN, WATSEG, QLOSS, GINS, ETAMOD, TN, TP, AL, DN1, DN2, DP1, DP2		
4		COMMON NAME		
5		DIMENSION T(20), SNA1(20), SNA2(20), SPA1(20), SPA2(20), RHONA1(20), 1 RHONA2(20), RHOPA1(20), RHOPA2(20), THCN1(20), THCN2(20), THCP1(20), 2 THCP2(20)		
6		DIMENSION NAME(2)		
7		VOLTS = SRJSEG*PARCS*(AN + AP)*AL		
10		DEN = (ALONEN*DN1/AL) + (ALONEP*DP1/AL) + (ALTWON*DN2/AL) + 1 (ALTWOP*DP2/AL)		
11		WATSEG = DEN * VOLTS		
12		COSTS = DOLS * WATSEG		
13		COSTES = DOLA * SRJSEG * PARCS		
14		RETURN		
15		END		

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ISN	30338 STATEMENT	FORTRAN SOURCE LIST	03/03/66
0	STEP 7227	LIST	
1		SUBROUTINE GENBP3	
2		COMMON T, SNA1, SNA2, SPA1, SPA2, RHONA1, RHONA2, RHOPA1, RHOPA2, THCN1, 1 THCN2, THCP1, THCP2, KL, LM, ICASE, IMAT, NEN2, TH, TC, OH, RMIS, VLD, PSYST, 2 PADC, COLPA, EMUC, TITE, DOLS, DOLA, TWINS, QINS, THCNN1, THCNN2, THCNN3, 3 THCNN2, ALST2N, ALST:P, RINT, ETAPC, PGENT, RECO, REMOD, REMODK, 4 NANTEL, SRJ, PALRT, LCAT, SAINTS	
3		COMMON SEEB, DELHC, DELNH, DELNC, DELPH, DELPC, ELST1N, ELST2N, ELST1P, 1 ELST2P, AN, AP, CCCR, PELT, RTJ1, QTN2, ALONEN, ALTON, QTP1, QTP2, ALONEP, 2 ALTHOP, JIFRN, JIFR, POWC, HEATN2, HEATP2, ETAS, SRJSEG, ANUH, PARCS, 3 VOLTS, DEN, WATSEG, QLOSS, QINS, ETAMOD, TN, TP, AL, DN1, DN2, DP1, DP2	
4		COMMON NANTE	
5		1 DIMENSION T(20), SNA1(20), SNA2(20), SPA1(20), SPA2(20), RHONA1(20), 1 RHONA2(20), RHOPA1(20), RHOPA2(20), THCN1(20), THCN2(20), THCP1(20), 2 THCP2(20)	
6		DIMENSION NANTE(2)	
7		SAINTS = SRJSEG * PARCS * (AN * AP) / PADC	
10		QLOSS = TWINS * DELHC * ((1, -PADC) / PADC) * SRJSEG * PARCS * AN * AP / AL	
11		QINS = PGENT / ETAS	
12		ETAMOD = PSYST / (QINS + QLOSS)	
13		RETURN	
14		END	

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ISN	SOURCE STATEMENT	FORTRAN SOURCE LIST	03/03/66
0	SIBFYC 7220	LIST	
	CTGCAT	RELIABILITY CALCULATIONS	
1	SUBROUTINE CATRES		
2	COMMON T, SNA1, SNA2, SPA1, SPA2, RHONA1, RHONA2, RHOPA1, RHOPA2, THCN1,		
	1 THCN2, THCP1, THCP2, KL, LM, ICASE, IMAT, NEN2, TH, TC, GH, RMIS, VLD, PSYST,		
	2 PADC, COLPA, EMUC, TIME, DOLS, DOLA, THINS, GINS, THCNN1, THCNN2, THCNP1,		
	3 THCNP2, ALST2N, ALST2P, RINT, ETAPC, PGENT, RECO, REMOD, REMODK,		
	4 NAMEL, SERJ, FALRAT, LLCAT, SAINTS		
3	COMMON SEEB, DELHC, DELNH, DELNC, DELPH, DELPC, ELST1N, ELST2N, ELST1P,		
	1 ELST2P, AN, AP, COCUR, PELT, QTN1, QTN2, ALONEN, ALTHON, QTP1, QTP2, ALONEP,		
	2 ALYHOP, DIFRN, DIFRP, POWC, HEATN2, HEATP2, ETAS, SRJSEB, ANUM, PARCS,		
	3 VOLTS, DEN, WATSEQ, QLOSS, GINS, ETAMOD, TN, TP, AL, DN1, DN2, DP1, DP2		
4	COMMON NAME		
5	DIMENSION T(20), SNA1(20), SNA2(20), SPA1(20), SPA2(20), RHONA1(20),		
	1 RHONA2(20), RHOPA1(20), RHOPA2(20), THCN1(20), THCN2(20), THCP1(20),		
	2 THCP2(20)		
6	DIMENSION NAME(2)		
7	RECO = EXP(-1.*FALRAT*TIME)		
10	IF (NAMEL) 20,20,30		
11	20 REMOD = 1.-(1.-EXP(-1.*SERJ*FALRAT*TIME))*PARCS		
12	GO TO 90		
13	30 REMOD = (1.-(1.-EXP(-1.*FALRAT*TIME))*PARCS)**SERJ		
14	REMODK = (RECO**SERJ)**PARCS		
15	NUM = PARCS* SERJ		
16	NEX = NUM - 1		
17	ANUM = NUM		
20	REMODK = REMODK*ANUM*(RECO**NEX)*(1.-RECO)		
21	DO 50 I = 2, LLCAT		
22	K = 1		
23	DO 40 M = 1, K		
24	NEN = 1		
25	NEN = NEN * M		
26	NFACT = 1		
27	NFACT = NFACT*(INT(SERJ) - K * M)		
30	40 CONTINUE		
32	NFACT = NFACT/NEN		
33	REMODK = REMODK*PARC**I*FLOAY(NFACT)*RECO**NEX*(1.-RECO)**I		
34	50 CONTINUE		
36	GO TO 90		
37	90 RETURN		
40	END		

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ISN	SOURCE STATEMENT	FORTRAN SOURCE LIST	03/03/66
0	SYBFC 722V LIST		
1	SUBROUTINE OUTPUT		
2	COMMON T, SNA1, SNA2, SPA1, SPA2, RHONA1, RHONA2, RHOPA1, RHOPA2, THCN1, 1 THCN2, THCP1, THCP2, KL, LM, ICASE, IMAT, NEN2, TH, TC, QH, RMIS, VLD, PSYST, 2 PADC, COLPA, EMUC, TIME, DOLS, DOLA, THINS, GINS, THCNN1, THCNN2, THCNP1, 3 THCNP2, ALST2N, ALST2P, RINT, ETAPC, PGENT, RECO, REMOD, REMODK, 4 NAMEL, SERJ, FALRAY, LLCAT, SAINTS		
3	COMMON SEEB, DELHC, DELNH, DELNC, DELPH, DELPC, ELST1N, ELST2N, ELST1P, 1 ELST2P, AN, AP, COCUC, PELT, QTN1, QTN2, ALONEN, ALTWON, QTP1, QTP2, ALONEP, 2 ALTWOP, DIFRN, DIFRP, POWC, HEATN2, HEATP2, ETAS, SRJSEG, ANUM, PARCS, 3 VOLTS, DEN, WATSEG, QLOSS, GINS, ETAMOD, TN, TP, AL, DN1, DN2, DP1, DP2		
4	COMMON NAME		
5	DIMENSION T(20), SNA1(20), SNA2(20), SPA1(20), SPA2(20), RHONA1(20), 1 RHONA2(20), RHOPA1(20), RHOPA2(20), THCN1(20), THCN2(20), THCP1(20), 2 THCP2(20)		
6	DIMENSION NAME(2)		
7	WRITE(NTAPE,100) IA, IB, IC, IPAGE		
10	WRITE(NTAPE,101) TH, TC, TN, TP		
11	WRITE(NTAPE,102) AL, QH, RMIS, VLD		
12	WRITE(NTAPE,103) PSYST, COLPA, EMUC, TIME		
13	WRITE(NTAPE,104) DV1, DN2, DP1, DP2		
14	WRITE(NTAPE,105) DOLS, DOLA, PADC, THINS		
15	WRITE(NTAPE,106) NAME, RHON1, THCNN1, RHON2		
16	WRITE(NTAPE,107) THCNN2, RHOP1, THCNP1, RHOP2		
17	WRITE(NTAPE,108) THCNP2, DELHC, DELNH, DELNC		
20	WRITE(NTAPE,109) DELPH, DELPC, SEEB, ELST1N		
21	WRITE(NTAPE,110) ELST2N, ELST1P, ELST2P, AN		
22	WRITE(NTAPE,111) AP, RINT, PELT, QTN1		
23	WRITE(NTAPE,112) QTN2, ALONEN, ALTWON, QTP1		
24	WRITE(NTAPE,113) QTP2, ALONEP, ALTWOP, DIFRN		
25	WRITE(NTAPE,114) DIFRP, RINT, COCUC, POWC		
26	WRITE(NTAPE,115) HEATN2, HEATP2, ETAS, ETAPC		
27	WRITE(NTAPE,116) PGENT, SRJSEG, ANUM, PARCS		
30	WRITE(NTAPE,117) VOLT, DEN, WATSEG, COSTS		
31	WRITE(NTAPE,118) COSTES, SAINTS, QLOSS, GINS		
32	WRITE(NTAPE,119) ETAMOD, RECO, REMOD, REMODK		
33	100 FORMAT(1H1,70HYTHERMOELECTRIC GENERATOR OPTIMIZATION - MONSANTO RES 1 EARCH CORPORATION ,5X,4HDATE,3X,12,1H/,12,1H/,12,10X,4HPAGE, 2 3X,12, ///)		
34	101 FORMAT(5X,4HTH =,4X,E12.5,5X,4HTC =,4X,E12.5,5X, 1 4HTN =,4X,E12.5,5X,4HTP =,4X,E12.5)		
35	102 FORMAT(5X,4HAL =,4X,E12.5,5X,4HOM =,4X,E12.5,5X, 1 6HRMIS =,2X,E12.5,5X,5HVLD =,3X,E12.5)		
36	103 FORMAT(5X,8HPSYST =,E12.5,5X,8HCOLPA =,E12.5,5X, 1 6HEHUC =,2X,E12.5,5X,6HTIME =,2X,E12.5)		
37	104 FORMAT(5X,5HDN1 =,3X,E12.5,5X,5HDN2 =,3X,E12.5,5X, 1 5HDP1 =,3X,E12.5,5X,5HDP2 =,3X,E12.5)		
40	105 FORMAT(5X,6HDOLS =,2X,E12.5,5X,6HDOLA =,2X,E12.5,5X, 1 6HPADC =,2X,E12.5,5X,6HTHINS =,E12.5)		
41	106 FORMAT(5X,8HNAME =,E12.5,5X,8HRRHON1 =,E12.5,5X, 1 8HTHCNN1 =,E12.5,5X,8HRRHON2 =,E12.5)		
42	107 FORMAT(5X,8HTHCNN2 =,E12.5,5X,8HRRHOP1 =,E12.5,5X, 1 8HTHCNP1 =,E12.5,5X,8HRRHOP2 =,E12.5)		
43	108 FORMAT(5X,8HTHCNP2 =,E12.5,5X,8HDELHC =,E12.5,5X, 1 8HDELNH =,E12.5,5X,8HDELNC =,E12.5)		

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44	109 FORMAT(5X,8HDELPH = ,E12.5,5X,8HDELPC = ,E12.5,5X, 1 6HSEEB = ,2X,E12.5,5X,8HELST1N = ,E12.5)		
45	110 FORMAT(5X,8HELST2N = ,E12.5,5X,8HELST1P = ,E12.5,5X, 1 8HELST2P = ,E12.5,5X,4HAN = ,4X,E12.5)		
46	111 FORMAT(5X,4HAP = ,4X,E12.5,5X,6HPRINT = ,2X,E12.5,5X, 1 6HPELT = ,2X,E12.5,5X,6HQTN1 = ,2X,E12.5)		
47	112 FORMAT(5X,6HWTN2 = ,2X,E12.5,5X,8HALONEN = ,E12.5,5X, 1 8HALTWN = ,E12.5,5X,6HQTNP1 = ,2X,E12.5)		
50	113 FORMAT(5X,6HQTNP2 = ,2X,E12.5,5X,8HALONEN = ,E12.5,5X, 1 8HALTWN = ,E12.5,5X,8HDIFRN = ,E12.5)		
51	114 FORMAT(5X,8HDIFRP = ,E12.5,5X,6HPRINT = ,2X,E12.5,5X, 1 8HCOCUR = ,E12.5,5X,6HPOWC = ,2X,E12.5)		
52	115 FORMAT(5X,8HHEATN2 = ,E12.5,5X,8HHEATP2 = ,E12.5,5X, 1 6HETAS = ,2X,E12.5,5X,8HETAPC = ,E12.5)		
53	116 FORMAT(5X,8HPRGENT = ,E12.5,5X,8HSRJSE = ,E12.5,5X, 1 6HANUM = ,2X,E12.5,5X,8HPARCS = ,E12.5)		
54	117 FORMAT(5X,6HVOLT = ,2X,E12.5,5X,5HDEN = ,3X,E12.5,5X, 1 8HWATSEG = ,E12.5,5X,8HCOSTS = ,E12.5)		
55	118 FORMAT(5X,8HCOSTES = ,E12.5,5X,8HSAINTS = ,E12.5,5X, 1 8HQLOSS = ,E12.5,5X,6HOLNS = ,2X,E12.5)		
56	119 FORMAT(5X,8HETAMOD = ,E12.5,5X,6HRECO = ,2X,E12.5,5X, 1 8HREMOD = ,E12.5,5X,8HREMODK = ,E12.5)		
57	RETURN		
60	END		

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SYMBOL TABLE - APPENDIXII-B

TH	-	Hot junction temperature
TC	-	Cold junction temperature
TN	-	Segmenting temperature in N-leg
TP	-	Segmenting temperature in P-leg
SNA1(I)	-	Seebeck coefficient of N1-material at temperature T(I)
SNA2(I)	-	Seebeck coefficient of N2-material at temperature T(I)
SPA1(I)	-	Seebeck coefficient of P1-material at temperature T(I)
SPA2(I)	-	Seebeck coefficient of P2-material at temperature T(I)
RHONA1(I)	-	Resistivity of N1-material at temperature T(I)
RHONA2(I)	-	Resistivity of N2-material at temperature T(I)
RHOPA1(I)	-	Resistivity of P1-material at temperature T(I)
RHOPA2(I)	-	Resistivity of P2-material at temperature T(I)
THCN1(I)	-	Thermal conductivity of N1-material at temperature T(I)
THCN2(I)	-	Thermal conductivity of N2-material at temperature T(I)
THCP1(I)	-	Thermal conductivity of P1-material at temperature T(I)
THCP2(I)	-	Thermal conductivity of P2-material at temperature T(I)

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T(I)	-	Reference temperature
AL	-	Total length of N-leg, P-leg
QH	-	Heat flux at the hot junction
RMIS	-	Mismatch ratio - external load vs. internal resistance
VLD	-	Load voltage of the module
PSYST	-	System power level required
COLPA	-	Contact loss parameter
EMUC	-	Fractional degradation rate/1000 hr
TIME	-	Mission length
DN1	-	Density of N1-material
DN2	-	Density of N2-material
DP1	-	Density of P1-material
DP2	-	Density of P2-material
DOLS	-	Average cost of N- and P-materials/lbs.
DOLA	-	Average cost of N- and P-materials/couples
PADC	-	Packing density of T.E. material in module
TH1NS	-	Thermal conductivity of insulation material
VOLTS	-	Volume of thermoelectric material required
RECO	-	Reliability of individual T.E. couple
REMOD	-	Reliability with parallel circuit
REMODK	-	Reliability of module if LLCAT couple failures are allowed

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FALRAT	- Average estimated couple failure rate/1000 hours
QINS	- Heat input to module
RINT	- Internal resistance of couple
ETAPC	- Thermodynamic efficiency of power conditioning equipment
PGENT	- Gross electrical power generated
LLCAT	- Number of allowed catastrophic couple failures
SAINTS	- Heated area at hot junction
SEEB	- Effective Seebeck coefficient for temperature conditions of the couple.
DELHC	- Temperature difference, hot junction to cold junction
DELNH	- Temperature difference between hot junction and interface, N-leg
DELNC	- Temperature difference between interface and cold junction, N-leg
DELPH	- Temperature difference between hot junction and interface, P-leg
DELPC	- Temperature difference between interface and cold junction, P-leg
ELST1N	- Length of N-leg from hot junction to interface
ELST2N	- Length of N-leg from interface to cold junction
ELST1P	- Length of P-leg from hot junction to interface
ELST2P	- Length of P-leg from interface to cold junction
AN	- Cross-sectional area of N-leg
AP	- Cross-sectional area of P-leg

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COCUR - The couple current
PELT - The Peltier heat
QTN1 - Heat flux from hot junction to interface of N-leg
QTN2 - Heat flux from interface to cold junction of N-leg
ALONEN - Length estimate of high-temperature segment, N-leg
ALTWON - Length estimate of low-temperature segment, N-leg
QTP1 - Heat flux from hot junction to interface of P-leg
QTP2 - Heat flux from interface to cold junction of P-leg
ALONEP - Length estimate of high-temperature segment, P-leg
ALTWOP - Length estimate of low-temperature segment, P-leg
POWC - Couple output power
ETAS - Couple efficiency
SRJSEG - Number of series junctions
ANUM - Ratio between required and calculated output power
PARCS - Number of parallel circuits
DEN - Average density of combined T.E. material
WATSEG - Weight of T.E. material required
QLOSS - Heat loss bypassing elements
ETAMOD - Efficiency of the module
IA,IB,IC - Date
IPAGE - Page number
COSTS - Cost of T.E. material/lb
COSTES - Cost of T.E. material/couples

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APPENDIX II-C

DESIGN ANALYSIS AND COMPUTER CODE FOR
CASCADED THERMOELECTRIC GENERATORS AT
MILLIWATT POWER LEVELS

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Appendix II-C - Design Analysis and
Computer Code for Cascaded Thermoelectric
Generators at Milliwatt Power Levels.

The technical discussion in this appendix will be limited to cascaded two stage converter. The following assumptions are made for this analysis.

1. The thermoelectric properties are constant averages over the design temperature range.
2. The Thomson power is neglected.
3. The element geometries are not dimensionally optimized. The lengths of the elements in each stage of the cascaded design are equal.

Figure C-1 Two-Stage Cascaded Thermoelectric Converter

Figure C-1 shows a representative section of a cascaded two stage converter. An electrically insulating diathermic wall separates the couples of Stage I and II. The equivalent thermal circuit is shown in Figure C-2.

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Figure C-2 Thermal Circuit of Two-Stage Cascaded Converter

The power delivered by Stage I is

$$P_I = Q_{IN} \cdot \text{ETA1}$$

$$P_{II} = Q_{IN} \cdot (1 - \text{ETA1}) \cdot (\text{ETA2})$$

where ETA1 and ETA2 are the individual efficiencies of the two stages.

The total power delivered is therefore

$$P_I + P_{II} = P_{\text{GENT}} = Q_{IN}(\text{ETA1} + \text{ETA2} - \text{ETA1} \cdot \text{ETA2})$$

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and the compound efficiency is

$$\eta = \text{ETA1} + \text{ETA2} - \text{ETA1} \cdot \text{ETA2}$$

Harman (C-1) has treated the problem of a two-stage converter in which the separating wall is truly diathermic, that is

$$T_{H1} - \Delta T_1 = T_{H2}$$

The present analysis (C-2) deals with the more realistic case of two converters separated by a finite temperature drop in the intermediate wall. Thermodynamically, this may be regarded as a series of three heat engines, with the central one adiabatically insulated and operating at zero efficiency. The compound efficiency is then the same as that given above.

Figure C-3 shows the equivalent electrical circuit of a two stage converter powering a resistive load in series connection.

Figure C-3 Electrical Circuit of a Two-Stage Cascaded Converter

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The two circuits will be independent if $I_I = I_{II}$, that is, the current in the top branch is zero. For purposes of analysis, the latter divides the load resistance into two parts:

$$R_{LOAD} = R_{LI} + R_{LII}$$

The open circuit voltage generated by Stage I is

$$V_{ocI} = EN2 \cdot S1 \cdot DELT1$$

and by Stage II

$$V_{ocII} = EN2 \cdot S2 \cdot DELT2$$

where

$$\begin{aligned} EN1, EN2 &= \text{number of couples} \\ S1, S2 &= \text{total Seebeck coefficient} \\ DELT1, DELT2 &= \text{temperature difference} \end{aligned}$$

The current flowing through the converter circuit is

$$COCUR = \frac{EN1 \cdot S1 \cdot DELT1}{R_{LI} + EN1 \cdot R_{OI}} \quad (C-1A)$$

$$COCUR = \frac{EN2 \cdot S2 \cdot DELT2}{R_{LII} + EN2 \cdot R_{OII}} \quad (C-1B)$$

where

$$R_{OI} \text{ and } R_{OII} = RH01,2 \quad ELAR1,2$$

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R_{OI} and R_{OII} = internal resistance of a couple in stage I, II respectively.

$ELAR_{1, 2}$ = L/A ratio of elements in stage I and II respectively

Following Joffe (C-3), it is convenient to define two mismatch ratios between associated load resistance and internal resistance.

$$RMIS1 = R_{LI} / EN1 \cdot R_{OI} \quad (C-2A)$$

$$RMIS2 = R_{LII} / EN2 \cdot R_{OII} \quad (C-2B)$$

Equation (C-1A, B) can then be rewritten as

$$COCUR = \frac{S1 \cdot DELT1}{R_{OI} \cdot (RMIS1 + 1)} \quad (C-3A)$$

$$COCUR = \frac{S2 \cdot DELT2}{R_{OII} \cdot (RMIS2 + 1)} \quad (C-3B)$$

The power generated by each stage is therefore

$$P_I = \frac{EN1 \cdot (S1)^2 \cdot (DELT1)^2}{R_{OI}} \cdot \left[\frac{RMIS1}{(RMIS1 + 1)^2} \right] \quad (C-4)$$

$$P_{II} = \frac{EN2 \cdot (S2)^2 \cdot (DELT2)^2}{R_{OII}} \cdot \left[\frac{RMIS2}{(RMIS2 + 1)^2} \right] \quad (C-5)$$

The thermal power balance at the hot-junction of Stage I is

$$\begin{aligned} QIN &= EN1 \cdot S1 \cdot COCUR \cdot TF1 + FN1 \cdot K_{OI} \cdot DFLT1 \\ &- 0.5 \cdot (COCUR)^2 \cdot EN1 \cdot P_{OI} \end{aligned} \quad (C-6)$$

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and as the hot junction of Stage II

$$\begin{aligned} QIN(1-ETA1) &= EN2 \cdot S2 \cdot COCUR \cdot TH2 + \\ &EN2 \cdot K_{OI} \cdot DELT2 - 0.5(COCUR)^2 \cdot EN^2 \cdot R_{OII} \end{aligned} \quad (C-7)$$

where

$$\begin{aligned} K_{OI}, K_{OII} &= THCN1,2 / ELAR1,2 \\ &= \text{thermal conductance of a couple in} \\ &\quad \text{stage I, II respectively} \end{aligned}$$

The thermodynamic efficiency of Stage I is

$$ETA1 = P_I / QIN$$

or upon substitution of equations (C-4) and (C-6),

$$\begin{aligned} ETA1 &= \frac{DELTA1}{TH1} \cdot \\ &\frac{RMIS1 / (RMIS1 + 1)}{1 + (RMIS1 + 1) / Z_1 \cdot TH1 - DELTA1 / 2 \cdot TH1 \cdot (RMIS1 + 1)} \end{aligned} \quad (C-8)$$

In analogous manner for Stage II,

$$ETA2 = P_{II} / QIN(1-ETA1)$$

whence, upon substitution of equations (C-5) and (C-7),

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$$\text{ETA2} = \frac{\text{DELT2}}{\text{TH2}} .$$

$$\frac{\text{RMIS2}/(\text{RMIS2} + 1)}{1 + (\text{RMIS2} + 1)/Z_2 \cdot \text{TH2} - \text{DELT2}/2 \cdot \text{TH2} \cdot (\text{RMIS2} + 1)} \quad (\text{C-9})$$

where

$$Z_{1,2} = (\text{S1},2)^2 / \text{RHO1},2 \cdot \text{THCN1},2$$

The thermal flow at the hot junctions of Stage I is

$$\text{QH} = \text{QIN}/2 \cdot \text{EN1} \cdot \text{ACRO1}$$

where ACRO1 = cross-sectional area of an element in the first stage

also

$$\text{QIN} = \frac{\text{PGENT}}{(\text{ETA1} + \text{ETA2} - \text{ETA1} \cdot \text{ETA2})}$$

whence

$$\text{EN1} \cdot \text{ACRO1} = \frac{\text{PGENT}}{2 \cdot \text{QH} \cdot (\text{ETA1} + \text{ETA2} - \text{ETA1} \cdot \text{ETA2})} \quad (\text{C-10})$$

also

$$\text{PGENT} = \frac{\text{PSYST}}{\text{ETAPC} \cdot (1 - \text{EMUC} \cdot \text{TIME}) \cdot \text{COLPA}} \quad (\text{C-11})$$

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where

PSYST	=	systems power level required
ETAPC	=	efficiency of the power conditioning equipment
EMUC	=	fractional power degradation rate
TIME	=	mission length
COLPA	=	contact loss parameter

If an equal degree of occupancy of the intermediate wall between stages is specified, then

$$EN1 \cdot ACRO1 = EN2 \cdot ACRO2 \quad (C-12)$$

and the thermal shunt losses are approximately

$$QLOS1,2 = 2 \cdot THINS \cdot DELT1,2 \cdot EN1,2 \cdot ACRO1,2 \cdot (1-PADC)/PADC \cdot EL1,2 \quad (C-13)$$

where

EL1,2	=	length of the elements in the Stage I, II respectively
PADC	=	packing density of TE material in Stage I, II respectively
ETACAS	=	$PSYST/(QIN + QLOS1 + QLOS2)$ (C-14)

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Introducing the thermoelectric properties, load voltage VLD the systems power and the loss parameters into the equations (C-2A), (C-2B), (C-3A), (C-3B), (C-4), (C-5), (C-6), (C-7), (C-10), (C-11), (C-12), (C-13), and (C-14) gives a system of simultaneous equations for the design parameters of the two stages. If RLOAD, TERM, COCUR, ELAR1 and ELAR2 are first determined in terms of input,

$$RLOAD = \frac{(VLD)^2 (ETAPC \cdot (1 - EMUC \cdot TIME) \cdot COLPA)}{PSYST} \quad (C-15)$$

$$TERM = \frac{1}{1 - ETA1} \cdot$$

$$\frac{\frac{(S2)^2 \cdot DELT2 \cdot TH2}{RHO2 \cdot (RMIS2 + 1)} + THCN2 \cdot DELT2 - 0.5 \frac{(S2)^2 \cdot (DELT2)^2}{RHO2 \cdot (RMIS2 + 1)^2}}{\frac{(S1)^2 \cdot DELT1 \cdot TH1}{RHO1 \cdot (RMIS1 + 1)} + THCN1 \cdot DELT1 - 0.5 \frac{(S1)^2 \cdot (DELT1)^2}{RHO1 \cdot (RMIS1 + 1)^2}} \quad (C-16)$$

(C-17)

$$ELAR1 = \frac{S1 \cdot DELT1}{(COCUR \cdot RHO1 \cdot (RMIS1 + 1))} \quad (C-18A)$$

$$ELAR2 = \frac{S2 \cdot DELT2}{(COCUR \cdot RHO2 \cdot (RMIS2 + 1))} \quad (C-18B)$$

then EN1, EN2, EL1, EL2, ACRO1, ACRO2, and ETACAS can be subsequently determined

$$EN2 = \frac{RLOAD}{TERM \cdot RMIS1 \cdot RHO1 \cdot (ELAR1)^2 \cdot ELAR2 + ELAR2 \cdot RMIS2 \cdot RHO2} \quad (C-19)$$

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$$EN1 = EN2 \cdot ELAR1 \cdot TERM / ELAR2 \quad (C-20)$$

$$ACRO1 = \frac{COCUR \cdot VLD}{2 \cdot QH \cdot EN1 \cdot (ETA1 + ETA2 - ETA1 \cdot ETA2)} \quad (C-21)$$

$$ACRO2 = EN1 \cdot ACRO1 / EN2 \quad (C-22)$$

$$EL1 = ELAR1 \cdot ACRO1 \quad (C-23)$$

$$EL2 = ELAR2 \cdot ACRO2 \quad (C-24)$$

$$ETACAS = \frac{PSYST}{QIN + QLOS1 + QLOS2} \quad (C-25)$$

where

ETACAS = systems thermal efficiency of the cascaded generator.

Pages 220 and 221 show a computer program coded in FORTRAN IV language for determining these parameters. Necessary input data also include the values of ETA1 and ETA2 and thus these values have to be determined previously, for example, by using TERMEY (See Appendix A)

An additional option of the computer code is the provision of analyzing generators utilizing parallel circuits. PARC is a variable denoting the number of parallel circuits in the generator.

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References

- C-1 Harman, T. C., "Multiple Stage Thermoelectric Generation of Power," J. Appl. Phys., Vol. 29, No. 10, p. 1471 ff., 1958
- C-2 G. Sonnenschein, Personal Communication
- C-3 Joffe, A. F., "Semiconductor Thermoelements and Thermoelectric Cooling," p. 36 ff., Infosearch, Ltd., (1956).

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CASCAD	ISN	SOURCE STATEMENT	FORTRAN SOURCE LIST	03/16/66
0	81BFTC	CASCAD LIST		
	CJOB		DLZANDD0008876500	
	C	CASCAD COMPUTES SYSTEMS EFFICIENCY AND COUPLE PARAMETERS OF A		
	C	CASCADED THERMOELECTRIC GENERATOR SYSTEM		
1		DIMENSION INAME(2)		
2		INTAPE = 5		
3		NTAPE = 6		
4	5	READ(INTAPE,95) IA,IB,IC,IPAGE,((INAME(I),I = 1,2)		
15		READ(INTAPE,100) EMUC,TIME,QH,COLPA,PSYST,PARC,ETA1,ETA2,THINS,		
		1 PADC,RMIS1,RMIS2		
16		READ(INTAPE,101) S1,S2,RHO1,RHO2,TH1,TH2,THCN1,THCN2,DELT1,DELT2		
17		VLD = 1.5		
20	10	ETAPC = EXP(-0.323*(1./VLD)**0.553)		
21		IPAGE = IPAGE + 1		
22		EMUM = 1. - EMUC * TIME		
23		PGENT = PSYST/(ETAPC*EMUM*COLPA)		
24		RLOAD = VLD**2*PARC/PGENT		
25		COCUR = PGENT/(VLD*PARC)		
26		ELAR1 = S1*DELT1		
27		ELAR1 = ELAR1/(COCUR*RHO1*(RMIS1 + 1.))		
30		ELAR2 = S2*DELT2		
31		ELAR2 = ELAR2/(COCUR*RHO2*(RMIS2 + 1.))		
32		RES1 = RMIS1*RHO1		
33		RES2 = RMIS2*RHO2		
34		ONE1 = S1**2*DELT1*TH1/(RHO1*(RMIS1 + 1.))		
35		ONE2 = S2**2*DELT2*TH2/(RHO2*(RMIS2 + 1.))		
36		TWO1 = THCN1*DELT1		
37		TWO2 = THCN2*DELT2		
40		THREE1 = 0.5 * S1**2 * DELT1**2/(RHO1*(RMIS1 + 1.))**2)		
41		THREE2 = 0.5*S2**2*DELT2**2/(RHO2*(RMIS2 + 1.))**2)		
42		TERM = (ONE2+TWO2-THREE2)/(ONE1+TWO1-THREE1)		
43		TERM = TERM/(1.-ETA1)		
44		EN2 = RLOAD/(TERM*RES1*(ELAR1**2/ELAR2)+ELAR2*RES2)		
45		EN2 = IFIX(EN2)		
46		EN1 = IFIX(EN1)		
47		EN1 = TERM*ELAR1*(EN2/ELAR2)		
50		ACRO1 = PGENT/(2.*QH*PARC*EN1)		
51		ACRO1 = ACRO1/(ETA1+ETA2-ETA1*ETA2)		
52		ACRO2 = EN1*ACRO1/EN2		
53		EL1 = ELAR1*ACRO1		
54		EL2 = ELAR2*ACRO2		
55		QLOS1 = PARC*THINS*DELT1*2.*EN1*ACRO1*(1.-PADC)/(PADC*EL1)		
56		QLOS2 = PARC*THINS*DELT2*2.*EN2*ACRO2*(1.-PADC)/(PADC*EL2)		
57		QIN = PGENT/(ETA1+ETA2-ETA1*ETA2)		
60		ETACAS = (PSYST/(QIN+QLOS1+QLOS2))*100.		
61		WRITE(NTAPE,102) IA,IB,IC,IPAGE,((INAME(I), I = 1,2)		
66		WRITE(NTAPE,103) PSYST,VLD		
67		WRITE(NTAPE,104) QH,ETAPC		
70		WRITE(NTAPE,105) PGENT,QLOS1		
71		WRITE(NTAPE,106) QLOS2,ETACAS		
72		WRITE(NTAPE,107) ELAR1,ELAR2		
73		WRITE(NTAPE,108) EN1,EN2		
74		WRITE(NTAPE,109) EL1,EL2		
75		WRITE(NTAPE,110) ACRO1,ACRO2		
76	15	IF(VLD-3.)20,20,30		

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CASCAD	ISN	SOURCE STATEMENT	FORTTRAN SOURCE LIST CASCAD	03/16/66
	77	20 VLD = VLD + 1.5		
	100	25 GO TO 10		
	101	30 IF (VLD-9.)40,45,45		
	102	40 VLD = VLD + 3.		
	103	42 GO TO 10		
	104	45 GO TO 5		
	105	95 FORMAT(4I3,2A6)		
	106	100 FORMAT(12F6.2)		
	107	101 FORMAT(10E7.2)		
	110	102 FORMAT(1H1,49HMONSANTO RESEARCH CORPORATION CASCADED GEN CALCS 1 10X,4HDATE,3X,12,1H/,12,1H/,12,10X,4HPAGE,3X,16, 5X,2A6, ///)		
	111	103 FORMAT(1H0,4X,30HSYSTEM POWER LEVEL-----,1PE12.5,2X, 1 10HWATTS ,11X,30HLOAD VOLTAGE-----,1PE12.5, 2 2X,5HVOLTS ///)		
	112	104 FORMAT(5X,30HHEAT FLUX DENS AT INTERFACE---,1PE12.5,2X, 1 9HWATTS/CM2,12X,30HEFF OF POWER COND EQUIP-----, 2 1PE12.5, ///)		
	113	105 FORMAT(5X,30HGENERATOR POWER-----,1PE12.5,2X, 1 5HWATTS,16X,30HHEAT LOSS - 1ST STAGE-----,1PE12.5, 2X, 2 5HWATTS ///)		
	114	106 FORMAT(5X,30HHEAT LOSS - 2ND STAGE-----,1PE12.5,2X, 1 5HWATTS,16X,30HCASCADED SYSTEM EFFICIENCY----,1PE12.5, 2 2X, 7HPERCENT ///)		
	115	107 FORMAT(5X,30HL/A RATIO - 1ST STAGE-----,1PE12.5,2X, 1 4HCM-1,17X,30HL/A RATIO - 2ND STAGE-----,1PE12.5, 2 2X, 4HCM-1 ///)		
	116	108 FORMAT (5X,30HNO OF SERIES CPLS - STAGE 1---,1PE12.5,23X,30HNO OF 2SERIES CPLS - STAGE 2---,1PE12.5,///)		
	117	109 FORMAT(5X,30HELEMENT LENGTH - 1ST STAGE----,1PE12.5,2X, 1 2HCM,19X,30HELEMENT LENGTH - 2ND STAGE----,1PE12.5, 2 2X, 2HCM ///)		
	120	110 FORMAT(5X,30HELEMENT CROSS SEC-1ST STAGE---,1PE12.5,2X, 1 3HCM2,18X,30HELEMENT CROSS SEC-2ND STAGE---,1PE12.5, 2 2X, 3HCM2 ///)		
	121	END		

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SYMBOL TABLE - APPENDIX C

S1	-	Total average seebeck coefficient per couple, stage 1
S2	-	Total average seebeck coefficient per couple, stage 2
RH01	-	Total average resistivity per couple, stage 1
RH02	-	Total average resistivity per couple, stage 2
THCN1	-	Total average thermal conductivity per couple, stage 1
THCN2	-	Total average thermal conductivity per couple, stage 2
THI	-	Hot junction temperature - stage 1
TH2	-	Hot junction temperature - stage 2
VLD	-	Load voltage
THINS	-	Thermal conductivity of the insulation material
ETAPC	-	Thermodynamic efficiency of the power conditioning unit
EMUC	-	Corrected average degradation rate for apportioned reliability requirements
TIME	-	Mission time - hours
QH	-	Heat flux density at generator heated area
COLPA	-	Contact loss parameter
PSYST	-	System power level
PARC	-	Number of parallel circuits
ETA1	-	Thermodynamic efficiency of couples in stage 1

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ETA2 - Thermodynamic efficiency of couples in stage 2
PADC - Packing density of T.E. material
RMIS1 - Mismatch ratio - stage 1
RMIS2 - Mismatch ratio - stage 2
IPAGE - Page number
PGENT - Gross electrical power generated
RLOAD - Generator load resistance
COCUR - Couple current
ELAR1 - L/A ratio - stage 1
ELAR2 - L/A ratio - stage 2
RES1 - Resistivity - stage 1
RES2 - Resistivity - stage 2
EL1 - Element length - stage 1
EL2 - Element length - stage 2
ACRO1 - Element cross sectional area - stage 1
ACRO2 - Element cross sectional area - stage 2
QLOS1 - Heat loss bypassing elements - stage 1
QLOS2 - Heat loss bypassing elements - stage 2
QIN - Heat flux required
ETACAS - Efficiency of cascaded system
ENI - Number of couples, stage 1
EN2 - Numbers of couples, stage 2

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APPENDIX II-D

RELIABILITY ANALYSIS OF SERIES AND SERIES-
PARALLEL CONFIGURATIONS OF THERMOCOUPLES
IN THERMOELECTRIC GENERATORS

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Appendix II-D - Reliability Analysis of Series and Series-Parallel Configurations of Thermocouples in Thermoelectric Generators.

The analysis is made under the following assumptions.

1. Failure occurs through catastrophic failure of couples only.
2. The circuit is subject only to failures which occur at random intervals and the failure rate is constant.
3. The circuit is subject only to failures of couples and not to failures of electrical connections between couples.
4. All couples in the circuit have an equal failure rate.

The reliability of the individual couple in any circuit configuration is

$$RECO = \text{EXP} (-FALRAT \cdot \text{TIME}) \quad (1)$$

where

RECO = reliability of the individual couple

FALRAT = (constant) failure rate, number of couples per hr.

TIME = mission length, hr.

The reliability of SERJ couples in series is

$$REMOD = \text{EXP} (-SERJ \cdot FALRAT \cdot \text{TIME}) \quad (2)$$

The reliability of PARC parallel circuits each of SERJ couples in series is

$$REMOD = 1 - [1 - \text{EXP} (-SERJ \cdot FALRAT \cdot \text{TIME})]^{PARC} \quad (3)$$

$$REMOD = [1 - [1 - \text{EXP} (\cdot FALRAT \cdot \text{TIME})]^{PARC}]^{SERJ} \quad (4)$$

If the occurrence of LLCAT catastrophic couple failures can be accepted, i.e., if LLCAT catastrophic couple failures is not equated with circuit failure then

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$$\text{REMODK} = \sum_{l=0}^{\text{LLCAT}} \text{PARC} \cdot \left(\frac{\text{SERJ}}{I} \right) \cdot [\text{EXP}(-\text{FALRAT} \cdot \text{TIME})]^{\text{PARC} \cdot \text{SERJ} - I} \cdot [1 - \text{EXP}(-\text{FALRAT} \cdot \text{TIME})]^I \quad (5)$$

The formulae listed above were coded in FORTRAN-IV language. Subroutine CATRE, the program for calculation of circuit reliabilities using the above formulae was incorporated in the thermoelectric generator described in Appendices A, B, and C. Subroutine CATRE utilizes an internal option NAMTEL. Setting NAMTEL = 0 causes subroutine CATRE to compute the formulae (1) and (3). The reliabilities thus calculated are of importance in considering the reliability of thermoelectric wire-type generators in which bundles of series-connected couples are connected in parallel. NAMTEL=1 causes CATRE to determine (1) and (5). These reliability parameters are usually being considered in the determination of the reliability of series circuits with larger-than-zero fold redundancy of the individual couples, a circuit configuration common to semiconductor material thermoelectric generators.

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SYMBOL TABLE - APPENDIX "D"

NAMTEL	- option control for selection of calculation procedure required for 0-for wire generator, 1-for semiconductor generator.
LLCAT	- number of catastrophic couple failures allowed
PARC	- number of parallel circuits
SERJ	- number of series couples
TIME	- mission length
FALRAT	- number of couple failures/time
RECO	- reliability of the individual couple
REMOD	- reliability of PARC parallel circuits each of SERJ couples in series
REMODK	- reliability of a circuit consisting of SERJ couples with PARC - fold redundancy of each couple and with LLCAT allowable catastrophic couple failures

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APPENDIX II-E

THERMOELECTRIC AND PHYSICAL DATA FOR
VARIOUS MATERIALS OF POTENTIAL VALUE
TO LARGE MILLIWATT THERMOELECTRIC
GENERATOR SYSTEMS

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CONTENTS

(Note: Thermoelectric properties data for candidate materials are presented on facing pages.)

<u>Material</u>	<u>Page</u>
Bismuth Telluride, N-Type (ASARCO)	
Bismuth Telluride, P-Type (ASARCO)	
Lead Telluride, N-Type (MMM-TEGS-3N)	
Lead-Tin-Telluride, P-Type (MMM-TEGS-3P)	
Lead Telluride, N-Type (MMM-TEGS-2N)	
Lead Telluride, P-Type (MMM-TEGS-2P)	
MCC 40, N-Type (Monsanto)	
MCC 40, P-Type (Monsanto)	
Silicon Germanium Alloy, N-Type (RCA).	
Silicon Germanium Alloy, P-Type (RCA).	
Cupron Special (Wilbur B. Driver).	
Tophel Special (Wilbur B. Driver).	
Platinel 7674 N (Engelhard Industries).	
Platinel 5355 P (Engelhard Industries)	
Chromel - P (Hoskins).	
Constantan (Driver-Harris)	

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Appendix II-E - Thermoelectric and Physical Data
For Various Materials of Potential Value to Large
Milliwatt Thermoelectric Generator Systems.

Technical literature and sales brochures issued by suppliers of thermoelectric materials were reviewed in preparing for this parametric study. The review showed that the information available in many instances was not adequate for the large milliwatt generator program. Visits to material suppliers produced additional information, but frequently the entire body of data available consisted of single point data only. The paucity of reliability data was particularly noticeable.

The following pages summarize the thermoelectric and physical data of various materials which appeared promising for use in large milliwatt thermoelectric generator systems. In some cases, a few extrapolations were necessary to complete the thermoelectric property-vs-temperature plots. Extrapolated and calculated parts of the curves are designated by broken lines. For the wire thermocouple materials, the thermal conductivities were computed with the Wiedemann-Frank law from the corresponding resistivities.

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Thermoelectric Properties of
BISMUTH TELLURIDE, N-TYPE (ASARCO)

BISMUTH TELLURIDE, N-TYPE (ASARCO)

Useful Temperature Range (°C): R. T. -270
Melting Point (°C): 592
Melting Range (°C): 587 - 592

Composition: Bi_2Te_3
Dopant:

Density (gm cm^{-3}): 7.70
Sp.Heat ($\text{cal gm}^{-1}\text{°C}^{-1}$):
Coeff.of Lin.Th.Exp.(°C^{-1}): 1.40×10^{-5} avg.
Vapor Press (mmHg): neglig. below 300°C
Tensile Strength (psi):
Compressive Strength (psi):
Young's Modulus (psi):
Yield Point (psi):
Modulus of Rupture (psi):

Shape
Limitations: min. cross section
 $0.1 \times 0.1 \text{ cm}^2$
max. L/A
 $6 \times 10^2 \text{ cm}^{-1}$

Contacting
Methods: electroplated copper
on nickel barrier

Environmental Stability: air to 200°C
vacuum to 250°C
inert atm to 250°C

Radiation Stability: See ref. 1 and 2

Materials Compatibility:

- Refs.: 1. USAEC REP. No. WCAP 1680,
May 1962.
2. J. Appl. Phys. Vol. 34,
No. 9, Sept. 1963.
3. Letter 11.4.65. Iobst to
Sonnenschein.
4. Letter 1.10.66 Beere to
Iobst.

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Thermoelectric Properties of
BISMUTH TELLURIDE, P-TYPE (ASARCO)

BISMUTH TELLURIDE, P-TYPE (ASARCO)

Useful Temperature Range (°C): R. T. - 270
Melting Point (°C): 601
Melting Range (°C): 698 - 604

Composition: Bi_2Te_3
Dopant:

Density (gm cm^{-3}): 6.76
Sp. Heat ($\text{cal gm}^{-1}\text{°C}^{-1}$):
Coeff. of Lin. Th. Exp. (°C^{-1}): 1.40×10^{-5}
Vapor Press (mmHg): neglig. below 300°C
Tensile Strength (psi):
Compressive Strength (psi):
Young's Modulus (psi):
Yield Point (psi):
Modulus of Rupture (psi):

Shape
Limitations: min. cross section
 $0.1 \times 0.1 \text{ cm}^2$
max. L/A
 $6 \times 10^2 \text{ cm}^{-1}$

Contracting
Methods: electroplated copper
on nickel barrier

Environmental Stability: air to 250°C
vacuum to 250°C
inert atm to 250°C

Radiation Stability: See ref. 1 and 2

Materials Compatibility:

- Refs.: 1. USAEC REP. No. WCAP 1680, May 1962.
2. J. Appl. Phys. Vol. 34, No. 9, Sept. 1963.
3. Letter 11.4.65. Iobst to Sonnenschein.
4. Letter 1.10.66 Beere to Iobst.

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Thermoelectric Properties of
LEAD TELLURIDE, N-TYPE (MMM-TEGS-3N)

LEAD TELLURIDE, N-TYPE (MMM-TEGS-3N)

Useful Temperature Range (°C): R. T. - 600

Melting Point (°C):

Melting Range (°C):

Composition: PbTe

Dopant: PbI₂

Density (gm cm⁻³): 8.15
 Sp. Heat(cal gm⁻¹°C⁻¹):
 Coeff.of Lin.Th.Exp. (°C⁻¹): 1.8 x 10⁻⁵ avg.
 Vapor Press. (mmHg): 10⁻⁴ at 500°C
 Tensile Strength (psi): >10³
 Compressive Strength (psi): >10⁴
 Young's Modulus (psi): 2 x 10⁻⁶
 Yield Point (psi):
 Modulus of Rupture (psi):

Shape max. length 2.5 cm
 Limitations: max. L/A, 60 cm⁻¹
 Contacting hot side: pressure
 Methods: contact to iron
 cold side: soft solder
 up to 160°C

Environmental Stability: oxidizes in air
 inert atm. to 500°C

Radiation Stability: See refs. Advanced
 Energy Conversion,
 Vol. 2. pp. 79-85. 1962

Materials Compatibility: iron and low carbon steel
 silica insulation

- Refs.: 1. 3M Electrical Products
 Catalog C 297/10,
 August 31, 1959.
 2. Lead Telluride Alloys and
 Junctions. Thermoelectric
 Materials and Devices,
 Reinhold Publishing Corp.,
 N.Y. 1960.

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Thermoelectric Properties of
LEAD-TIN-TELLURIDE, P-TYPE (MMM-TEGS-3P)

LEAD-TIN-TELLURIDE, P-TYPE (MMM-TEGS-3P)

Useful Temperature Range (°C): R. T. - 600
Melting Point (°C): 840
Melting Range (°C):

Composition: (PbSn)Te
Dopant:

Density (gm cm⁻³): 6.7
Sp.Heat(cal gm⁻¹°C⁻¹):
Coeff.of Lin.Th.Exp.(°C⁻¹): 1.8x10⁻⁵
Vapor Press (mmHg): ~10⁻⁴ at 500°C
Tensile Strength (psi): >5x10²
Compressive Strength (psi): >10⁴
Young's Modulus (psi): 2x10⁶
Yield Point (psi):
Modulus of Rupture (psi):

Shape
Limitations: max. length 2.5 cm
max. L/A, 60 cm⁻¹

Environmental Stability: oxidizes in air Refs.: 1. 3M Electrical Products
inert atm to 500°C Catalog C 297/10,
August 31, 1959.

Radiation Stability: See refs. Advanced
Energy Conversion 2. Lead Telluride Alloys
Vol. 2. pp. 79-85. 1962 and Junctions. Thermo-
electric Materials and
Devices, Reinhold Publish-
ing Corp., N.Y. 1960.

Materials Compatibility: iron and low carbon steel
silica insulation

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Thermoelectric Properties of
LEAD TELLURIDE, N-TYPE (MMM-TEGS-2N)

LEAD TELLURIDE, N-TYPE (MMM-TEGS-2N)

Useful Temperature Range (°C): R. T. - 600
Melting Point (°C): 931
Melting Range (°C):

Composition: PbTe
Dopant: PbI₂

Density (gm cm⁻³): 8.15
Sp.Heat (cal gm⁻¹°C⁻¹):
Coeff.of Lin.Th.Exp.(°C⁻¹): 1.8x10⁻⁵ avg.
Vapor Press (mmHg): 10⁻⁴ at 500°C
Tensile Strength (psi): >10³
Compressive Strength (psi): >10⁴
Young's Modulus (psi): 2x10⁻⁶
Yield Point (psi):
Modulus of Rupture (psi):

Shape
Limitations: max. length 2.5 cm
max. L/A, 60 cm⁻¹
Contacting
Methods: hot side: pressure
contact to iron
cold side: soft solder
up to 160°C

Environmental Stability: oxidizes in air
inert atm to 500°C

Radiation Stability: See refs. Advanced
Energy **Conversion**
Vol. 2. pp 79-85. 1962

Materials Compatibility: iron and low carbon steel
silica insulation

- Refs.: 1. 3M Electrical Products
Catalog C 297/10,
August 31, 1959.
2. Lead Telluride Alloys
and Junctions. Thermo-
electric Materials and
Devices, Reinhold Publish-
ing Corp., N.Y. 1960

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Thermoelectric Properties of
LEAD TELLURIDE, P-TYPE (MMM-TEGS-2P)

LEAD TELLURIDE, P-TYPE (MMM-TEGS-2P)

Useful Temperature Range (°C): R. T. - 600
Melting Point (°C): 931
Melting Range (°C):

Composition: PbTe
Dopant: Na

Density (gm cm⁻³): 8.15
Sp.Heat (cal gm⁻¹°C⁻¹):
Coeff.of Lin.Th.Exp.(°C⁻¹): 1.8×10^{-5} avg.
Vapor Press (mmHg): 10^{-4} at 500°C
Tensile Strength (psi): $>10^3$
Compressive Strength (psi): $>10^4$
Young's Modulus (psi): 2×10^6
Yield Point (psi):
Modulus of Rupture (psi):

Shape
Limitations: max. length 2.5 cm
max. L/A, 60 cm⁻¹
Contacting
Methods: hot side: pressure
contact to iron
cold side: soft solder
up to 160°C

Environmental Stability: oxidizes in air
inert atm to 500°C

Radiation Stability: See refs. Advanced
Energy Conversion
Vol. 2. pp. 79-85. 1962

Materials Compatibility: iron and low carbon steel
silica insulation

- Refs.: 1. 3M Electrical Products
Catalog C 297/10,
August 31, 1959.
2. Lead Telluride Alloys
and Junctions. Thermo-
electric Materials and
Devices, Reinhold Publish-
ing Corp., N.Y. 1960.

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Thermoelectric Properties of
MCC 40, N-TYPE (MONSANTO)

MCC 40, N-TYPE (MONSANTO)

Useful Temperature Range (°C): R. T. - 900
Melting Point (°C):
Melting Range (°C): 1050 - 1330

Composition: Modified SiGe
Dopant:

Density (gm cm⁻³): 3.4
Sp.Heat (cal gm⁻¹°C⁻¹): 1.8x10⁻³ avg. to 900°C
Coeff.of Lin.Th.Exp.(°C⁻¹): 4.2x10⁻⁶ avg. to 1000°C
Vapor Press (mmHg):
Tensile Strength (psi):
Compressive Strength (psi):
Young's Modulus (psi):
Yield Point (psi):
Modulus of Rupture (psi):

Shape
Limitations: max. length 4.0cm
max. L/A 5x10²cm⁻¹

Contacting
Methods: Integral bond to graphite,
tungsten

Environmental Stability: vacuum to 900°C

Radiation Stability:

Materials Compatibility: graphite, tungsten

Thermoelectric properties of
MCC 40, P-TYPE (MONSANTO)

MCC 40, P-TYPE (MONSANTO)

Useful Temperature Range (°C): R. T. - 900
Melting Point (°C):
Melting Range (°C): 1100 - 1300

Composition: Modified SiGe
Dopant:

Density (gm cm⁻³): 3.4
Sp.Heat (cal gm⁻¹°C⁻¹): 1.8x10⁻³ avg. to 900°C
Coeff.of Lin.Th.Exp.(°C⁻¹): 4.1x10⁻⁶ avg. to 1000°C
Vapor Press (mmHg):
Tensile Strength (psi):
Compressive Strength (psi):
Young's Modulus (psi):
Yield Point (psi):
Modulus of Rupture (psi):

Shape
Limitations: max. length 4.0cm
max. L/A 5x10²cm⁻¹

Contacting
Methods: integral bond to
graphite, moly-
bdenum, tungsten

Environmental Stability: vacuum to 900°C

References:

Radiation Stability:

Materials Compatibility: graphite, molybdenum,
tungsten

REF ID: A66710

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Thermoelectric Properties of
SILICON GERMANIUM ALLOY, N-TYPE (RCA)

SILICON GERMANIUM ALLOY, N-TYPE (RCA)

Useful Temperature Range (°C): R. T. - 1000
Melting Point (°C):
Melting Range (°C): 1200 - 1324

Composition: SiGe
Dopant: As

Density (gm cm ⁻³):	3.42	Shape	
Sp.Heat (cal gm ⁻¹ °C ⁻¹):	0.13 avg. to 900°C	Limitations:	min. cross section
Coeff.of LinTh.Exp.(°C ⁻¹):	4.8x10 ⁻⁶ avg. to 900°C		0.1x0.1 cm
Vapor Press (mmHg):			max. L/A
Tensile Strength (psi):	4.4x10 ³ at 500°C		10 ² cm ⁻¹
Compressive Strength (psi):	>1.5x10 ⁵		
Young's Modulus (psi):		Contacting	
Yield Point (psi):		Methods:	
Modulus of Rupture (psi):	4x10 ³		

Environmental Stability: air to 700°C
vacuum to 900°C

Radiation Stability:

Materials Compatibility:

- Refs.: 1. RCA Bulletin
"Thermoelectrics",
March 1962.
2. RCA Bulletin, July
1964.

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Thermoelectric Properties of
SILICON GERMANIUM ALLOY, P-TYPE (RCA)

SILICON GERMANIUM ALLOY, P-TYPE (RCA)

Useful Temperature Range (°C): R. T. - 1000
Melting Point (°C):
Melting Range (°C): 1200 - 1324

Composition: SiGe
Dopant: B

Density (gm cm⁻³): 3.42
Sp.Heat (cal gm⁻¹°C⁻¹): 0.13 avg. to 900°C
Coeff.of Lin.Th.Exp.(°C⁻¹): 4.8x10⁻⁶ avg. to 900°C
Vapor Press (mmHg):
Tensile Strength (psi): 3.9x10³ at 500°C
Compressive Strength (psi): >1.5x10⁵
Young's Modulus (psi):
Yield Point (psi):
Modulus of Rupture (psi): 3.3x10³

Shape
Limitations: min.cross section
0.1x0.1 cm
max. L/A
10² cm⁻¹

Contacting
Methods:

Environmental Stability: air to 700°C
vacuum to 900°C

Radiation Stability:

Materials Compatibility:

- Refs.: 1. RCA Bulletin
"Thermoelectrics",
March 1962
2. RCA Bulletin, July
1964

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Thermoelectric Properties of
CUPRON SPECIAL (WILBUR B. DRIVER)

CUPRON SPECIAL (WILBUR B. DRIVER)

Useful Temperature Range (°C): R.T. - 900
Melting Point (°C): 1250
Melting Range (°C):

Composition: 59.5 Cu-40 Ni-0.5Mn
Dopant:

Density (gm cm⁻³): 8.90
Sp.Heat (cal gm⁻¹°C⁻¹): 0.094 at 20°C
Coeff.of Lin.Th.Exp.(°C⁻¹): 1.49×10^{-5} to 100°C
Vapor Press (mmHg):
Tensile Strength (psi): 4.5×10^4
Compressive Strength (psi):
Young's Modulus (psi):
Yield Point (psi): 2.6×10^4
Modulus of Rupture (psi):

Shape
Limitations: wire, ribbon
Contacting
Methods: resistance welding
inert gas welding

Environmental Stability: air to 700°C
vacuum to 900°C
inert atm to 900°C

Refs.: 1. New Alloy for High EMF
Generation, Wilbur B.
Driver Co., Newark, N.J.

Radiation Stability:

2. Letter Niebling to Carney,
12-15-65

Materials Compatibility:

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Thermoelectric Properties of
TOPHEL SPECIAL (WILBUR B. DRIVER)

TOPHEL SPECIAL (WILBUR B. DRIVER)

Useful Temperature Range (°C): R. T. - 1000
Melting Point (°C): 1450
Melting Range (°C):

Composition: 90Ni -10Cr
Dopant:

Density (gm cm⁻³): 8.63
Sp.Heat (cal gm⁻¹°C⁻¹): 0.11 at 20°C
Coeff.of Lin.Th.Exp.(°C⁻¹): 1.63×10^{-5} to 750°C
Vapor Press (mmHg):
Tensile Strength (psi): 6.2×10^4
Compressive Strength (psi):
Young's Modulus (psi):
Yield Point (psi): 3.2×10^4
Modulus of Rupture (psi):

Shape
Limitations: wire, ribbon
Contacting
Methods: resistance welding
torch welding
inert gas welding

Environmental Stability: air to 900°C

Radiation Stability:

Materials Compatibility:

- Refs.: 1. New Alloys for High EMF
Generation, Wilbur B.
Driver Co., Newark, N.J.
2. Letter Niebling to Carney,
12-15-65

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Thermoelectric Properties of
PLATINEL 7674 N (ENGELHARD INDUSTRIES)

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PLATINEL 7674 N (ENGELHARD INDUSTRIES)

Useful Temperature Range (°C): R. T. - 1300
Melting Point (°C): 1447
Melting Range (°C):

Composition: Au-65, Pd-35
Dopant:

Density (gm cm⁻³): 15.91
Sp. Heat (cal gm⁻¹°C⁻¹):
Coeff. of Lin. Th. Exp. (°C⁻¹):
Vapor Press (mmHg):
Tensile Strength (psi): 6.6x10³ at 1000°C
Compressive Strength (psi):
Young's Modulus (psi):
Yield Point (psi):
Modulus of Rupture (psi):

Shape
Limitations: wire

Contacting
Methods:

Environmental Stability: air to 1300°C
reducing atm. to 1000°C
not for use in vacuum

Radiation Stability:

Materials Compatibility: high purity Al₂O₃

References:

1. Temperature - Its Meas. in Science & Industry, Vol. 3, Part 2, 1962
2. J. Res. N.B.S. Vol. 68C No. 4, Oct-Dec 1964
3. Engelhard Industries, Data File, Rev. 1.5.65.

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Thermoelectric Properties of
PLATINEL 5355 P (ENGELHARD INDUSTRIES)

PLATINEL 5355 P (ENGELHARD INDUSTRIES)

Useful Temperature Range (°C): R. T. - 1300
Melting Point (°C): 1608
Melting Range (°C):

Composition: Pd-55, Pt-31, Au-14
Dopant:

Density (gm cm⁻³): 14.93
Sp.Heat (cal gm⁻¹°C⁻¹):
Coeff.of Lin.Th.Exp.(°C⁻¹):
Vapor Press (mmHg):
Tensile Strength (psi): 1.16x10⁴ at 1000°C
Compressive Strength (psi):
Young's Modulus (psi):
Yield Point (psi):
Modulus of Rupture (psi):

Shape
Limitations: wire

Contacting
Methods:

Environmental Stability: air to 1300°C
reducing atm. to
1000°C
not for use in
vacuum

References: same as for
7674

Radiation Stability:

Materials Compatibility: high purity Al₂O₃

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Thermoelectric Properties of
CHROMEL - P (HOSKINS)

CHROMEL - P (HOSKINS)

Useful Temperature Range (°C): R. T. - 1000
Melting Point (°C): 1430
Melting Range (°C):

Composition: 90 Ni - 10 Cr
Dopant:

Density (gm cm⁻³): 8.73
Sp.Heat (cal gm⁻¹°C⁻¹): 0.107 at 20°C
Coeff.of Lin.Th.Exp.(°C⁻¹): 1.67x10⁻⁵ avg. to 1000°C
Vapor Press (mmHg):
Tensile Strength (psi): 1.65x10⁴ at 1000°C
Compressive Strength (psi):
Young's Modulus (psi):
Yield Point (psi):
Modulus of Rupture (psi):

Shape
Limitations: wire, sheet

Contacting
Methods: resistance welding
torch welding
inert gas welding
brazing

Environmental Stability: air to 1000°C

Radiation Stability:

Materials Compatibility:

Refs.: Thermoelectric Properties
and Design Data for Temperature
Measurements, Driver-
Harris Company, 1959

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Thermoelectric Properties of
CONSTANTAN (DRIVER-HARRIS)

CONSTANTAN (DRIVER-HARRIS)

Useful Temperature Range (°C): R. T. - 900
Melting Point (°C):
Melting Range (°C): 1220 - 1290

Composition: 45Ni - 55 Cu
Dopant:

Density (gm cm ⁻³):	8.9	Shape	
Sp.Heat (cal gm ⁻¹ °C ⁻¹):	0.094	Limitations:	wire, sheet and castings
Coeff.of Lin.Th.Exp. (°C ⁻¹):	1.88x10 ⁻⁵ to 1000°C		
Vapor Press (mmHg):			
Tensile Strength (psi):	1.35x10 ⁵ cold worked		
Compressive Strength (psi):		Contacting	resistance welding
Young's Modulus (psi):		Methods:	torch welding
Yield Point (psi):	2.1x10 ⁴		inert gas welding
Modulus of Rupture (psi):			brazing

Environmental Stability: air to 900°C Refs.: Metals Handbook, A S M, 1960

Radiation Stability:

Materials Compatibility:

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Supplement to Appendix II-E - Thermoelectric
Properties of MCC 40 N/P Materials

The data in this supplement supercede the data presented on pages 248 - 251. They are based on measurements performed during the period January 1, 1966 through April 10, 1966 and reflect the continued development of the MCC 40 N/P materials.

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* $k = .032$ watts/cm $^{\circ}\text{K}$ at 53°C ; curvature estimate from data for hot pressed MCC 40N

Thermoelectric Properties of MCC 40, N-TYPE (MONSANTO)

MCC 40, N-TYPE (MONSANTO)

Useful Temperature Range (°C): R. T. - 900°
Melting Point (°C):
Melting Range (°C): 1050 - 1330

Composition: modified silicon-germanium (proprietary)
Dopant:

Density (gm cm⁻³): 3.4
Sp.Heat (cal gm⁻¹°C⁻¹): 1.8x10⁻³ avg. to 900°C
Coeff.of Lin.Th.Exp.(°C⁻¹): 4.2x10⁻⁶ avg. to 1000°C
Vapor Press (mmHg):
Tensile Strength (psi):
Compressive Strength (psi):
Young's Modulus (psi):
Yield Point (psi):
Modulus of Rupture (psi):

Shape Essentially any shape
Limitations: may be fabricated;
optimum design determines
max. length and/or
max. L/A
Contacting
Methods: integral bond to
graphite, tungsten

Environmental Stability: vacuum to 900°C

Radiation Stability:

Materials Compatibility: graphite, tungsten

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* $k = .036$ watts/cm $^{\circ}\text{K}$ at 32°C ; curvature estimated from data for hot pressed MCC 40P

Thermoelectric Properties of MCC 40, P-TYPE (MONSANTO)

MCC 40, P-TYPE (MONSANTO)

Useful Temperature Range (°C): R. T. - 900
Melting Point (°C):
Melting Range (°C): 1100 - 1300

Composition: modified silicon-germanium (proprietary)
Dopant:

Density (gm cm⁻³): 3.4
Sp.Heat (cal gm⁻¹°C⁻¹): 1.8×10^{-3} avg. to 900°C
Coeff.of Lin.Th.Exp.(°C⁻¹): 4.1×10^{-6} avg. to 1000°C
Vapor Press (mmHg):
Tensile Strength (psi):
Compressive Strength (psi):
Young's Modulus (psi):
Yield Point (psi):
Modulus of Rupture (psi):

Shape
Limitations: Essentially any shape
may be fabricated;
optimum design determines
max. length and/or
max. L/A
Contacting
Methods: integral bond to
graphite, moly-
bdenum, tungsten

Environmental Stability: vacuum to 900°C

References:

Radiation Stability:

Materials Compatibility: graphite, molybdenum,
tungsten

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APPENDIX III-A

CHARACTERISTICS AND FUEL FORMS
VS LINER CAVITY POWER DENSITY
FOR STRONTIUM-90

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APPENDIX III-A

STRONTIUM-901. RADIOISOTOPE

There are 16 known isotopes of strontium, of which four are stable and found in nature. Fission by U-235 or Pu-239 and decay of the fission products forms all strontium isotopes except the lightest five. The longest lived radioisotope from fission is Sr-90 (27.7 yr) and the second longest is Sr-89 (54 days), so that approximately one year after removal from the reactor the radioactive portion of strontium fission products is essentially pure Sr-90. Unfortunately, fission product decay also forms the stable isotopes, Sr-86, Sr-87 and Sr-88, so that the optimum practical ratio of Sr-90 to total strontium is about 50%.

The formation and decay scheme for Sr-90 is:

Since the half-life for Y-90 is so much shorter than for Sr-90, Y-90 is in secular equilibrium and its rate of decay (events per time unit) is governed by the rate of decay of Sr-90. The total energy release (6.772 w/kc) is therefore the sum of energy released by Sr-90 (1.184 w/kc) and Y-90 (5.558 w/kc).

Decay of Sr-90 and Y-90 releases beta particles, but no gamma photons; however, bremsstrahlung by the betas does produce x-rays. The x-rays from Y-90 bremsstrahlung, particularly above 0.8 Mev, are of significance in radiation shielding (see Table III-2), and, by comparison, the beta particles and Sr-90 bremsstrahlung x-ray can be neglected.

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The sum of the energy in the x-rays is less than 1% of the decay energy, and since the range of beta particles is very short in solid matter, nearly all the heat deposition occurs in the fuel. By contrast, a nuclide like Co-60, for which the larger portion of decay energy is in the gamma photons (with a longer range) will deposit an appreciable portion of its heat beyond the fuel.

Strontium is a Group II element with properties and compounds similar to calcium and barium. Because of its chemical similarity to calcium, radiostrontium (Sr-90) is an unusually hazardous material and has been assigned a very low MPC (maximum permissible concentration). Strontium taken up in the ecological cycle, or entering the body directly through inhalation and ingestion, will interchange with calcium and thereby become concentrated in components of normally high calcium concentration, such as bone.

Significant features of Sr-90 as a fuel are:

- 1) It has a relatively high fission yield ensuring availability and low cost for heat source applications.
- 2) It has a long half-life.
- 3) It has a reasonably high power density (due principally to the daughter nuclide, Y-90).
- 4) Hot cell processes for heat source formation have been proven.
- 5) It requires radiation shielding.

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2. FUEL FORMS VS. LINER CAVITY POWER DENSITY

The available combinations of Sr-90 fuel compound and densification process are compared in terms of the net power density for the liner cavity, assuming the cavity length-to-diameter ratio is one. Values are shown for 15 and 30 w(t), representative of the low and high strontium power requirements for the application.

(a) FUEL FORMS ANALYZED ARE:

- 1) SrTiO_3 , cold-pressed, sintered and loaded into the liner
- 2) SrTiO_3 , step-pressed in the liner
- 3) SrTiO_3 , hot-pressed and loaded into the liner
- 4) Sr_2TiO_4 , step-pressed in the liner
- 5) SrF_2 , step-pressed in the liner
- 6) SrO , hot-pressed (in Pt foil) and loaded into the liner

(b) ASSUMPTIONS

- 1) Thermal power, P 15 and 30 w
- 2) Fuel and liner geometry right circular cylinder
- 3) Number of pellets per liner one
- 4) Fuel to cavity clearance (gap):

Axial, L_g	0.100 in.
Diametral, D_2 , cold-press	0.050 in.
step press	0
hot-press	0.020 in. + 0.010 in foil

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(c) BULK FUEL POWER DENSITY, W_f (see Table III-8 for basic data)

- 1) $SrTiO_3$, cold pressed and sintered

$$W_f = \left(\frac{142}{148}\right) (0.5) \left(\frac{89}{185}\right) (0.95) (5.11) (0.8) \cong 0.90 \text{ w/cc}$$

- 2) $SrTiO_3$, step-pressed in the liner

$$W_f = (1.12) (0.75) = 0.84 \text{ w/cc}$$

- 3) $SrTiO_3$, hot-pressed

$$W_f = (1.12) (0.90) \cong 1.0 \text{ w/cc}$$

- 4) Sr_2TiO_4 , step-pressed

$$W_f = \left(\frac{142}{148}\right) (0.5) \left(\frac{2 \times 89}{290}\right) (0.95) (5.0) (0.7) \cong 1.0 \text{ w/cc}$$

- 5) SrF_2 , step-pressed

$$W_f = \left(\frac{142}{148}\right) (0.5) \left(\frac{89}{127}\right) (0.95) (4.24) (0.9) \cong 1.2 \text{ w/cc}$$

- 6) SrO , hot-pressed (foil not included)

$$W_f = \left(\frac{142}{148}\right) (0.5) \left(\frac{89}{105}\right) (0.95) (4.0^*) (0.9) \cong 1.4 \text{ w/cc}$$

* Assumed crystalline density, rather than 4.7 gm/cc to account for the effect of impurities.

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(d) RELATIONSHIPS

Liner cavity volume, $V_c = (16.38) \frac{\pi}{4} D_c^2 L_c$ cc,

for all linear dimensions in inches. Since $L_c = D_c$,

$$V_c = 12.86 D_c^3 \quad (1)$$

Bulk fuel volume, $V_f = 12.86 D_f^2 L_f = \frac{P}{W_f}$

Since $D_c = D_f + D_g = L_c = L_f + L_g$,

$L_f = D_f + D_g - L_g$, and

$$(12.86) D_f^2 (D_f + D_g - L_g) = \frac{P}{W_f} \quad (2)$$

Finally, power density with respect to liner cavity volume,

$$W_c = P/V_c \text{ (w/cc)}. \quad (3)$$

The results of the analysis are shown in Table III-9.

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APPENDIX III-B

CHARACTERISTICS AND FUEL FORM
VS LINER CAVITY POWER DENSITY
FOR PLUTONIUM-238

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APPENDIX III-B

PLUTONIUM-2381. RADIOISOTOPE

Plutonium does not occur in nature but at least 14 isotopes have been made in reactors and accelerators. Plutonium-238 can be made by two paths in a reactor, starting with uranium. In the path that yields the greater amount of product, Np-237 (neptunium) is formed, separated from the uranium fuel and re-irradiated to produce Pu-238. The steps are as follows:

The product is only 80% Pu-238 because of additional neutron captures as follows:

The amounts of the heavier isotopes in Pu-238 fuel are approximately 15% for Pu-239, 2.9% for Pu-240 and 0.8% for Pu-241.

The alternate scheme for producing Pu-238 involves decay of Pu-241 (half-life, 13 yr) to Am-241, chemical separation of Am-241 and re-irradiation. The americium irradiation scheme is

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Plutonium-238 decays by alpha emission with a half-life of 86.4 yr. It is beta-stable, but has a half life at 4.9×10^{10} yr for spontaneous fission. Because of this greater probability for alpha decay, almost all the heat is generated in the alpha particles and deposited in the fuel when these short-range particles are stopped. The slowed-down alpha particles combine with electrons to become helium atoms.

Neutrons from spontaneous fission, and in the case of PuO_2 fuel, from (α, n) reactions in O-18, are the major shielding problems with Pu-238. However, the neutron abundance is low, approximately 2×10^4 n/sec/gm, and shielding gained from normal construction of the system frequently is adequate. Gamma and x-ray are associated with all decays and interactions of Pu-238 and its impurities. The most significant photons are the 0.8 Mev photon from Pu-238 decay and the 2.67 Mev photon from the decay of Te-208, a daughter of the impurity Pu-236 (formed by an n,2n reaction on Np-237, followed by beta decay); but their abundance is too low to be a dose rate or shielding problem in applications like the large milliwatt RTG. Isotopic and other impurities in Pu-238 do not significantly affect the heat generation or shielding requirements for Pu-238 heat sources. The same is true for the decay daughters of Pu-238, due primarily to the long half-life for the first daughter, U-234. The Pu-238 decay scheme is as follows:

Although plutonium is an actinide rare earth element, it can be separated almost quantitatively from the other rare earths. Consequently, the cationic purity of plutonium in Pu-238 heat sources is greater than 99%.

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Plutonium is a "bone seeker" like strontium. Its long half-life, copious local ionization inherent with alpha emission, and low excretion rate, combine to establish a very low MPC for Pu-238.

Significant features of Pu-238 as a fuel are:

- 1) Its requirement of the least shielding of any of the potential radioisotope heat sources.
- 2) Its long half-life.
- 3) Its dependence upon total reactor power in operation to ensure adequate availability at acceptable cost.
- 4) Its reasonable high power density.
- 5) The proven acceptability of hot cell processes for heat source formation.
- 6) Its low MPC.

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2. FUEL CAPSULE DESIGN

Two fuel compounds are recommended for this application, the metal for hot junction temperatures below 1000°F and the oxide at 1000°F and above. Both materials are assumed to be formed into a single pellet per RTG. The metal pellet is cast and contains no matrix material. The oxide pellet is an intimate mixture of PuO_2 and a matrix metal pressed and sintered to the final form. Molybdenum should be used as the matrix material if the liner is a molybdenum-based alloy; tungsten powder should be used with a tungsten-based alloy liner.

The fuel pellet is constrained at one end of the liner by a frame of small volume but the frame is not gas-tight. The liner is sealed by fusion welding and when placed in the capsule, shims are added to limit axial movement. The capsule is sealed by conventional Mound practice which for Hastelloy C consists of a root-pass weld followed one or more filler - pass welds.

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APPENDIX III-C

CHARACTERISTICS AND FUEL FORMS
VS LINER CAVITY POWER DENSITY
FOR PROMETHIUM-147

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APPENDIX III-C

PROMETHIUM-147

1. RADIOISOTOPE

Promethium does not occur in nature and there are no stable isotopes. Ten isotopes have been identified, of which three (Pm-147, Pm-149 and Pm-151) are formed by fission product decay, and three others (Pm-146 and Pm-148m and Pm-148) are formed by (n, 2n) and neutron capture reactions in the reactor.

Pm-148 (5.4d), Pm-149 (50 hr) and Pm-151 (27 hr) decay out in a relatively short time.

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Final purification and use of Pm-147 is delayed about one half-life (2.62 yr) to reduce the Pm-148 m (42 d) fraction to where its radiations (beta and gamma) do not contribute significantly to the fuel dose rate. Since the half-lives of Pm-146 and Pm-147 are reasonably close, the Pm-146 impurity must be accepted in the fuel.

Pm-147 emits a low energy beta (0.225 Mev at 100% of the disintegrations) but no gamma photons. Bremsstrahlung from the Pm-147 beta can be ignored in shielding calculations. Even though the curie ratio of Pm-146 to Pm-147 is about 1/4 ppm at final purification, the photons from Pm-146 are the significant radiation sources in shielding analysis (see Table III-2).

Pm-147 beta particles account for essentially all the heat generated and this heat is deposited almost quantitatively in the fuel.

Promethium is lanthanide rare earth element with properties and compounds similar to the entire rare earth group, but most closely resembling its nearest neighbors neodymium (Nd) and samarium (Sm). It is separated by column elution to a cationic purity at separation of greater than 99%. Considering the relatively short half-life of Pm-147 and the time required to prepare a heat source this purity is assumed reduced to about 95% at the start of a heat source application due to the growth of the daughter nuclide, Sm-147.

The "critical organ" for promethium uptake is bone, but bone affinity for promethium is much less than for strontium and plutonium. Consequently, it is a lesser biological hazard (see Table III-7).

Significant features of Pm-147 as a fuel are:

- 1) Its moderately high fission yield, ensuring availability for limited heat source application
- 2) Its relatively high MPC
- 3) Its reasonably high power density
- 4) Its moderate shielding requirements
- 5) Its unusually high cost per thermal watt, compared to other product heat sources

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6) Its probable qualification for hot cell fuel forming and encapsulation

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2. FUEL FORMS VS. LINER POWER DENSITY

The available (or near-term available) combinations of Pm-147 fuel compounds and densification processes are compared in terms of the net power density for the liner cavity, assuming the cavity length-to-diameter ratio is one. Values are shown for 15 and 45 w(t), representative of the low and high promethium power requirements for this application.

(a) FUEL FORMS ANALYZED:

- 1) Pm_2O_3 , hot-pressed and loaded into the liner
- 2) Pm_2O_3 , step-pressed in the liner
- 3) Pm_2O_3 , compacted in the sealed liner by high energy compaction, followed by machining of the liner to its final size (compaction performed only in thick-walled containers).
- 4) Pm metal , cast pellet and loaded into the liner

(b) ASSUMPTIONS:

- 1) Thermal power, P 15 and 45 w
- 2) Fuel and liner geometry right circular cylinder
- 3) Number of pellets per liner - one
- 4) Fuel to cavity clearance (gap):
 Axial, L_g , (case 3) 0
 , all others 0.100 in.
 Diametral, D_g , (Cases 1 and 4) 0.020 in.
 (Cases 2 and 3) 0

(c) BULK FUEL POWER DENSITY, W_f (see Table III-8 for basic data)

- 1) Pm_2O_3 , hot pressed

$$W_f = \left(\frac{928}{2788}\right) \left(\frac{147 \times 2}{342}\right) (0.95) (7.3) (0.9) = 1.78 \text{ w/cc}$$

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- 2) Pm_2O_3 , step-pressed

$$W_f = (1.98)(0.74) = 1.48 \text{ w/cc}$$

- 3) Pm_2O_2 , high-energy compaction

$$W_f = (1.98)(1.0) = 1.98 \text{ w/cc}$$

- 4) Pm, cast metal

$$W_f = \left(\frac{928}{2788}\right)(0.95)(7.3)(0.95) = 2.19 \text{ w/cc}$$

- (d) RELATIONSHIPS (See Appendix III-D)

The results of this analysis are shown in Table III-10.

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NOTE: These appendixes are numbered according to the text section in which they were cited. Since Section IV did not cite any appendix material, this volume does not include Appendix IV.

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APPENDIX V-A

DATA ON HIGH TEMPERATURE INSULATIONS

This appendix includes, in addition to data sheets containing product descriptions and chemical and physical properties, a list of conversion factors for thermal conductivity units, a brief bibliography of reports pertaining to high temperature insulation materials, and a list of fabricators of such materials.

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DATA SHEET

HIGH TEMPERATURE INSULATION

PRODUCT: "MIN-K"

VENDOR: Johns-Manville Aerospace Products
 22 East 40th Street
 New York, N. Y. 10016

PRODUCT DESCRIPTION: MIN-K insulation is a bonded structure reinforced with fibrous media and containing appreciable quantities of particulate matter, the ultimate structural elements of which are exceedingly small. This creates pores in the structure so minute that a large proportion of the gas molecules collide with the walls of the structure rather than with other molecules. Thus, the amount of heat transferred by molecular conduction is below that which occurs in a still air space. The material also contains an opacifying media which minimizes the transmission of radiant energy through the insulation.

The thermal conductivity of the material decreases with ambient gas pressure and can also be reduced by surrounding the material with a gas whose conductivity is less than air.

<u>MAXIMUM USEABLE TEMPERATURES:</u>	MIN-K-501	MIN-K-1301	MIN-K F-100-10 (Flexible)
	500°F	1300°F	1200°F
<u>NOMINAL DENSITIES, lb/ft³</u>	10	20	10
<u>COMPRESSIVE STRENGTHS:</u> (10% Compression)	32.5psi	200.0 psi	Not to be used as a load bearing material.

<u>Mean Temperature, °F</u>	<u>Thermal Conductivities:</u>		
	k,	Btu (hr)(ft ²)(°F/ft)	
	MIN-K 501	MIN-K-1301	MIN-K F-100-10
100	---	---	0.015
200	0.0117	---	0.0167
300	0.0125	0.0166	---
400	0.0133	0.0175	0.0208
600	---	0.0192	0.0242
800	---	0.0208	0.0292
1000	---	0.0225	---

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DATA SHEET
HIGH TEMPERATURE INSULATION

PRODUCT: Linde Super Insulation

VENDOR: Union Carbide Corporation
Linde Division, Manager of New Ventures,
270 Park Avenue
New York 17, N. Y.
22 Battery Street (Local Office)
San Francisco, Calif. (UYkon 2-1360)

PRODUCT DESCRIPTION:

Linde Super Insulation is an evacuated insulation comprised of multi-layers of highly reflecting metal foil radiation shields and fibrous mats. The Super Insulation system which are custom designed have densities similar to those of conventional insulations, but have thermal conductivities four to forty times lower.

The metal foil radiation shields are as thin as mechanically practical to permit minimum weight and flexible contour fitting of the insulation system. Fibrous mats of glass or quartz separate the shields. Very thin filaments are used to reduce the area of the contact points and to provide a long conduction path through the fibers. The resulting small voids also minimize gaseous conduction.

A vacuum approaching 10^{-3} mm Hg is used to reduce the total number of gas molecules available for gaseous conduction.

OPERATING TEMPERATURE RANGE: -450°F to about 2200°F

THERMAL CONDUCTIVITY:

Figure V-2 in the text showed the "apparent" thermal conductivity for a typical Super Insulation system over the temperature interval between the temperature shown on the abscissa and ambient. It is to be realized that the thermal conductivity of such an insulation system depends on the boundary temperatures, the number and diameter of the fibers separating the shields, the number of shields, the separation of the shields, type of residual gas, the magnitude of the vacuum, and the surface pressure causing compression of the insulation system.

Because each custom designed Super Insulation system will have different characteristics, the conducting values shown on the attached curve are to be considered "typical". A design should be based on data supplied by the vendor for the specific application.

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DATA SHEET
HIGH TEMPERATURE INSULATION

PRODUCT: "Kaowool"

VENDOR: Refractories Division
Babcock and Wilcox Co.
Augusta, Georgia

PRODUCT DESCRIPTION: B&W Kaowool is an alumina-silica ceramic fiber with an average diameter of 2.8 microns and up to 10 in. long formed into blankets of various weight (3, 4, 6 and 8 lb/ft³).

MAXIMUM USEABLE TEMPERATURE: 2300°F (melting point - 3200°F)

ORGANIC BINDERS: None

NOMINAL AVAILABLE WIDTHS: 24 and 48 inches

NOMINAL LENGTH: 24 feet

NOMINAL THICKNESS: 1/4 inch (6 and 8 lb/ft³)
1/2 inch (all densities)
3/4 inch (all densities)
1 inch (all densities)
1-1/2 inch (3, 4 and 6 lb/ft³)
2 inch (3 and 4 lb/ft³)
(1 inch wide by 1 inch thick strips are also available)

<u>CHEMICAL ANALYSIS:</u>	Alumina,	Al ₂ O ₃ - 45.1 percent
	Silica,	SiO ₂ - 51.9
	Iron Oxide,	Fe ₂ O ₃ - 1.3
	Titania,	TiO ₂ - 1.7
	Magnesia,	MgO - Trace
	Calcium,	CaO - 0.1
	Alkalies as	Na ₂ O - 0.2
	Boric Anhydride,	B ₂ O ₃ - 0.08

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"Kaowool" Data Sheet (continued)

THERMAL CONDUCTIVITY:

<u>Mean Temperature</u>	k, $\frac{\text{Btu}}{(\text{ft}^2)(\text{hr})(^\circ\text{F}/\text{ft})}$		
		<u>8 lb/ft³</u>	<u>3 lb/ft³</u>
300°F		0.25	0.031
400		0.029	0.039
500		0.0334	0.049
600		0.0395	0.060
700		0.0442	0.074
800		0.050	0.089
900		0.0575	0.104
1000		0.065	0.122

DATA SOURCE:

B&W Brochure R511-3003 20M

DATA DATE:

May 1963

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DATA SHEET

HIGH TEMPERATURE INSULATION

PRODUCT: "Fiberfrax"VENDOR: Carborundum Co.
Refractories Division
Niagra Falls, New YorkPRODUCT DESCRIPTION: Fiberfrax is an alumina-silica material available in bulk fibers, blankets, rope, paper, textile and several other forms.MAXIMUM USEABLE TEMPERATURE: 2300°FORGANIC BINDER: NoneCHEMICAL ANALYSIS:
Al₂O₃ - 51.2 percent
SiO₂ - 47.1
B₂O₃ - 0.6
Na₂O - 0.5
MgO, CaO, Fe₂O₃ - 0.5 totalSPECIFIC HEAT: 0.24 - 0.28 Btu/lb-°F (For fiber-binder mixture)THERMAL CONDUCTIVITY:

<u>Mean Temperature</u>	<u>Btu</u> <u>(hr)(ft²)(°F/ft)</u>
600°F	0.043
1000	0.061
1400	0.079
1800	0.102
2000	0.113

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DATA SHEET

HIGH TEMPERATURE INSULATION

PRODUCT: Micro-Quartz Felt (3 lb/ft³)

VENDOR: Libby-Owens-Ford Co.
1810 Madison Ave.
Toledo 1, Ohio

PRODUCT DESCRIPTION: Micro-Quartz is composed of 98% pure quartz fibers averaging approximately 1-micron in fiber diameter.

MAXIMUM USEABLE TEMPERATURE: 2279°F

AVAILABLE FORMS: Micro-quartz is available as flexible felt blankets (3/16 in. or 1/2 in. thick) or in bulk form.

THERMAL CONDUCTIVITY:

<u>Mean Temperature</u>	k,	Btu
		<u>(hr)(ft²)(°F/ft)</u>
200°F		0.0216
400		0.0334
600		0.0465
800		0.059
1000		0.0716
1200		0.085
1400		0.097

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DATA SHEET
HIGH TEMPERATURE INSULATION

PRODUCT: Foamglas

VENDOR: Pittsburgh Corning Corp.
One Gateway Center
Pittsburgh 22, Penn.

PRODUCT DESCRIPTION: Foamglas is a cellular glass insulation containing millions of individual, hermetically sealed glass cells, each a tiny dead-air insulating space.

MAXIMUM USEABLE TEMPERATURE: 800°F

DENSITY: 9 lb/ft³

COEFFICIENT OF EXPANSION: $4.6 \times 10^{-6}/^{\circ}\text{F}$

COMPRESSIVE STRENGTH: 100 psi

SPECIFIC HEAT: 0.20 Btu/lb

THERMAL CONDUCTIVITY:

<u>Mean Temperature</u>	$k, \frac{\text{Btu}}{(\text{hr})(\text{ft}^2)(^{\circ}\text{F}/\text{ft})}$
0°F	0.029
50	0.0316
300	0.046

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DATA SHEET

HIGH TEMPERATURE INSULATION

PRODUCT: Thermoflex (RF 300, 3 lbs/ft³)

VENDOR: Johns-Manville Co.
22 East 40th Street
New York, N. Y.

PRODUCT DESCRIPTION: Thermoflex is a light weight refractory - fiber/felt insulation. The fibers average 3 microns in diameter and have a diameter range of 1 to 5 microns.

MAXIMUM USEABLE TEMPERATURE: 2000°F

THERMAL CONDUCTIVITY:

<u>Mean Temperature</u>	$k, \frac{\text{Btu}}{(\text{hr})(\text{ft}^2)(^\circ\text{F}/\text{ft})}$
500	0.046
600	0.054
700	0.063
800	0.074
900	0.085
1000	0.097

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DATA SHEETHIGH TEMPERATURE INSULATIONPRODUCT: Dyna-FlexVENDOR: Johns-Manville Aerospace Products
22 East 40th Street
New York, N. Y. 10016PRODUCT DESCRIPTION: Dyna-Flex is a strong flexible high-temperature felt insulation based on long-fiber alumina-silica chromia fibers.MAXIMUM TEMPERATURE: 2700°FLINEAR SHRINKAGE: 2% at 2400°FDENSITY: 8 lb/cu ftTHERMAL CONDUCTIVITY:

<u>Mean Temperature</u>	$k, \frac{\text{Btu}}{(\text{hr})(\text{ft}^2)(^\circ\text{F}/\text{ft})}$
1000°F	0.0672
1500	0.112

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DATA SHEET

HIGH TEMPERATURE INSULATION

PRODUCT: Refrasil Batt A-100

VENDOR: H. L. Thompson Fiber Glass Co.
1600 W. 135th Street
Gardena, California

PRODUCT DESCRIPTION: Refrasil is a trade name of a variety of products based on vitreous fibers of up to 99% SiO₂. The nominal fiber diameter is 0.00005 inches. The batt is supplied in the form of felted pads.

MAXIMUM USEABLE TEMPERATURE: 2000°F

NOMINAL AVAILABLE WIDTHS: 42 in.

NOMINAL THICKNESS: 0.19 in.

NOMINAL DENSITY: 6.0 lb/ft³ (0.05 available)

NOMINAL BREAKING STRENGTH: 75 gm/in.

THERMAL CONDUCTIVITY:

<u>Mean Temperature</u>	$k, \frac{Btu}{(hr)(ft^2)(^{\circ}F/ft)}$
600°F	0.0375
800	0.046
1000	0.054
1200	0.063
1400	0.075

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DATA SHEET

HIGH TEMPERATURE INSULATION

PRODUCT: SolamiVENDOR: Solar Aircraft Co.
3200 Pacific Highway
San Diego, CaliforniaPRODUCT DESCRIPTION: Solami insulation is basically a sandwich construction consisting of a core, made up of a multitude of embossed metal sheets, confined between two thicker gauge metal sheets.MAXIMUM USABLE TEMPERATURE: 1800°FDENSITY: 40 lb/ft³THERMAL CONDUCTIVITY:

<u>Mean Temperature</u>	k, $\frac{\text{Btu}}{(\text{hr})(\text{ft}^2)(^\circ\text{F}/\text{ft})}$
500°F	0.731*
700	0.0833
900	0.095
1100	0.107
1300	0.120

* NOTE: Ambient gas conduction is believed to account for over one-half of the heat transfer in this material. Tabled values are corrected to one inch thickness in ambient air.

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DATA SHEET

HIGH TEMPERATURE INSULATION

PRODUCT: "Feltmetal"

VENDOR: Huyck Metals Co.
45 Woodmont Rd.
Milford, Conn.

PRODUCT DESCRIPTION: Feltmetal is a randomly interlocked structure of micron-sized metallic fibers which have been sintered to produce metallic bonds at all the points where the fibers touch each other.

THERMAL CONDUCTIVITY: (15 micron fibers)

<u>Mean Temperature</u>	$k, \frac{\text{Btu}}{(\text{hr})(\text{ft}^2)(^\circ\text{F}/\text{ft})}$	
	<u>Type A Nickel (17% density)</u>	<u>302 SS (45% density)</u>
200°F	0.36	0.28

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DATA SHEETHIGH TEMPERATURE INSULATIONPRODUCT: Eccospheres SIVENDOR: Emerson and Cuming Inc.
Dielectric Materials Division
Canton, Mass.PRODUCT DESCRIPTION: Eccospheres SI are hollow micron-sized, thin-walled bubbles made from silica. They are supplied as a fine, free flowing powder. Particle size is in the range of 30 to 125 microns; wall thickness is about 2 microns.MAXIMUM USABLE TEMPERATURE: 2500°FBULK DENSITY: About 11 lb/ft³TRUE PARTICLE DENSITY: About 16.2 lb/ft³CHEMICAL COMPOSITION: 95% SiO₂PERMEABILITY OF PARTICLE WALL: Impermeable to water and other liquidsCOMPRESSIVE STRENGTH UNDER
HYDROSTATIC LOADING: About 1000 psiTHERMAL CONDUCTIVITY:
(Loosely packed material)

<u>Mean Temperature</u>	<u>Btu</u>
	<u>(hr) (ft²) (°F/ft)</u>
0°F	0.03
300	0.04

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DATA SHEET

HIGH TEMPERATURE INSULATION

PRODUCT: Santocel A

VENDOR: Monsanto Chemical Co.
Inorganic Chemicals Div.
St. Louis 66, Missouri

PRODUCT DESCRIPTION: Santocel A is a silica aerogel produced as a fluffy white powder and granules. It is characterized by minute ultimate particle size, free-flowing properties, resistance to settling and a low thermal conductivity. The average ultimate diameter is 25 millimicrons. The pore diameter is less than the mean free path of air at normal temperatures and pressures so that the thermal conductivity of the bulk material is less than that of still air.

USABLE TEMPERATURE RANGE: Liquid helium to 1300°F

CHEMICAL ANALYSIS:

SiO ₂	- 95-95%
Na ₂ SO ₄	- 2.5-3.5%
Volatile (moisture)	- 3-4%

LOOSE BULK DENSITY: 5.0 lb/ft³

ABSOLUTE DENSITY: 2.2 gm/cc

PORE VOLUME: 93-95%

SPECIFIC HEAT: 0.234 cal/gm/°C

THERMAL CONDUCTIVITY: (At atmospheric pressure)

Mean Temperature	Btu
	(hr) (ft ²) (°F/ft)
-100°F	0.0098
0	0.0115
100	0.0133
200	0.0153
300	0.0176

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Santocel A (Continued)

THERMAL CONDUCTIVITY-DEPENDENCE ON
PRESSURE: (At -130°F mean temperature)

<u>Pressure, mm Hg</u>	<u>Btu</u> <u>(hr) (ft²) ($^{\circ}\text{F}/\text{ft}$)</u>
760	0.0095
100	0.0072
10	0.0048
1	0.0031
0.1	0.0018
0.01	0.0010
0.001	0.00075

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DATA SHEET

HIGH TEMPERATURE INSULATION

PRODUCT: Dyna-Quartz

VENDOR: Johns-Manville Aerospace Products
22 East 40th Street
New York, New York 10016

PRODUCT DESCRIPTION: Dyna-Quartz is specially heat-treated Micro-Quartz felt in the form of lightweight, semi-rigid tiles or blocks of exceptional dimensional stability at high temperatures. It is composed of clean 99% pure silica fibers and contains no binder. The material is first water felted, then heat treated for dimensional stability. The rough tiles are then machined to desired size. It is particularly suited to high temperature applications where lightweight and medium load bearing properties are important. Close dimensional tolerances can be achieved with this material due to its semi-rigid form and its ability to be cut, fitted, and machined and sanded to size.

MAXIMUM USABLE TEMPERATURE: 2750°F (3000°F transient exposure)

AVAILABLE FORMS: Semi-rigid tiles and blocks in thicknesses of 1/4", 1/2", 1", 1-1/2", 2" and 3"; 14" lengths and 12" widths. These forms are available with densities of 4.5, 6.2, 8.0 and 10.0 lb/ft³.

DIMENSIONAL STABILITY: Less than 1% shrinkage after a 24-hour soak at 2750°F

FLEXIBILITY: Thin sections of Dyna-Quartz are somewhat flexible and conformable to curved sections.

SPECIFIC HEAT:

<u>Temperature, °F</u>	<u>Btu/lb</u>
400	0.229
600	0.248
800	0.263
1000	0.272
1200	0.279
1400	0.284
1600	0.288
1800	0.292

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Dyna-Quartz (Continued)

STRENGTH:

<u>Product Density, lb/ft³</u>	<u>Modulus of Rupture, psi</u>	<u>Inter-Laminar, psi</u>
4.5	19	2.3
6.2	35	3.3
8.0	58	4.0
10.0	90	4.2

COMPRESSION-DEFLECTION
PROPERTIES (Typical):

<u>Deflection, %</u>	<u>Load, psi</u>			
	<u>Product Density (lb/ft³)</u>			
	<u>4.5</u>	<u>6.2</u>	<u>8.0</u>	<u>10.0</u>
2	1.5	3.0	5.0	12.2
4	3.2	6.5	10.6	16.1
6	4.0	9.0	12.5	19.7
8	4.5	9.6	13.2	20.8

THERMAL CONDUCTIVITY:

<u>Product Density, lb/ft³</u>	<u>Btu</u>									
	<u>(hr) (ft²) (°F/ft)</u>									
	<u>Mean Temperature, °F</u>									
	<u>600</u>	<u>800</u>	<u>1000</u>	<u>1200</u>	<u>1400</u>	<u>1600</u>	<u>1800</u>	<u>2000</u>	<u>2100</u>	
4.5	.0442	.0516	.0608	.070	.080	.0935	.106	.121	.129	
6.2	.0442	.0509	.0584	.0667	.0759	.086	.0975	.109	.116	
8.0	.0434	.050	.0566	.0632	.0717	.080	.090	.101	.107	
10.0	.0434	.0491	.055	.0608	.0675	.075	.0833	.0926	.075	

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INSULATION MATERIALS

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2. Investigation of Materials for Vacuum Insulation up to 4000°F, ASD-TDR-62-88, A. D. Little Co., January 1962.
3. C. E. Moeller, et al., Thermophysical Properties of Thermal Insulating Materials, ASD-TDR-62-215, February 1962.
4. D. Wang (Linde) "Multiple Layer Insulation", Aerodynamically Heated Structures, P. E. Glasser (ed), Prentice-Hall, Englewood Cliffs, N. J. (1962).
5. Lightweight Thermal Protection System Development, ASD-TDR-63-596, 1962, Vol. II.
6. D. J. Powers (Bell Aerosystems), Heat Exposure Tests on Thermal Insulation Materials, AD 281822, 10 August 1962.

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THERMAL CONDUCTIVITY UNIT CONVERSION FACTORS

<u>To Convert From</u>	<u>To</u>	<u>Multiply By</u>
gm-cal/(sec) (cm ²) (°C/cm)	Btu/(hr) (ft ²) (°F/in.)	2903.0
watts/(cm ²) (°C/cm)	Btu/(hr) (ft ²) (°F/in.)	694.0
gm-cal/(hr) (cm ²) (°C/cm)	Btu/(hr) (ft ²) (°F/in.)	0.8064
gm-cal/(sec) (cm ²) (°C/cm)	Btu/(hr) (ft ²) (°F/ft)	241.9
watts/(cm ²) (°C/cm)	Btu/(hr) (ft ²) (°F/ft)	57.79
kg-cal/(hr) (m ²) (°C/m)	Btu/(hr) (ft ²) (°F/ft)	0.672
Btu/(hr) (ft ²) (°F/ft)	Btu/(hr) (ft ²) (°F/in.)	12.0
Btu/(hr) (in. ²) (°F/in.)	Btu/(hr) (ft ²) (°F/ft)	12.0
gm-cal/(sec) (cm ²) (°C/cm)	Btu/(sec) (in. ²) (°F/in.)	0.0056
watts/(m ²) (°C/m)	Btu/(hr) (ft ²) (°F/ft)	0.577

NOTE: The units of thermal conductivity in the English system are:

$$\frac{\text{Btu}}{(\text{hr}) (\text{ft}^3) (^\circ\text{F}/\text{ft})} = \frac{(\text{Btu}) / (\text{hr}) (\text{ft}^2)}{^\circ\text{F}/\text{ft}} = \frac{\text{Btu}}{(\text{hr}) (\text{ft}) (^\circ\text{F})}$$

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FABRICATORS OF HIGH TEMPERATURE INSULATIONS

1. Solar Aircraft Company
2200 Pacific Highway
San Diego, California	8. Johns-Manville Company
22 East 40th Street
New York, New York
2. H. L. Thompson Fiber Glass Company
1600 W. 135th Street
Gardena, California	9. Libby-Owens-Ford Co.
1810 Madison Ave.
Toledo, Ohio
3. Eagle-Picher Company
959 American Building
Cincinnati, Ohio	10. Linde Division
Union Carbide Corp.
270 Park Ave.
New York, New York 10017
4. R. T. Vanderbilt Company
230 Park Avenue
New York, New York	11. Huyck Metals Co.
45 Woodmont Street
Milford, Conn.
5. Pittsburgh Corning Corporation
One Gateway Center
Pittsburgh 22, Penn.	12. Emerson & Cuming Inc.
Dielectric Materials Div.
Canton, Mass.
6. Baldwin-Ehret-Hill
1153 Breunig Ave.
Trenton, New Jersey	13. Harbison-Walker Refractories Co.
307 5th Avenue
Pittsburg, Penn.
7. Owens-Corning Fiberglass Corp.
717-T Fifth Ave.
New York, New York	

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