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EFFECTS OF LOAD CONDITIONS ON LONG TERM
RADIOISOTOPE THERMOELECTRIC GENERATOR
OPERATION

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EFFECTS OF LOAD CONDITIONS ON LONG TERM
RADIOISOTOPE THERMOELECTRIC GENERATOR OPERATION

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ABSTRACT

Results of the analysis performed indicate that both the effects of decreasing heat input and the system load conditions must be considered in order to obtain maximum performance at end-of-life (EOL). Furthermore, this maximum EOL performance does not occur at the same load condition for maximum beginning-of-life performance.

Date Published - December 1970

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EFFECTS OF LOAD CONDITIONS ON LONG TERM RADIOISOTOPE THERMOELECTRIC GENERATOR OPERATION

Introduction

Most of the radioisotope thermoelectric generators (RTG's) in use today were designed for optimum efficiency conditions based on constant hot and cold junctions. The optimized design specifies a particular cross-sectional area ratio of the n-elements to p-elements in the thermoelectric couple and also specifies a particular load resistance for this couple. This paper deals with the case in which an RTG was designed this way but operates under different temperature and load conditions. These different conditions arise either from decreased heat input due to radioisotopic decay which changes the hot and cold junction temperatures and the internal resistance or from changes in the load resistance which also affect the RTG temperatures. Constant load voltage and constant load resistance are both considered with respect to the effects on end-of-life (EOL) performance.

Calculational Approach

The basic thermoelectric calculations are made in the typical (see Reference 1) simplified manner utilizing the following equations:

$$\eta_t = P_o/Q_n$$

$$Q_n = K\Delta T + \alpha T_h I - \frac{1}{2}I^2 R$$

$$P_o = I^2 R_o$$

where

$$K = (A_n K_n + A_p K_p)/L = \text{total couple thermal conductance}$$

$$A_n = \text{cross-sectional area of the n-element}$$

$$A_p = \text{cross-sectional area of the p-element}$$

$$K_n = \text{average thermal conductivity of the n-element}$$

$$K_p = \text{average thermal conductivity of the p-element}$$

$$I = \alpha \Delta T / (R + R_o) = \text{couple current}$$

$$\alpha = |\alpha_n| + |\alpha_p|$$

$$\alpha_n = \text{average Seebeck coefficient of the n-element}$$

$$\alpha_p = \text{average Seebeck coefficient of the p-element}$$

$$R = \text{extraneous resistance + element resistances}$$

$$R_o = \text{load resistance}$$

$$\Delta T = T_h - T_c$$

$$T_h = \text{hot junction temperature}$$

$$T_c = \text{cold junction temperature}$$

The average material properties were obtained by integration of the area under the property versus temperature curves in the temperature region of interest and then dividing the integrated area by the base ΔT .

The above relationships can be used to arrive at an optimized converter configuration. The optimized variables are the area ratio of the n and p elements and the load resistance. The length of the elements and the operating temperatures are selected by the designer. Using this approach, a converter can be designed for either a maximum beginning-of-life (BOL) efficiency or power but not both. Several such converters in use or being designed are evaluated under load conditions other than those for which the system was optimized.

In all of the cases considered, it was assumed that the BOL hot junction temperature and the radiator emissivity and area were constant for each converter regardless of the load resistance. This requires that both the BOL input heat and the cold junction temperature vary with load variations. The $\sigma \epsilon A$ products for the radiators were determined from either measured or predicted converter operational characteristics. Using these constant radiator characteristics, assuming that the radiator is losing heat to a 0°K sink and the cold junction is 8°C hotter than the radiator, the cold junction temperature is varied until convergence is obtained between the amount of heat leaving the elements and the amount of heat lost by the radiator. The BOL equilibrium condition for a given load is thus achieved.

The next step is to evaluate the system performance at the end-of-life (EOL). The first obvious effect will result from the decrease in the heat input to the thermoelectric elements. The resulting radiator temperature can be determined from the expression

$$Q = \sigma \epsilon A T_{\text{rad}}^4$$

since Q is known from the isotope decay and $\sigma \epsilon A$ is the previously determined constant. The hot junction temperature which will force the available heat through the element and be in equilibrium with the cold junction and radiator temperature constraints must then be determined. This procedure was followed for two load conditions: (1) the load resistance is the same as at BOL, and (2) the load voltage

is held at the same as at BOL. If the EOL thermoelectric properties are expected to differ from the BOL properties, the EOL properties can be used in calculating the EOL operating characteristics.

Appendix A lists a typical input and typical output from a typical version of the computer code used. Variations to the code occur in the main program DT1VQ depending on whether temperature equilibrium is being achieved or EOL voltage and heat input constraints are being imposed on a system with EOL properties different than the BOL properties. The listing in Appendix A is the latter type.

Results and Discussion

This analytical approach was applied to four different thermoelectric systems: (1) Isotec Transit, (2) Isotec with optimized TAGS p-elements, (3) SNAP-27, and (4) the proposed Multi-Hundred Watt (MHW) SiGe system. Table I gives the element dimensions and identifies the materials used. All systems were assumed to be using Pu^{238} fuel and to have 10 percent of the heat generated by the fuel not transmitted through the element but be dissipated as a bypass loss. The BOL thermoelectric properties of these materials are given in Appendix B; also shown are the EOL (12 year) properties of 80 percent, SiGe as predicted in Reference 2. It should be noted that the two sources from which the BOL and EOL 80 percent SiGe p-material properties were taken disagree on the thermal conductivity values. This difference makes the EOL degradation calculations show a greater degradation than may actually exist since it is believed that the p-material properties do not change with time. The predicted EOL properties (Reference 3) of the Isotec Transit material expressed as percent changes from BOL properties are as follows.

<u>Property</u>	<u>N-Element</u>	<u>P-Element</u>
Seebeck Coefficient	- .8	- 9.2
Resistivity	+ 17.6	- 7.3
Thermal Conductivity	- 3.5	- 1.9

The BOL and EOL power output and efficiency for both constant load voltage and resistance as well as the BOL heat input are shown in Figures 1 through 8. Two EOL conditions are shown for the Isotec

Transit system using BOL material properties and GGA predicted EOL property changes. Two EOL conditions are also shown for the SNAP-27 system. The case where the extraneous resistance is doubled represents an increase in the contact resistances. The three EOL cases for the MHW represent 5 year and 10.5 year system predictions with BOL material properties and a 10.5 year system with EOL material properties. Even though the EOL properties are for 12 years operation, they are used in the 10.5 year case since the predicted changes between these two periods is rather insignificant.

TABLE I Thermoelectric Couple Description

System	Element Length (cm)	N-Element		P-Element	
		Diameter (cm)	Material	Diameter (cm)	Material
Isotec Transit	.419	.325	2N PbTe (NGGA)	.264	Modified 3P PbSnMnTe (PGGA6)
Isotec TAGS	.457	.328	2N PbTe	.245	TAGS GeTeAgSb
SNAP-27	1.016	.526	3N PbTe	.627	3P PbTe
MHW	2.032	.417	80% SiGe	.417	80% SiGe

Two obvious characteristics of Figures 1-8 are (1) constant load voltage conditions result in higher EOL power and efficiency, and (2) maximum EOL power and efficiency do not occur at the same BOL load matching factor for the two types of loads. Furthermore, the constant load voltage case gives maximum EOL power and efficiency at a different BOL load matching factor, and thus load voltage, than that for maximizing BOL output characteristics. This is of specific interest since many of the systems used in space operate at a constant load voltage.

Since constant load voltage conditions are generally more desirable from a degradation standpoint and are in rather wide use, all of the following results are based on constant load voltage conditions. The BOL load matching factors for maximum BOL and EOL power and efficiency are given in Table II. Table III lists the BOL couple load voltages for the same conditions. Figure 9 demonstrates the effect of decreased heat input on the BOL load matching factor for maximum BOL power or efficiency for the MHW system. Figures 10 and 11

show that system degradation increases with larger BOL load matching factors. Table IV gives the numerical results from which Figures 10 and 11 were obtained. Figures 12 and 13 show the EOL hot junction temperatures and both the BOL and EOL cold junction temperatures as a function of BOL load matching factor for the three systems. The BOL hot junction temperatures are 400°C, 574°C and 1100°C, and the $\sigma \times \text{emissivity} \times \text{area}$ ($\sigma \epsilon A$) products per couple for these three systems are 6.0893×10^{-5} , 5.4115×10^{-5} and $7.053 \times 10^{-5} \text{ w/K}^4$ for the Isotec, SNAP-27 and MHW systems, respectively.

TABLE II BOL Load Matching Factors for Maximum Efficiency and Power

<u>System</u>	<u>BOL</u>		<u>EOL at Constant Load Voltage</u>		
	<u>Maximum Efficiency</u>	<u>Maximum Power</u>	<u>Condition</u>	<u>Maximum Efficiency</u>	<u>Maximum Power</u>
Isotec Transit	1.35	1.125	.96Q	1.2	1.05
			.96Q + EOL Properties	1.2	1.05
Isotec TAGS	1.35	1.15	.96Q	1.25	1.075
SNAP-27	1.33	1.14	.96Q	1.22	1.06
			.96Q + Rext doubled	1.25	1.1
MHW	1.28	1.075	.96Q	1.19	1.04
			.92Q	1.15	.98
			.92Q + EOL Properties	1.1	1.0

TABLE III BOL Load Millivoltages for Maximum Efficiency and Power

<u>System</u>	<u>BOL</u>		<u>EOL at Constant Load Voltage</u>		
	<u>Maximum Efficiency</u>	<u>Maximum Power</u>	<u>Condition</u>	<u>Maximum Efficiency</u>	<u>Maximum Power</u>
Isotec Transit	54.90	50.45	.96Q	52.05	48.72
			.96Q + EOL Properties	52.05	48.72
Isotec TAGS	58.86	54.59	.96Q	56.83	52.77
SNAP-27	79.42	74.01	.96Q	76.46	71.37
			.96Q + Rext doubled	77.36	72.71
MHW	238.78	221.08	.96Q	232.14	217.56
			.92Q	228.43	210.91
			.92Q + EOL Properties	223.60	213.15

TABLE IV Performance of Several Systems at Different Load Matching Factors

Material and System	BOL m	<u>Beginning of Life</u>			<u>End of Life at Constant Load Voltage</u>			
		Power	Efficiency	Condition	Power	P_{EOL}/P_{BOL}	Efficiency	η_{EOL}/η_{BOL}
NGGA/PGGAG	.747	82.08 mw	4.58%		76.97	.9377	4.47	.9760
	.896	84.55	4.78		78.83	.9323	4.64	.9707
Isotec	1.007	85.43	4.87		79.26	.9278	4.71	.9671
	1.084	85.69	4.91		79.28	.9252	4.73	.9633
	1.153	85.73	4.94		79.03	.9218	4.74	.9595
	1.252	85.52	4.96		78.55	.9185	4.75	.9577
	1.51	83.98	4.95	.96 Q1	76.36	.9093	4.69	.9475
	.747			.96 Q1	73.15	.8912	4.26	.9301
	.896			and	75.08	.8880	4.42	.9247
	1.007			GGA	75.49	.8836	4.48	.9199
	1.084			predicted	75.54	.8815	4.51	.9185
	1.153			EOL	75.25	.8778	4.52	.9150
	1.252			changes	74.78	.8744	4.52	.9113
	1.51	same	same		72.60	.8645	4.46	.9010
NGGA/TAGS	.752	85.92	4.72		80.91	.9417	4.63	.9809
	.902	88.58	4.93		82.92	.9361	4.81	.9757
Isotec	1.039	89.63	5.05		83.54	.9321	4.90	.9703
	1.108	89.75	5.08		83.49	.9303	4.93	.9686
	1.181	89.75	5.11		83.26	.9277	4.94	.9667
	1.301	89.46	5.14		82.60	.9233	4.94	.9611
	1.529	87.94	5.12	.96 Q1	80.61	.9166	4.89	.9551
3N/3P	.781	178.3	4.46		171.1	.9596	4.46	1.000
	.940	183.1	4.64		174.8	.9547	4.62	.9957
SNAP-27	1.006	184.1	4.69		175.5	.9533	4.66	.9936
	1.076	184.6	4.73		175.6	.9512	4.69	.9915
	1.158	184.7	4.76		175.3	.9491	4.71	.9895

Table IV (cont)

Material and System	BOL m	Beginning of Life			End of Life at Constant Load Voltage			
		Power	Efficiency	Condition	Power	P_{EOL}/P_{BOL}	Efficiency	η_{EOL}/η_{BOL}
80% SiGe Multi-Hundred Watt	1.256	184.3 mw	4.78%	.96 Qi	174.3	.9457	4.71	.9854
	1.576	179.8	4.75		168.6	.9377	4.64	.9768
	.781				158.6	.8895	4.13	.9260
	.940			and	161.9	.8842	4.28	.9224
	1.006			Rext	162.4	.8821	4.32	.9211
	1.076			increased	162.6	.8808	4.34	.9175
	1.158			100%	162.6	.8803	4.36	.9160
	1.256				161.5	.8763	4.37	.9142
	1.576	same	same		156.4	.8699	4.31	.9074
	.801	546.8	7.41	.96 Qi	514.6	.9411	7.26	.9798
	.931	555.3	7.61		520.9	.9381	7.44	.9777
	1.035	557.6	7.72		521.7	.9356	7.52	.9741
	1.123	557.2	7.77		520.2	.9336	7.55	.9717
	1.238	554.2	7.79		516.1	.9313	7.56	.9705
	1.447	544.2	7.77		504.2	.9265	7.49	.9640
	1.658	530.5	7.67		489.0	.9218	7.36	.9596
	.801				481.8	.8811	7.09	.9568
	.931				486.0	.8752	7.24	.9514
	1.035				485.4	.8705	7.30	.9456
	1.123				482.8	.8665	7.31	.9408
	1.238				477.4	.8614	7.30	.9371
	1.447				463.6	.8519	7.19	.9254
	1.658	same	same	.92 Qi	447.0	.8426	7.02	.9153
	.801			.92 Qi	417.2	.7630	6.14	.8286
	.931			and	420.7	.7576	6.27	.8239
	1.035			12 year	420.7	.7545	6.32	.8187
	1.123			property	418.5	.7511	6.33	.8147
	1.238			data	412.9	.7450	6.31	.8100
	1.447				400.9	.7367	6.22	.8005
	1.658	same	same		386.1	.7278	6.06	.7901

The above analytical results indicate that: (1) limited flexibility of existing systems can be achieved by load variations, and (2) if a load can't be varied during operation, optimization should be made based on EOL expectations rather than BOL conditions. The flexibility available allows for either maximum EOL or BOL power or efficiency and some control over the degradation. Even if EOL expectations are limited to the decreased input resulting from isotopic decay, there are gains to be achieved by selecting the load matching factor for EOL optimization.

Conclusions

1. For BOL load matching factors less than ~ 1.5 , degradation under a constant voltage load condition is less than under a constant resistance load.
2. EOL optimum load conditions are not the same as BOL optimum load conditions, especially in the constant load voltage case.
3. Degradation increases with larger load matching factors under constant voltage loads.

References

1. Direct Energy Conversion, Stanley W. Angrist, Allyn and Bacon, Inc., Boston, 1965.
2. Thermoelectric Properties of 80 a/o Si-20 a/o Ge Alloy as a Function of Time and Temperature, Memorandum #6, March 3, 1970, Prepared for Jet Propulsion Laboratory, Pasadena, Calif. by Valvo Raag, Resalab Scientific, Menlo Park, Calif.
3. Transit RTG Program Report No. 2, document 11464-6010-T0-01, Revision page 2-29, 23 September 1970, TRW Systems Group, Redondo Beach, Calif.

Figure 1 - Power Output vs. BOL Load Matching Factor for the Isotec NGGA/PGGA6 System

Figure 2 - Efficiency and Heat Input vs. BOL
 Load Matching Factor for the Isotec NGGA/PGGA6 System

Figure 3 - Power Output vs. BOL Load Matching Factor
for the Isotec NGGA/TAGS System

Figure 4 - Efficiency and Heat Input vs. BOL Load Matching Factor for the Isotec NGGA/TAGS System

Figure 5 - Power Output vs. BOL Load Matching Factor for SNAP-27

Figure 6 - Efficiency and Heat Input vs.
BOL Load Matching Factor for SNAP-27

Figure 7 - Power Output vs. BOL Load Matching Factor for the MHW System

Figure 8 - Efficiency and Heat Input vs. BOL Load Matching Factor for the MHW System

Figure 9 - BOL Load Matching Factor for Maximum Power or Efficiency as a Function of decreased heat input for the MHW System

Figure 10 - Degradation of Isotec and SNAP-27 systems vs. BOL Load Matching Factors

Figure 11 - Degradation of the MHW system vs. BOL Load Matching Factor

Figure 12. EOL Hot Junction Temperature vs.
BOL Load Matching Factor

Figure 13 - Cold Junction Temperature vs.
BOL Load Matching Factor

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APPENDIX A

Listing of Computer Code: Typical Input and Output

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THERMOELECTRIC MATERIAL COMPARISON

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THERMOELECTRIC MATERIAL COMPARISON

APPENDIX B

Thermoelectric Properties

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C	PROGRAM DTIVQ(INPUT,OUTPUT,TAPE60=INPUT,TAPE10)		
C	CODE PERFORMS THE ANALYSIS	A	3
C	OF A THERMOELECTRIC COUPLE BY THE	A	4
C	AVERAGE VALUE METHOD.	A	5
C	SEE R. M. WHITES DTIB FROM WHICH THIS WAS CONCOCTED		
C		A	7
C	ALPN = N MATERIAL SEEBECK	A	8
C	ALPP = P MATERIAL SEEBECK	A	9
C	ALP = ALPN + ALPP	A	10
C		A	11
C	RHON = N MATERIAL RESISTIVITY	A	12
C	RHOP = P MATERIAL RESISTIVITY	A	13
C	R = MATERIAL RESISTANCE	A	14
C	RLOSS=EXTRANFOUS RESISTANCE AS A FRACTION OF R ABOVE		
C	RC = CIRCUIT RESISTANCE		
C	RT = TOTAL INTERNAL RESISTANCE	A	16
C	RO = EXTERNAL RESISTANCE	A	15
C		A	20
C	CONN = N MATERIAL CONDUCTIVITY (THERMAL)	A	21
C	CONP = P MATERIAL CONDUCTIVITY (THERMAL)	A	22
C	CK = TOTAL THERMAL CONDUCTANCE	A	23
C		A	24
C	ZL =LENGTH	A	25
C	DIAP = DIAMETER OF P ELEMENT	A	26
C	DIAN = DIAMETER OF W ELEMENT	A	27
C	AP = AREA OF P ELEMENT	A	28
C	AN = AREA OF N ELEMENT	A	29
C	GAMP = AP/ZL	A	30
C	GAMN = AN/ZL	A	31
C		A	32
C	TEMPERATURE NAMES END IN C OR K FOR CENT. OR KELVIN	A	33
C	TH = TEMP HOT	A	34
C	TC = TEMP COLD	A	35
C	DELT = TH-TC	A	36
C		A	37
C	Z = FIGURE OF MERIT	A	38
C	ZM =RATIO OF LOAD TO INTERNAL RESISTANCE	A	39
C	ZQ = SYSTEM THERMAL FLUX	A	40
C	ZI = CURRENT (AMPS)	A	41
C	VT = COUPLE TERMINAL VOLTAGE	A	42
C	ZO = OUTPUT POWER	A	43
C	EFF = COUPLE EFFICIENCY	A	44
C	QLOSS=FRACTION OF HEAT LOST		
C		A	51
C	DIMENSION S(25,7)	A	55
C	COMMON TCK,THK,TCC,THC,ZL,AN,AP,RO,CONP,CONN,RHOP,RHON,		
1	ALP,EFF,CK,R,RC,RT,ZI,VT,ZM,ZO,ZQ,Z,ZQO,RLOSS,QLOSS		
2,VT0			
C	READ INPUT DATA	A	60
101	READ 107, MODE,NCON,TITLE,TITLEN,TITLEP	A	61
102	CALL POLY (S,NCON,TITLE,TITLEN,TITLEP)	A	63
103	READ 108, RLOSS,QLOSS		
	DO 111 I =1,7		
104	READ 109, ZL,DIAP,DIAN,THC,TCC,RO	A	65

105	AN=78.5398*DIAN**2	A	68
	AP=78.5398*DIAP**2	A	69
	ZL=10.*ZL	A	70
	THK=THC+273.16		
	TCK=TCC+273.16		
	CALL AVE (S,NCON,TCC,THC,CONN,RHON,ALPN,CONP,RHOP,ALPP)	A	71
	ALP=ALPN+ALPP	A	72
	CALL CALC		
	CALL PRINT (S,ALPN,ALPP,DIAN,DIAP,TITLE,TITLEN,TITLEP)		
	SFA = 7.053		
	IF(I.EQ.1) V=189.11		
	IF(I.FQ.1) Q=7.38		
	IF(I.FQ.2) V=205.44		
	IF(I.FQ.2) Q=7.29		
	IF(I.FQ.3) V=217.06		
	IF(I.EQ.3) Q=7.23		
	IF(I.FQ.4) V=225.92		
	IF(I.FQ.4) Q=7.18		
	IF(I.FQ.5) V=236.60		
	IF(I.FQ.5) Q=7.11		
	IF(I.FQ.6) V=253.40		
	IF(I.FQ.6) Q=7.01		
	IF(I.FQ.7) V=267.70		
	IF(I.FQ.7) Q=6.92		
	RQO=RO		
	DO 111 L=1,9,8		
	ALL=L-1		
	ZQO= Q*(1.-.01*ALL)		
	DO 111 IK=1,2		
	ZQR=ZQO-ZO		
	TCKR=(ZQR*1000./SFA)**.25*100.		
	TCK=TCKR+8.0		
	TCC=TCK-273.16		
	VTQ=V		
	RO=RQO		
	CALL AVE (S,NCON,TCC,THC,CONN,RHON,ALPN,CONP,RHOP,ALPP)		
	ALP=ALPN+ALPP		
	CALL CALC		
	CALL QCONST (S,NCON,ALPN,ALPP,SUM,CLP,CLN,CKPP,CKPN,ANN,APP)		
	CALL PRINT (S,ALPN,ALPP, DIAN,DIAP,TITLE,TITLEN,TITLEP)	I	90
	PRINT 123,ALL		
	CALL VCONST (S,NCON,ALPN,ALPP,SUM,CLP,CLN,CKPP,CKPN,ANN,APP)		
	CALL PRINT (S,ALPN,ALPP, DIAN,DIAP,TITLE,TITLEN,TITLEP)	I	90
201	PRINT 123,ALL		
123	FORMAT(* HEAT INPUT IS REDUCED BY *,F4.1, * PERCENT*)		
111	CONTINUE		
106	PRINT 110	A	81
107	FORMAT (2(3X,I2),10X,3(3X,A7))	A	85
108	FORMAT (6F12.5)	A	86
109	FORMAT (10X,6F10.5)	A	87
110	FORMAT (1H1,////)	A	88
	END	A	89-
	SUBROUTINE VCONST(S,NCON,ALPN,ALPP,SUM,CLP,CLN,CKPP,CKPN,ANN,APP)		
C	THIS ITERATE= RO UNTIL VT IS SAME AS VTQ		

```

COMMON TCK,THK,TCC,THC,ZL,AN,AP,RO,CONP,CONN,RHOP,RHON,
1      ALP,EFF,CK,R,RC,RT,ZI,VT,ZM,ZO,ZQ,Z,ZQ0,RLOSS,QLOSS
2,VT0
  G=.01
1  IF(VT.LT.VT0) GO TO 20
10 RO=RO-RT*G
  ZI=ALP*(THC-TCC)/(RT+RO)
  VT=1000.*(ALP*(THC-TCC)-ZI*RT)
  IF(VT.GT.VT0) GO TO 10
  CALL QCONST (S,NCON,ALPN,ALPP,SUM,CLP,CLN,CKPP,CKPN,ANN,APP)
  IF(VT.GT.VT0) GO TO 10
20 RO=RO+RT*G
  ZI=ALP*(THC-TCC)/(RT+RO)
  VT=1000.*(ALP*(THC-TCC)-ZI*RT)
  IF(VT.LT.VT0) GO TO 20
  CALL QCONST (S,NCON,ALPN,ALPP,SUM,CLP,CLN,CKPP,CKPN,ANN,APP)
  IF(VT.LT.VT0) GO TO 20
  G=.1*G
  IF(ABS(VT-VT0).GT.0.1) GO TO 1
  RETURN
END
SUBROUTINE QCONST(S,NCON,ALPN,ALPP,SUM,CLP,CLN,CKPP,CKPN,ANN,APP)
C  ITERATE TO DETERMINE THC FOR VARIABLE RO AND CONSTANT ZQ
COMMON TCK,THK,TCC,THC,ZL,AN,AP,RO,CONP,CONN,RHOP,RHON,
1      ALP,EFF,CK,R,RC,RT,ZI,VT,ZM,ZO,ZQ,Z,ZQ0,RLOSS,QLOSS
2,VT0
  H=1.
10 THC = THC+H
  CALL AVE (S,NCON,TCC,THC,CONN,RHON,ALPN,CONP,RHOP,ALPP)
  ALP=ALPN+ALPP
30 CALL CALC
  IF(ZQ.LT.ZQ0) GO TO 10
  IF(ZQ.GT.ZQ0) GO TO 15
  H = .1*H
11 THC = THC-H
  CALL AVE (S,NCON,TCC,THC,CONN,RHON,ALPN,CONP,RHOP,ALPP)
  ALP=ALPN+ALPP
31 CALL CALC
  IF(ZQ.GT.ZQ0) GO TO 11
  GO TO 20
15 THC = THC-H
  CALL AVE (S,NCON,TCC,THC,CONN,RHON,ALPN,CONP,RHOP,ALPP)
  ALP=ALPN+ALPP
32 CALL CALC
  IF(ZQ.GT.ZQ0) GO TO 15
  H = .1*H
16 THC = THC+H
  CALL AVE (S,NCON,TCC,THC,CONN,RHON,ALPN,CONP,RHOP,ALPP)
  ALP=ALPN+ALPP
33 CALL CALC
  IF(ZQ.LT.ZQ0) GO TO 16
20 CONTINUE
  RETURN
END

```

	SUBROUTINE CALC	F	1
C	SUBROUTINE DOES ACTUAL THERMOELECTRIC COUPLE CALCULATIONS. METHOD	F	2
C	SIMILAR TO THAT IN TEXT DIRECT ENERGY CONVERSION BY ANGRIST.	F	3
	COMMON TCK,THK,TCC,THC,ZL,AN,AP,RO,CONP,CONN,RHOP,RHON,		
1	ALP,EFF,CK,R,RC,RT,ZI,VT,ZM,ZO,ZQ,Z,ZQO,RLOSS,QLOSS		
2,VTQ			
C	SYSTEM CALCULATIONS	F	6
	GAMN=AN/ZL	F	7
	GAMP=AP/ZL	F	8
	CK=(GAMP*CONP+GAMN*CONN)/10.	F	9
	R=10.*(RHOP/GAMP+RHON/GAMN)	F	10
	RC=.014		
	RT=R+RC		
	ZI=ALP*(THC-TCC)/(RT+RO)	F	13
	VT=1000.*(ALP*(THC-TCC)-ZI*RT)	F	14
	ZM=RO/RT	F	15
	ZO=ZI**2*RO	F	16
	ZQ=CK*(THC-TCC)+ALP*THK*ZI-.5*RT*ZI**2		
	ZQ=ZQ/(1.-QLOSS)		
	EFF=100.*ZQ/ZO	F	19
	RTURN	F	20
	END	F	21-
	SUBROUTINE PRINT (S,ALPN,ALPP, DIAN,DIAP,TITLE,TITLEN,TI	G	1
C	SUBROUTINE PRINTS THE FINAL OUTPUT VALUES	G	3
1	TITLEP)	G	2
	DIMENSION S(25,7)	G	4
	COMMON TCK,THK,TCC,THC,ZL,AN,AP,RO,CONP,CONN,RHOP,RHON,		
1	ALP,EFF,CK,R,RC,RT,ZI,VT,ZM,ZO,ZQ,Z,ZQO,RLOSS,QLOSS		
2,VTQ			
C	EVALUATE THE POLYNOMIAL	G	7
	ZL=ZL/10.	G	8
	DIAN=SQRT(AN/78.5398)	G	9
	DIAP=SQRT(AP/78.5398)	G	10
	PRINT 103, TITLE,TITLEN,ALPN,RHON,CONN,TITLEP,ALPP,RHOP,CONP	G	11
	PRINT 104, QLOSS		
	PRINT 108		
	PRINT 110		
	PRINT 101, ZL,DIAP,DIAN,THC,TCC,ZI	G	18
	ZL=10.*ZL		
	PRINT 102, CK,RT,RO,ZO,VT,ZQ	G	19
	PRINT 105,ZM,EFF		
	RETURN	G	21
C		G	22
101	FORMAT (//,23X,*LENGTH*,5X,*PDIA*,5X,*NDIA*,5X,*THOT*,5X,*TCOLD*,3	G	23
	1X,*CURRENT*/,24X,*(CM)*,6X,*(CM)*,5X,*(CM)*,6X,*(C)*,6X,*(C)*,5X,*	G	24
	2(AMPS)*/,24X,2(F5.3,4X),F5.3,3X,F6.1,4X,F6.1,4X,F6.3///)	G	25
102	FORMAT (20X,*THERMAL*,3X,*INTERNAL*,3X,*EXTERNAL*,5X,*POWER*,5X,*T	G	26
	1ERM*,5X,*THERMAL*/,20X,*CONDUCT*,4X,*RESIST*,5X,*RESIST*,5X,*OUTPU	G	27
	2T*,4X,*OUTPUT*,5X,*INPUT*/20X,*WATTS/C*,5X,*OHMS*,7X,*OHMS*,7X,*WA	G	28
	3TTS*,4X,*MVOLTS*,5X,*WATTS*/,19X,4(E9.3,2X),F6.2,3X,2(E8.2,3X)/)	G	29
103	FORMAT(1H1,7(/),47X,A7,///,43X,*COUPLE ANALYSIS*///,	G	30
	1 38X,*AVERAGE N VALUES *,A7,///,34X,*SEEBECK*,3X,*RESISTIVITY*,	G	31
	2 2X,*THERMAL K* /33X,3(E9.3,3X),///,	G	32
	3 38X,*AVERAGE P VALUES *,A7,///,34X,*SEEBECK*,3X,*RESISTIVITY*,	G	33

	4 2X,*THERMAL K* /33X,3(E9.3,3X)///)	G	33A
104	FORMAT(30X,*EXTRANEIOUS RESISTANCE IS 14. MOHMS OF THE COUPLE RESIS		
	TANCE *///30X,*HEAT LOSS IS *,F4.2,* OF THE TOTAL HEAT INPUT*///)		
105	FORMAT(//,32X,*LOAD MATCHING FACTOR IS*,F6.3,//		
1	,32X,*THE COUPLE EFFICIENCY = *,F5.2,* PERCENT*//)	G	
108	FORMAT(34X,*THE P DIAMETER IS NOT OPTIMISED*//)	G	40
110	FORMAT(31X,*THE EXTERNAL RESISTANCE IS NOT OPTIMISED*//)	G	42
	END	G	43-
	SUBROUTINE POLY (S,NCON,TITLE,TITLEN,TITLEP)	B	1
	DIMENSION S(25,7)	B	2
	ACONST=1.E-6	B	3
C	READ MATERIAL PROPERTIES	B	4
	DO 101 J=1,7	B	5
	READ 104, (S(I,J),I=1,NCON)	B	6
101	CONTINUE	B	7
	DO 102 I=1,NCON	B	8
	S(I,4)=ACONST*S(I,4)	B	9
102	S(I,7)=ACONST*S(I,7)	B	10
C	PRINT MATERIAL PARAMETERS	B	11
	PRINT 106	B	12
	PRINT 105, TITLEN	B	13
	PRINT 107	B	14
	PRINT 103, (S(I,1),S(I,2),S(I,3),S(I,4),I=1,NCON)	B	15
	PRINT 108	B	16
	PRINT 105, TITLEP	B	17
	PRINT 107	B	18
	PRINT 103, (S(I,1),S(I,5),S(I,6),S(I,7),I=1,NCON)	B	19
	RETURN	B	21
C		B	22
C		B	23
103	FORMAT (25X,F6.1,3(5X,E10.4)//)	B	24
104	FORMAT (6E12,8)	B	25
105	FORMAT (47X,A7//)	B	26
106	FORMAT(1H1,//////,40X,*N MATERIAL PARAMETERS*//)	B	27
107	FORMAT(27X,*TEMP*,4X,*THERMAL COND*,3X,*RESISTIVITY*,6X,	B	28
1	*SEEBECK*/,27X,*C)*,6X,*WATTS/CM-C*,7X,*OHM-CM*,8X,*VOLTS/C*//)	B	29
108	FORMAT(1H1,//////,40X,*P MATERIAL PARAMETERS*//)	B	30
	END	B	31-
	SUBROUTINE SPLINE (X,Y,N,XX,YY,NHOLD)	D	1
	DIMENSION X(50), Y(50), H(50), A(50), B(50), C(50), ALP(50), GAM(5	D	2
	10), G(50), F(50), M(50)	D	3
	COMMON /401/ M,H	D	4
	REAL M	D	5
	IF (NHOLD) 107,101,107	D	6
C	CALCULATION OF SPLINE MOMENTS	D	7
101	NHOLD=1	D	8
	N1=N-1	D	9
	N2=N-2	D	10
	DO 102 I=2,N	D	11
102	H(I)=X(I)-X(I-1)	D	12
	DO 103 J=2,N1	D	13
	A(J)=(H(J)+H(J+1))/3.	D	14
	B(J)=H(J)/6.	D	15
103	C(J)=H(J+1)/6.	D	16

	DO 104 I=2,N1	D	17
104	F(I)=(Y(I+1)-Y(I))/H(I+1)-(Y(I)-Y(I-1))/H(I)	D	18
	ALP(2)=A(2)	D	19
	GAM(2)=C(2)/ALP(2)	D	20
	G(2)=F(2)/ALP(2)	D	21
	DO 105 I=3,N1	D	22
	ALP(I)=A(I)-R(I)*GAM(I-1)	D	23
	GAM(I)=C(I)/ALP(I)	D	24
105	G(I)=(F(I)-R(I)*G(I-1))/ALP(I)	D	25
	M(1)=0.	D	26
	M(N)=0.	D	27
	M(N1)=G(N1)	D	28
	DO 106 I=2,N2	D	29
	J=N-I	D	30
106	M(J)=G(J)-GAM(J)*M(J+1)	D	31
C	DETERMINATION OF YY	D	32
107	I=2	D	33
	IF (XX.FQ.X(I)) GO TO 110	D	33A
	IF (XX.LT.X(1)) GO TO 109	D	34
	IF (XX.GT.X(N)) GO TO 109	D	35
	DO 108 I=2,N	D	36
	IF (XX.LE.X(I)) GO TO 110	D	37
108	CONTINUE	D	38
109	PRINT 112	D	39
	GO TO 111	D	40
110	YY=M(I-1)*(X(I)-XX)**3/(6.*H(I))+M(I)*(XX-X(I-1))**3/(6.*H(I))+(Y(I-1)-M(I-1)*H(I)**2/6.)*(X(I)-XX)/H(I)+(Y(I)-M(I)*H(I)**2/6.)*(XX-2X(I-1))/H(I)	D	41
		D	42
		D	43
111	RETURN	D	44
C		D	45
112	FORMAT(///,20X,*X VALUE OUT OF RANGE*)	D	46
	END	D	47-
	SUBROUTINE AVE (S,NCON,X1,X2,CONN,RHON,ALPN,CONP,RHOP,ALPP)	E	1
	DIMENSION S(25,7), A(6), X(50), Y(50), M(50), H(50)	E	2
	COMMON /401/ M,H	E	3
	REAL M	E	4
	AREA(S1,S2,S3,S4,X1,X2,X3,X4)=S1*((X4-X1)**4-(X4-X2)**4)/4.+S2*((X	E	5
	12-X3)**4-(X1-X3)**4)/4.+S3*((X4-X1)**2-(X4-X2)**2)/2.+S4*((X2-X3)*	E	6
	2-(X1-X3)2)/2.	F	7
	DELTA=X2-X1	F	8
C	CHECK VALUES	F	9
	IF ((X1.LT.S(1,1)).OR.(X2.GT.S(NCON,1))) PRINT 111	E	10
	IF ((X1.LT.S(1,1)).OR.(X2.GT.S(NCON,1))) GO TO 110	E	11
	DO 109 KK=1,6	E	12
	DO 101 I=1,NCON	E	13
	X(I)=S(I,1)	E	14
101	Y(I)=S(I,KK+1)	E	15
C	CALCULATE SPLINE MOMENTS	E	16
	NHOLD=0	E	17
	CALL SPLINE (X,Y,NCON,X1,YY,NHOLD)	E	18
C	COMPUTE THE AVERAGE	F	19
	AVFRAGE=0.	E	20
	DO 102 I=2,NCON	F	21
	KHOLD=I	E	22

```

      IF (X1.LT.S(I,1)) GO TO 103
102  CONTINUE
      PRINT 111
      GO TO 110
103  DO 104 I=1,NCON
      KHOLD2=I-1
      IF (X2.LE.S(I,1)) GO TO 105
104  CONTINUE
      PRINT 111
      GO TO 110
      COMPUTE LEFT END AREA
105  S1=M(KHOLD-1)/(6.*H(KHOLD))
      S2=M(KHOLD)/(6.*H(KHOLD))
      S3=Y(KHOLD-1)/H(KHOLD)-M(KHOLD-1)*H(KHOLD)/6.
      S4=Y(KHOLD)/H(KHOLD)-M(KHOLD)*H(KHOLD)/6.
      IF (KHOLD2.LT.KHOLD) GO TO 108
      AVERAGE=AVERAGE+AREA(S1,S2,S3,S4,X1,X(KHOLD),X(KHOLD-1),X(KHOLD))
      COMPUTE CENTRAL AREA
      IF (KHOLD2.EQ.KHOLD) GO TO 107
      KHOLD=KHOLD+1
      DO 106 J=KHOLD,KHOLD2
      S1=M(J-1)/(6.*H(J))
      S2=M(J)/(6.*H(J))
      S3=Y(J-1)/H(J)-M(J-1)*H(J)/6.
      S4=Y(J)/H(J)-M(J)*H(J)/6.
106  AVERAGE=AVERAGE+AREA(S1,S2,S3,S4,X(J-1),X(J),X(J-1),X(J))
      COMPUTE RIGHT END AREA
107  KHOLD2=KHOLD+1
      S1=M(KHOLD2-1)/(6.*H(KHOLD2))
      S2=M(KHOLD2)/(6.*H(KHOLD2))
      S3=Y(KHOLD2-1)/H(KHOLD2)-M(KHOLD2-1)*H(KHOLD2)/6.
      S4=Y(KHOLD2)/H(KHOLD2)-M(KHOLD2)*H(KHOLD2)/6.
      AVERAGE=AVERAGE+AREA(S1,S2,S3,S4,X(KHOLD2-1),X2,X(KHOLD2-1),X(KHOLD2))
      GO TO 109
      COMPUTE AVERAGE IF BOTH X1 AND X2 ARE IN SAME INTERVAL
108  AVERAGE=AVERAGE+AREA(S1,S2,S3,S4,X1,X2,X(KHOLD-1),X(KHOLD))
      ASSIGN AVERAGE TO ARRAY A
109  A(KK)=AVERAGE/DELTA
      CONN=A(1)
      RHON=A(2)
      ALPN=A(3)
      CONP=A(4)
      RHOP=A(5)
      ALPP=A(6)
110  RETURN
11  FORMAT(//////////,2JX,*VALUE OUT OF RANGE*//)
      END

```

4	12	12 YEAR	VR 80SI	VR 80SI		
0.	100.	200.	300.	400.	500.	T1
600.	700.	800.	900.	1000.	1102.	T2
.0516	.0495	.0475	.0456	.044	.0427	NK1
.0416	.0412	.0426	.0459	.0533	.0607	NK2

.0009	.00108	.00174	.0033	.0049	.00421	N12YR R1
.00354	.00291	.00232	.00181	.00137	.00093	N12YR R2
113.	145.	206.	282.	330.	320.	N12YR S1
307.	292.	275.	258.	245.	232.	N12YR S2
.0638	.061	.0585	.0561	.054	.0521	P K1
.0506	.0497	.0495	.0502	.0545	.0588	P K2
.00119	.00132	.00148	.00166	.00186	.00206	P R1
.00228	.0025	.00272	.00295	.00319	.00343	P R2
121.	156.	179.	200.	219.	238.	P S1
255.	271.	288.	304.	320.	336.	P S2
	.10					
2.032	.417	.417	1100.	302.2	.0654	
2.032	.417	.417	1100.	300.4	.076	
2.032	.417	.417	1100.	299.1	.0845	
2.032	.417	.417	1100.	298.1	.0916	
2.032	.417	.417	1100.	296.8	.101	
2.032	.417	.417	1100.	294.7	.118	
2.032	.417	.417	1100.	292.9	.135	

MHW S S
COUPLE ANALYSIS

AVERAGE N VALUES SICE 80

SEEBECK	RESISTIVITY	THERMAL K
2.385E-04	2.033E-03	4.553E-02

AVERAGE P VALUES SICE 80

SEEBECK	RESISTIVITY	THERMAL K
2.873E-04	2.506E-03	4.474E-02

EXTRANEIOUS RESISTANCE IS 14. MOHMS OF THE COUPLE RESISTANCE

HEAT LOSS IS .10 OF THE TOTAL HEAT INPUT

THE P DIAMETER IS NOT OPTIMISED

THE EXTERNAL RESISTANCE IS NOT OPTIMISED

LENGTH (CM)	PDIA (CM)	NDIA (CM)	THOT (C)	TCOLD (C)	CURRENT (AMPS)
2.032	.417	.417	1100.1	285.0	2.148

THERMAL CONDUCT WATTS/C	INTERNAL RESIST OHMS	EXTERNAL RESIST OHMS	POWER OUTPUT WATTS	TERM OUTPUT MVOLTS	THERMAL INPUT WATTS
6.067E-03	8.153E-02	1.180E-01	5.443E-01	253.44	7.01E+00

LOAD MATCHING FACTOR IS 1.447

THE COUPLE EFFICIENCY = 7.77 PERCENT

HEAT INPUT IS REDUCED BY 0.0 PERCENT

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R. C. Maydew, 9320
L. A. Hopkins, Jr., 9500
A. J. Clark, Jr., 9510
S. L. Jeffers, 9512
S. McAlees, Jr., 9513
Central Files, 3422-1 (15)
L. C. Baldwin, 3412
G. C. McDonald, 3416 (4)
Attn: P. S. Wilson