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LOW COST HIGH PERFORMANCE GENERATOR TECHNOLOGY PROGRAM

LCHPG ADDENDUM REPORT
SEPTEMBER 1975

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PREPARED FOR NUCLEAR RESEARCH AND APPLICATIONS DIVISION, ENERGY RESEARCH AND DEVELOPMENT
ADMINISTRATION UNDER ERDA CONTRACT E(49-15) -3075 (FORMERLY SNSO-3)

TELEDYNE ENERGY SYSTEMS

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**LOW COST HIGH PERFORMANCE
GENERATOR TECHNOLOGY PROGRAM**

ADDENDUM REPORT

TES-3075-43

September 1975

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Under Contract E(49-15)-3075
(Formerly Contract SNSO-3)

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FOREWORD

This document has been prepared for the United States Energy Research and Development Administration (Division of Space Nuclear Systems) by Teledyne Energy Systems under Contract E(4915)-3075, formerly Contract SNSO-3. This volume provides the progress completed under the reference contract for the months of July, August and September 1975. It is an addendum to the five volume LCHPG reports (series TES-SNSO-3) which described the LCHPG system design and component development up to June 1975.

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I. INTRODUCTION

In June 1975 the status of the LCHPG design yielded performance characteristics as summarized below for the current selenide thermocouples in a four string parallel array.

Output power	500 W(e)
Load voltage	28 VDC
Specific power	3.0 W/lb
Efficiency	10.1%
Fuel inventory	4950 W(t)
Weight	163 lbs
Hot junction temperature	900°C
Cold junction temperature	135°C
Radiator temperature	105°C

During the following three months improvements in predicted performance were achieved by reducing the number of parallel thermoelectric strings to two, redesigning the fin and rib sections, reducing the heat source volume requirements, and decreasing the cold junction temperature by 10°C. These changes resulted in the following improvements. (The current selenide performance characteristics and the hot junction temperature of 900°C were not changed.)

Output power	500 W(e)
Load voltage	28 VDC
Specific power	3.5 W/lb
Efficiency	10.8 %
Fuel inventory	4647 W(t)

Weight	142 lbs
Hot junction temperature	900°C
Cold junction temperature	125°C
Radiator temperature	92°C

The results of the design study are presented in Section II of this report.

Additional heat source design analysis was also conducted during this quarter and provided more sensitivity data on safety index as a function of heat source volume. These results were used to recommend a reduction in heat source volume for the converter design study. Further, preliminary safety assessments of fuel forms indicate that the granular fuel form (GPO) may be as safe as the solid fuel form (PPO). The safety analysis is not yet complete, but based on the early results, the reference fuel form for the performance studies was selected to be the granular fuel.

A safety assessment report is scheduled for completion in November and will form the basis for further discussion and design iteration in the heat source area. This assessment will also be supplemented by experimental impact tests at LASL to compare the behavior of GPO with PPO pellets. The tests are scheduled for the first quarter of 1976. Section III of this report describes the heat source design efforts for this quarter.

Section IV is a brief summary of the status of the components development program in support of the Ground Demonstration System (GDS) build.

Section V presents three mission application studies which were performed to support the NASA/ESA Out-of-the-Ecliptic, AFSATCOM, and GPS missions. An additional study was performed for the WESF Capsule application under this contract, but since the effort was large, a separate report covering the effort is being published concurrent with this addendum.

II. 500 WATT GENERATOR PERFORMANCE ASSESSMENT

A. INTRODUCTION

This addendum contains results of a system weight, efficiency and size analysis which was performed on the 500 W(e) LCHPG in an attempt to improve system efficiency and specific power over those presented in the June, 1975, System Design Study Report TES-SNSO-3-25 (Ref. 4). The companion part of this addendum, Section III, 500 Watt Generator Heat Source Assessment presents heat source volume, configuration and safety as related to the 500 W(e) LCHPG discussed herein.

This study was initiated due to:

1. Weight savings due to refined fin and rib sizing and weighing.
2. The desired emphasis on reducing heat source volume below 800 in.³ to effect further substantial weight savings.
3. The ability to translate these weight reductions into system efficiency gains by reducing cold junction temperature below 135°C.

Study ground rules were:

- 4 fin RTG with thermoelectric modules on two opposite sides of square cross section heat source
- Membrane isolation hot frame, fibrous insulation
500 watts(e), 28 volts
- Current standard selenides, 0% extraneous resistance, two parallel strings
- Thermoelement length = 0.3 inch

- Hot junction temperature = 900°C
- Composite bellows (Pt-30 Rh, Inconel 600)
- TES flexible sleeve cold end hardware, Cu sleeve, $\Delta T \approx 30^{\circ}\text{C}$ ⁽¹⁾
- Fiberfrax 660 H paper (in vacuum) in T/E module area
- 1-1/2 in. Min-K 1400 (in vacuum) on non-thermoelectric module sides⁽²⁾
- 2 in. Min-K 2000 (in helium) in ends⁽²⁾
- Heat source cavity volume (530, 623, 800 in.³)
- Cold junction temperature (100, 125, 150°C)
- Radiator temperature (65, 90, 115°C)⁽³⁾

-
- NOTE:
- (1) 3M improved lightweight cold end hardware will be evaluated for consideration upon receipt of data from 3M.
 - (2) Current investigation shows that Min-K may be structurally inadequate, in which case Glasrock or similar insulation will be considered. Such a change would be to the detriment of system performance.
 - (3) ΔT (cold junction - housing inner surface) $\cong 30^{\circ}\text{C}$
 ΔT (housing - heat pipe) $\cong 5^{\circ}\text{C}$
Present work indicates that a system weight savings (~ 3 lbs) may be realized by reducing the 30°C ΔT to 25°C .

B. PARAMETRIC STUDY RESULTS

Tables II-1, -2 and -3 present detailed summaries of the system performance and heat losses, weights and dimensions, respectively, for each of the three heat source volumes and cold junction temperatures considered in the study. Figures II-1, -2, and -3 present system weight, efficiency and span, respectively, as a function of cold junction temperature and heat source cavity volume. Additionally, Figure II-1 includes a few cross plotted constant system efficiency lines and indications of the range of specific power (watts(e)/lb).

The system performance data presented in this addendum were obtained using the computer codes POWER, TINSEL and PROWL (Ref. 1, 2 and 3 respectively), the latter two of which were developed during this three month study period.

Table II-4 presents a comparison of the current system performance data with those presented as the reference design in the previous study (Ref. 4). For comparison with the earlier data, the September, 1975 figures are tabulated for a heat source volume of 800 in.³ and a cold junction temperature of 135°C. A number of significant design changes have been made which have effected a system weight reduction. These are:

- Two parallel thermoelectric strings instead of four (which more than offset the copper flexible sleeve cold end hardware increase in weight over the aluminum).
- Refined rib sizing (structural analysis refinement).
- Refined rib weighing (elliptically shaped housing rib).
- Refined fin sizing taking into account end view factor effects.

TABLE II-1

500 W(e) LCHPG PERFORMANCE AND DETAILED HEAT LOSSES SUMMARY

Heat Source Volume (in. ³)	T _{cold} (°C)	$\Delta T_{\text{heat pipe}}$ (°C)	Heat Losses (Watts)						Q _{inventory} (watts)	η_{thermal} (%)	η_{system} (%)	Weight (lbs)	Specific Power (W/lb)
			T/E Module	T/E Module Periphery	Blank Sides	Ends	Bellows	Total					
530	100	3.5	299	164	136	42	57	698	4500	84.7	11.1	158	3.2
	125	4.2	283	159	132	40	56	670	4630	85.7	10.8	138	3.6
	150	5.0	268	154	128	39	55	640	4776	86.7	10.5	128	3.9
623	100	3.3	299	203	153	43	59	757	4558	83.6	11.0	166	3.0
	125	3.9	283	196	149	42	58	728	4686	84.6	10.7	146	3.4
	150	4.7	268	190	144	40	57	700	4831	85.7	10.4	137	3.6
800	100	2.9	299	215	161	61	69	805	4609	82.8	10.9	184	2.7
	125	3.5	283	208	156	60	68	775	4735	83.9	10.6	163	3.1
	150	4.1	268	201	152	57	67	746	4878	84.9	10.3	152	3.3

$$\eta_{\text{sys}} = \eta_{\text{T/E}} \times \eta_{\text{thermal}}$$

$\eta_{\text{T/E}}$	T _{cold} (°C)
13.15	100
12.62	125
12.13	150

TABLE II-2500 W(e) LCHPG DETAILED WEIGHTS SUMMARY

All Weights in Pounds															
Heat Source Volume (in ³)	T _{cold} (°C)	Heat Source			Total Heat Source	Insulation	1 F	Hot Shoes Cold Straps	Cold End Hardware	Isolation Hot Frame	Heat Pipes Saddles	Radiator Web	Housing Ends Coating	Ribs	Total
		Graphite	Clad	Fuel											
530	100	28.0	5.3	24.5	57.8	13.3	4.8	3.1	8.0	7.5	25.7	12.5	13.7	11.4	157.8
	125	27.9	5.4	25.2	58.5	13.3	5.1	3.2	8.0	7.5	13.3	9.5	11.9	7.6	137.9
	150	27.7	5.5	26.0	59.2	13.3	5.4	3.3	8.0	7.5	7.7	7.3	10.6	5.9	128.2
623	100	33.3	5.6	24.8	63.7	14.4	4.8	3.1	8.0	8.3	24.8	12.7	14.6	11.3	165.7
	125	33.2	5.7	25.5	64.4	14.4	5.1	3.2	8.0	8.3	12.8	9.6	12.7	7.7	146.2
	150	33.1	5.9	26.3	65.2	14.3	5.4	3.3	8.0	8.3	7.4	7.3	11.4	6.5	137.1
800	100	40.2	7.1	25.0	72.3	14.7	4.8	3.1	8.0	9.2	26.7	12.6	14.8	17.7	183.9
	125	40.2	7.2	25.7	73.1	14.7	5.1	3.2	8.0	9.2	13.7	9.5	13.0	13.1	162.6
	150	40.1	7.4	26.5	74.0	14.7	5.4	3.3	8.0	9.2	7.8	7.2	11.7	10.9	152.2

TABLE II-3
500 W(e) LCHPG DIMENSIONS SUMMARY

η_{fin} (optimum)		90																
All Dimensions in Inches																		
Heat Source Volume (in ³)	T _{cold} (°C)	Isolation Hot Frame Dimensions	Fin Height	RTG Height	Housing Width		Housing * Thickness Non- Module Side	Fin Width	Q _{inv} (watts)	Heat Pipe O. D.	# Pipes Fin Pair	Heat Pipe Spacing	Housing Rib Height		Housing Rib Thickness		Fin Rib Thickness	
					Module Side	Non- Module Side							Module Side	Non- Module Side	Module Side	Non- Module Side		
530	100	3 67 x 3 67 x 39 5	42 5	45 5	6 77	5 42	066	37 4	4500	352	12 7	3 41	2 1	1 5	03	02	050	
	125		42 5	45 5	6 77	5 42	058	28 1	4630	279	14 0	3 09	2 0	1 5	03	02	035	
	150		42 5	45 5	6 77	5 42	052	21 9	4776	222	15 4	2 82	2 0	1 5	03	02	025	
623	100	3 8 x 3 8 x 42 3	45 3	48 3	6 9	5 33	066	35 2	4558	341	13 8	3 40	2 1	1 5	03	02	045	
	125		45 3	48 3	6 9	5 33	058	26 1	4686	269	15 2	3 08	2 1	1 5	03	02	030	
	150		45 3	48 3	6 9	5 33	052	20 3	4831	215	16 7	2 81	2 0	1 5	03	02	025	
800	100	4 5 x 4 5 x 39 5	42 5	45 5	7 6	6 25	066	37 8	4609	355	12 7	3 40	2 4	1 6	05	04	050	
	125		42 5	45 5	7 6	6 25	058	28 1	4735	280	14 0	3 10	2 4	1 6	04	03	035	
	150		42 5	45 5	7 6	6 25	051	21 7	4878	224	15 4	2 81	2 4	1 6	04	03	025	

NOTE * Housing thickness on module sides is 0.050 inch in all cases

FIGURE II-1
 500 WATTS (e) LCHPG
 TOTAL LCHPG WEIGHT VS COLD JUNCTION TEMPERATURE AND HEAT SOURCE CAVITY VOLUME

FIGURE II-2

500 WATTS (e) LCHPG

LCHPG SYSTEM EFFICIENCY VS COLD JUNCTION TEMPERATURE AND HEAT SOURCE CAVITY VOLUME

FIGURE II-3

500 WATTS (e) LCHPG
 LCHPG FIN SPAN VS COLD JUNCTION TEMPERATURE

TABLE II-4

500 W(e) LCHPG PERFORMANCE/DIMENSIONS COMPARISON
OF SEPTEMBER 1975 WITH JUNE 1975 ANALYSES

	<u>September *</u> <u>1975</u>	<u>June</u> <u>1975</u>
Number parallel T/E strings	2	4
Bellows type	Composite	Homogeneous
T/E module insulation	Fiberfrax	Min-K
T/E element length	.3"	.3"
t _{ins.} (ends)	2.0"	2.0"
t _{ins.} (blank sides)	1.5"	1.5"
Heat source cavity volume (in. ³)	800	800
Output power, BOL (watts(e))	500	500
Load voltage (volts)	28	28
Specific power, BOL (watts/lb)	3.2	3.0
Steady state temperatures, BOL (°C)		
Sink	-79	-79
Radiator	101	105
Cold junction	135	135
Hot junction	900	900
Isolation hot frame	930	930
Inboard capsules	1030	1030
Efficiencies, BOL (%)		
Overall	10.5	10.4
Thermoelectric	12.4	12.4

NOTE: * This does not represent the new reference design but considers a heat source volume of 800 in.³ and a cold junction temperature of 135°C for comparison with the June, 1975 reference design.

TABLE II-4 (cont.)

	<u>September 1975</u>	<u>June 1975</u>
Thermal	84.5	83.9
Fuel Inventory, watts(t)	4774	4807
Weights (lbs)		
Isolation hot frame	9.2	10.4
T/E elements	5.2	5.2
Thermopile hardware (hot straps, cold straps, dielectric, cold end hardware)	11.2	12.9
Insulation	14.7	13.1
Heat pipes	7.3	8.4
Heat pipe saddles	4.0	3.0
Fin (web)	8.6	8.5
Housing/covers	8.5	11.9
Housing ribs	12.2 -	5.0
Fin ribs	(includes fin ribs)	7.8
Emissive coating	4.0	3.8
Heat shield and reentry insulators	40.2	40.8
Encapsulating members	7.2	7.7
Fuel	25.5	26.7
Total Weight	157.8	165.2
RTG height (inches)	45.5	45.5

TABLE II-4 (cont.)

	<u>September 1975</u>	<u>June 1975</u>
Fin tip-to-tip, diagonally (inches)	59.2	63.7
Housing cross section (inches)	6.3 x 7.6	7.0 x 7.6
η_{fin} (optimum)	.90	.85
Non-module side housing wall thickness (in.)	.054	.075
Module side housing wall thickness (in.)	.050	.050
Heat rejection subsystem weight (lbs)	44.6	48.4

All these improvements have enabled a savings of 7.4 lbs in system weight. The last three contributed to the 3.8 lb savings in heat rejection subsystem weight. With the improved rib and fin techniques, the optimum fin efficiency was increased (increasing the number of heat pipes), permitting a thinner housing wall thickness on the non-thermoelectric module sides. A small weight savings is obtained in the isolation hot frame by more detailed weighing techniques. Other savings are made in the thermopile hardware and heat source due to two parallel T/E strings and improved efficiency, respectively.

System performance results presented here consider Fiberfrax insulation in the thermoelectric module area instead of Min-K to insure long term compatibility with the selenide thermoelectrics. If an annular protective wrapping of Fiberfrax around each T/E element is satisfactory, with the remainder of the T/E module insulated with Min-K, system efficiency and specific power will be slightly improved. For example, consider the following detailed heat loss breakdown which corresponds to the data presented in Figure II-1 for a heat source volume of 530 in.³ and a cold junction temperature of 125°C.

<u>T/E Module Insulation</u>	<u>100% Fiberfrax*</u>	<u>30% Fiberfrax 70% Min-K*</u>
Heat losses (watts)		
T/E module	283	241
T/E module periphery	159	159
Non T/E sides	132	132
Ends	40	40
Bellows	<u>56</u>	<u>56</u>
Total	670	628

NOTE: * Thermal conductivity @ 500°C - Min-K = .015 Btu/hr - ft - °F

- Fiberfrax = .019 Btu/hr - ft - °F

(cont'd)

<u>T/E Module Insulation</u>	<u>100% Fiberfrax</u>	<u>30% Fiberfrax 70% Min-K</u>
η_{thermal} (%)	85.7	86.4
η_{system} (%)	10.8	10.9
$Q_{\text{inventory}}$ (watts)	4630	4588

For the configuration where Min-K is used in the T/E module, the assumption is made that 70% of the available T/E module insulation area is covered with Min-K; 30% is required for the protective Fiberfrax stuffing. A gain of 0.1% system efficiency is realized with an associated small (< 1.0 lb) weight savings.

C. REFERENCE DESIGN

Choice of a 500 watt reference design is made using Figures II-1, -2 and -3 to maximize system efficiency and specific power while keeping total fin span at a reasonable maximum (≈ 5 feet). From Figure II-2, it is clear that the lowest cold junction temperature and smallest heat source cavity volume maximize system efficiency. However, from Figures II-1 and -3, as cold junction temperature is lowered to 100°C ,

- fin span grows well above five ft., and
- system weight rises proportionately more rapidly than system efficiency.

Also, it may be desirable to avoid a design point too close to the selenide thermoelectric material phase change temperature of 110°C . Consideration of the various tradeoffs leads to a recommendation on cold junction temperature of 125°C .

This cold junction temperature would be controlled as necessary during ground operation to avoid phase temperature problems.

As noted earlier, system efficiency and specific power are maximized by minimizing heat source volume. Heat source safety analyses show that a heat source cavity volume of 557 in.³ is approaching the minimum "safe" volume that can supply the required thermal inventory for both granular (GPO) and pressed plutonium oxide (PPO) fuels. Further discussion is presented in the heat source section of this addendum (Section III). Thus, the recommended reference design, for both GPO and PPO fuels, has a heat source cavity volume of 557 in.³ and a cold junction temperature of 125°C. This design and its modularized version (composed of ten 50 W(e) modules) have their performance data presented in Table II-5. On the modularized design, the number of heat pipes (and ribs) per fin has been increased from 14 to 20 (on the 500 W(e) level) to permit 2 heat pipes per fin at the 50 W(e) module size. A small system weight penalty (< 1.2 lbs) is incurred for modularizing. Table II-6 presents a detailed system description of the modularized reference design.

If the minimum "safe" heat source volume is found to be smaller than 557 in.³, reduction from the reference design size to the "safe" size must be accomplished by reduction of the width of the two opposite non-thermoelectric module heat source sides. This is because

1. thermoelectric modules occupy the full area of two opposite sides of the 557 in.³ heat source, and
2. the full reference design height (~ 46.0 in.) is required to keep fin span approximately equal to five ft.

Table II-5 shows that a system efficiency, specific power and fin span of 10.76%, 3.5 watts(e)/lb and 61.2 inches are obtained for the modularized reference design.

TABLE II-5

500 W(e) LCHPG REFERENCE DESIGNS, PRESSED OR
GRANULAR PLUTONIUM OXIDES (PPO & GPO)

$$T_{\text{hot}} = 900^{\circ}\text{C}, \quad T_{\text{cold}} = 125^{\circ}\text{C}$$

	<u>Optimized (non-modularized)</u>	<u>Modularized</u>
Heat source volume (in. ³)	557	557
η_{system} (%)	10.76	10.76
η_{thermal} (%)	85.26	85.26
Weight, total (lbs)	140.6	141.8
Watts(e)/pound	3.56	3.53
Span (in.)	65.1	61.2
IHF dimensions (in.)	3.732 x 3.732 x 40.0	
Fin height (in.)	43.0	
RTG height (in.)	46.0	
Housing width-module side (in.)	6.832	
Housing width- non-module side (in.)	5.482	
Fin width (in.)	29.0	27.0
Heat pipe O. D. (in.)	0.281	0.251
No. pipes/fin pair	14	20
Heat pipe spacing (in.)	3.1	2.1
Housing rib ht. -module side (in.)	2.0	1.8
Housing rib ht - non-module side (in.)	1.5	1.3

TABLE II-5 (cont.)

	<u>Optimized (non-modularized)</u>	<u>Modularized</u>
Hous. rib thick. - module side (in.)	. 03	. 02
Hous. rib thick. - non-module side (in.)	. 02	. 02
Fin rib thickness (in.)	. 030	. 025
Hous. thick. - non module side (in.)	. 058	. 050
Hous. thick. - module side (in.)	. 050	. 050
Heat pipe ΔT ($^{\circ}C$)	4. 6	3. 4
<u>Weights (lbs)</u>		
Heat source		
Graphite		28. 0
Clad		6. 6
Fuel		<u>25. 7</u>
Total Heat Source		60. 3
Insulation		13. 3
T/E elements		5. 1
Hot shoes/cold straps		3. 1
Cold end hardware		7. 9
Isolation hot frame		7. 4
Heat pipes/saddles	13. 8	15. 6
Radiator web	9. 8	9. 1
Housing/ends/emissive coating	12. 2	11. 4
Ribs	<u>7. 7</u>	<u>8. 6</u>
Total	140. 6	141. 8

TABLE II-6
PERFORMANCE SUMMARY

OUTPUT POWER, BOL (watts(e))	500
LOAD VOLTAGE (volts)	28
SPECIFIC POWER, BOL (watts/lb)	3.5
STEADY STATE TEMPERATURES, BOL (°C)	
Sink	-79
Radiator	92*
Cold Junction	125
Hot Junction	900
Isolation Hot Frame	930
Heat Shield, Outer Surface	935
Heat Shield, Maximum	970
Pyrolytic Sleeve, Maximum	1015
Outboard Capsules	1015
Inboard Capsules	1025
EFFICIENCIES, BOL (%)	
Overall	10.8
Thermoelectric	12.6
Thermal	85.3
FUEL INVENTORY (watts(t))	4647

NOTE: * $\Delta T_{\text{cold end hardware}} = 30^{\circ}\text{C}$

$\Delta T_{\text{heat pipes}} = 3^{\circ}\text{C}$

TABLE II-6 (Cont.)CONFIGURATION/MATERIAL SUMMARY

<u>Item</u>	<u>Material</u>	<u>Configuration</u>
Fuel	PPO or GPO	Right circular cylinder, 58.1 watts/pellet, $L/D \approx 1$
Encapsulating Member	Pt-3008	Right circular cylinder, 0.020 in. thick, 4 per heat shield
Heat Shield	Graphite, 3D Type	Parallelepiped, 20 per RTG
Reentry Insulator	Pyrolytic Graphite	Sleeve plus end caps; surrounds each capsule
Compliant Pad	Graphite Felt	Disc
Isolation Hot Frame	Pt-30 Rh	Square can open at ends
Bellows	Pt-30 Rh/Inconel 600	Circular, 0.010 in. thick
Hot Frame Flanges	TZM at fueling end; Pt-30 Rh at other end	Transition pieces from square can to circular bellows
Seal Ring	Al/St Steel	Transition piece from bellows to housing; explosively bonded
Hot Side Dielectric	BeO or Al_2O_3	Either sprayed on straps or separate sheet
Hot Straps	Molybdenum	Sculptured; 0.070 in. thick
Thermoelectric P-Leg	Copper-Silver Selenide, Partitioned	Length = 0.3 inch Diameter = .314 inch No. = 320
Thermoelectric N-Leg	Current Standard Gadolinium Selenide	Length - 0.3 inch Diameter = .417 inch No. = 320
Cold Straps	Copper	0.010 in. thick; 2 string parallel circuit
Cold End Hardware	Copper BeO Dielectric, 17-7 PH Steel Spring	Flexible sleeve type; 15 one-mil wraps; helical, round wire compression type spring

TABLE II-6 (Cont.)
CONFIGURATION/MATERIAL SUMMARY

<u>Item</u>	<u>Material</u>	<u>Configuration</u>
Converter Insulation		
T/E Module	Fiberfrax 660 H Paper	12 lbs/ft ³
T/E Module Periphery	Min-K TE 1400	20 lbs/ft ³
End Plug Insulation	Min-K TE 1400 or Min-K 2000	2 inches thick
Housing	Aluminum	Rectangular section, 0.050 in. , minimum
Fins	Aluminum	0.020 in. , 27.0" x 43.0", 4 per RTG
Heat Pipes	Copper/Water	Internal axial grooves; 20 L pipes per RTG fin, 0.251 in. O. D.
Housing Rib	Aluminum	Module side - 1.8" high; .02" thick, non-module side - 1.3" high; .02" thick
Fin Rib	Aluminum	Tapered from root-to-tip; .025" thick
Electrical Receptacle (power output)	TBD	Hermetically sealed to housing
Emissive Coating	ZnO + K ₂ SiO ₄ binder (IITRI Z-93)	0.005" thick
Controlled Leak Device	TBD	Located in one end cover
Heat Source Cavity Gas Fill	Helium	Few psi up to 1/2 atm.
Converter Gas Fill	Vacuum	Leak-tight

Figures II-4, -5 and -6 are drawings of a 50 W(e) LCHP generator module, a detailed LCHPG end, and a 50 W(e) thermoelectric module couple layout, respectively. These figures are based on the data in Table II-5 for the modularized reference design. Figure II-4 is a detailed cut through the 500 W(e) reference design (GPO) showing a 50 W(e) segment. Ten of these are used to produce 500 W(e). Figure II-5 is a detailed drawing of one LCHPG end. This end is the same regardless of LCHPG power level and is used on the "fueling end"; a similar end (without load ring) is used on the other end. Figure II-6 shows the thermoelectric layout on the 50 W(e) module at the 557 in.³ reference design size. Note that the couples just fit on the sides of the two heat source blocks. The T/E center to center spacing of .603 in. is based on the size limitation of the flexible sleeve cold end hardware.

In summary, the 500 W(e) LCHPG reference design has a heat source volume of 557 in.³, a hot junction temperature of 900°C and a cold junction temperature of 125°C. Its performance data are:

- System efficiency = 10.76%
- Specific power = 3.53 watts(e)/lb
- Fin span = 61.2 inches
- RTG height = 46.0 inches
- System weight = 141.8 lbs

FIGURE II-4
LCHP GENERATOR 50 WATT UNIT ARRANGEMENT

FIGURE II-5

500 WATT REFERENCE DESIGN, END SECTION

FIGURE II-6

THERMOELECTRIC MODULE ARRANGEMENT

III. 500 WATT GENERATOR HEAT SOURCE ASSESSMENT

A. HEAT SOURCE CONFIGURATION STUDY

A heat source configuration study was completed for purposes of evaluating the safety characteristics of acceptable designs with respect to relatively small heat source volumes (400-800 in.³). With but two exceptions (as noted below), all module designs presented herein are subject to the design criteria and constraints presented in a following section of this report.* Designs are consistent with an overall length of 40 inches and 50 watt(e) modularization. The necessary inter-capsule 3D impact protection (i.e., $t_g = t_i$) has been included.

A summary of the module parameters and the more important safety aspects is as given in Table III-1. Capsule layouts are as shown in Figure III-1. Figure III-1 A is the June '75 "reference design," (configuration No. 1, Table III-1). Although space is available, inter-capsule graphite protection was not a part of this design. Figure III-1 B applies to designs 2 through 11, Table III-1. Capsules are oriented with axes parallel to the module Z (or 2.0 in.) dimension. Figure III-1 C applies to designs No. 12 through 20, Table III-1. For these designs, the capsule axis is parallel to the smaller of the stated x, y dimensions. Figure III-1 D applies to configuration No. 21, Table III-1. This module employs capsules with hemispherical ends and is shown in more detail in Figure III-2. Inter-capsule graphite protection, according to the current criterion, is not provided by this design. Actual construction details for the four capsule designs are as shown in Figure III-3. The dimensions of this figure approximate those of design No. 3, Table III-1.

*Parameter variation analysis section.

TABLE III-1
HEAT SOURCE MODULE PARAMETERS AND SAFETY ASPECTS

Ref. No.	Capsules Per Module	Thermal Watts Per Capsule	Module Dimensions (inches)	Total Heat Source Vol. (in. ³)	Module Weight (lbs)	Total Weight of Generator (lbs)	Fuel Form	Impact Velocity (ft/sec)	Capsule Temp. ⁽¹⁾ at Impact (°C)	Max. Capsule ⁽²⁾ Temp. (°C)	Heat Shield Thickness Exterior (in.) Between Capsules (in.)		Safety Index ⁽³⁾
1	9	24.3	4.5 x 4.5 x 1.796	900	3.42	162.6	PPO	130	690				6.1
2	4	58	3.6 x 3.6 x 2.0	518	2.92	137.5	GPO	151	736	1790	.27	.26	4.4
3	4		3.73 x 3.73 x 2.0	557	3.02	140.6	GPO	148	733	1782	.29	.29	4.7
4	4		4.0 x 4.0 x 2.0	640	3.28	147.9	GPO	144	729	1767	.34	.34	5.0
5	4		4.2 x 4.2 x 2.0	706	3.48	154.1	GPO	141	726	1757	.38	.38	5.3
6	4		3.408 x 3.408 x 2.0	465	2.75	132.6	PPO	155	760				4.8
7	4		3.6 x 3.6 x 2.0	518	2.93	137.5	PPO	151	748	1771	.33	.33	5.1
8	4		3.73 x 3.73 x 2.0	557	3.02	140.6	PPO	148	746	1763	.36	.36	5.3
9	4		4.0 x 4.0 x 2.0	640	3.29	147.9	PPO	144	738	1748	.41	.41	5.6
10	4		4.2 x 4.2 x 2.0	706	3.49	154.1	PPO	141	734	1739	.44	.45	5.8
11	4	58	4.4 x 4.4 x 2.0	774	3.7	161.7	PPO	139	731	1730	.48	.48	6.0
12	2	120	3.7 x 3.304 x 2.0	449	2.77	133.9	GPO	151	745	1787	.30	.30	4.4
13	2		3.7 x 3.9 x 2.0	577	3.05	141.5	GPO	146	737	1767	.35	.40	4.8
14	2		3.65 x 3.9 x 2.0	569	3.03	140.9	GPO	146	739	1768	.35	.35	4.8
15	2		3.7 x 4.663 x 2.0	690	3.40	151.9	GPO	141	730	1774	.40	.50	5.3
16	2		3.6 x 4.663 x 2.0	671	3.35	150.2	GPO	142	732	1777	.40	.40	5.2
17	2		3.7 x 2.643 x 2.0	391	2.50	126.3	PPO	161	774	1817	.30	.30	4.3
18	2		3.7 x 3.104 x 2.0	459	2.71	132.0	PPO	154	762	1782	.35	.40	4.8
19	2		3.7 x 3.368 x 2.0	546	2.98	139.4	PPO	148	749	1749	.40	.50	5.2
20	2	120	3.7 x 4.457 x 2.0	660	3.33	149.5	PPO	143	739	1718	.45	.60	5.6
21	2	150	4.0 x 3.6 x 2.0	451	3.35	131.2	GPO	153	750				4.1

(1) Based upon orbit decay reentry.

(2) Based upon prompt reentry (44,000 fps, -10° @ 400,000 ft), stable motion and smallest face leading.

(3) Assumes fuel energy capability at impact is identical for both fuel forms.

For the assumption of zero energy absorption, see parenthesis.

A. Nine 25 Watt Capsules
(Reference Design-July '75)

B. Four 58 Watt Capsules

C. Two 120 Watt Capsules

D. Two 150 Watt Capsules

FIGURE III-1

CONCEPTUAL HEAT SOURCE MODULE DESIGNS

Fuel:	Granular PuO_2
Capsule Material:	Pt-3008 ($t = .020$)
Insulator:	Pyrolytic graphite (total $t = 0.1$)
Heat Shield:	Graphite or carbon/carbon
Compliance:	Graphite felt or woven fibers

FIGURE III-2

300 W(t) HEAT SOURCE MODULE CONFIGURATION (TWO 150 W CAPSULES)

Legend:

1. Fuel Capsule
2. Pyrolytic Graphite Sleeve
3. Pyrolytic Graphite Disk (.10 th.)
4. Graphite Felt Pad (.10 compressed to .05 th.)
5. Threaded Graphite Cap (4)
6. Graphite Heat Shield
7. Fueling Port
8. Gas Vent
9. Granulated Plutonium Oxide

FIGURE III-3
TYPICAL DESIGN DETAILS - FOUR-CAPSULE MODULE

Graphite is common to all designs for the reentry protection of the fuel capsules. Sleeves and end caps with a total thickness of 0.1 inch of pyrolytic graphite are provided as insulators. All fuel capsules have a Pt-3008 clad thickness of 0.020 inch.

Both the granular (GPO) and solid(PPO) fuel form have been considered. The solid fuel is assumed to be 90% theoretical density (10.31 g/cc) with a corresponding power density of 4.12 watt/cc. The granular form was assumed to have an as-loaded density of 7.52 g/cc and a power density of 3.0 watts/cc. (This corresponds to fuel particles of 90% theoretical density with a packing fraction of ~ 73%.) For reasons noted in Section C of this chapter, the safety index evaluation of GPO design has not considered energy absorption in the fuel during the impact event. This deletion corresponds to a reduction of the safety index by ~ 0.6 for the designs reported herein.

The impact safety index as a function of total system weight for a 500 watt(e) generator is as shown on Figure III-4 . Approximate exterior systems weight (total RTG minus heat source weight) was determined from the following data.

Heat Source Volume	Systems Weight (lbs)
470	77.7
530	79.4
623	81.8
800	89.6

Some conclusions may be inferred from the results of this study. Note first that, for heat source modules of comparable volume, there is no apparent significant difference between the two and four capsule designs. Compare, for example, designs 6 with 18, designs 7 or 8 with 19 and 9 with 20 for the PPO fuel form. The same is true for the

GPO form. Compare, for example, designs 3 with 13 or 14. However, two-capsule designs feature fuel volume L/D's of 1.6 or greater, whereas four-capsule designs vary from about 0.7 to slightly greater than one. Considering model limitations, the four-capsule response predictions may be more accurate (ref. p. III-16).⁽¹⁾

A requirement of an impact safety index of about 5 has been established as a reasonable goal.⁽²⁾ The impact safety index of the MHW system has been estimated⁽³⁾ to be 4.3 with a corresponding weight of 177 lbs. An LCHPG heat source with an index of 5 would correspond to a weight saving of from 32 (GPO) to 42 (PPO) lbs and a factor of 5 increase in impact protection.

(1) See parameter variation analysis section.

(2) See discussion, TES-SNSO-3-25, p. IV-31.

(3) See discussion, TES-SNSO-3-25, p. IV-35.

FIGURE III-4

B. HEAT SOURCE DESIGN STUDY PARAMETER VARIATION ANALYSIS

A study was performed which attempted to assess the individual effects of the heat source module design parameters on the impact safety index. The heat source design variables are

- (1) fuel capsule inventory
- (2) number of fuel capsules per heat source
- (3) fuel volume L/D
- (4) capsule wall thickness
- (5) exterior graphite thickness
- (6) module dimensions

The study was complicated by interrelationships between variables. As stated, the parameters are not, by any means, independent. For example, fixed module dimensions capsule fuel inventory and volume L/D imposes obvious limits to the amount of graphite impact protection afforded each capsule.

RTG systems requirements impose constraints on the heat source module. Current designs involving thermoelectric elements on two faces require an overall length of the heat source cavity of about 40 inches. Shorter systems would require undesirably large lateral fin dimensions. Furthermore, a modularization requirement exists. Currently, the thermoelectric converter is divided into 50 watt modules. A consistent heat source design must be such that an integral number of units is associated with each thermoelectric module. Finally, we consider the program goal to maximize performance according to the watts(e) per unit weight criterion. Here minimizations of total heat source weight and volume are important.

A total heat source configuration which appears to meet the system constraints while still affording sufficient safety (at least with respect to accidents involving impact) is that of 20 heat source modules stacked one on top the other. The total stack height is 40 inches; hence, a two inch "Z" dimension for an individual module. Total heat source volumes under consideration range from less than 500 to 800 in.³.

Consistent with these constraints and the desire to preserve realism in the study, a reference basic configuration was selected. The basic module characteristics are as follows:

Fuel - PPO (4.12 watts/cc, 10.31 g/cc)

Four (4) fuel capsules per module, 58.4 watts each

Fuel diameter 1.246 in., fuel length 0.71 in.

Module dimensions - 4.0" x 4.0" x 2.0"

Clad thickness - 0.020 in. (Pt-3008)

Capsules are oriented with their axes parallel to the Z (2.0 in.)

dimension of the module

Pyrolytic sleeves and end caps for each fuel capsule, 0.10 in. thickness

All gaps (fuel to clad, clad to pyrolytic, pyrolytic to 3D⁽¹⁾ graphite) are 0.005 in.

The fuel capsule inventory is consistent with a requirement of 4670 watts (thermal) for a 500 watt (electrical) generator. A manufacturing constraint is that the minimum 3D graphite dimension be about 0.060 in. Specifically, this applies to the inter-capsule cavity spacing.

(1) A number of graphites and carbon/carbon composites are potentially heat shield candidate materials. However, with what data exists at this time, a 3D carbon/carbon is tentatively selected and applied to this study.

The exterior graphite thickness has not yet been specified. We first consider variation of this parameter.

As shown in the above sketch, the graphite thickness available in the x - z sense is $t_g = (2.0 - 0.98) / 2 = 0.51$ in. Actual designs would however require an additional 0.1 in. for graphite felt "packing material" placed between the pyrolytic graphite and 3D graphite plug to secure the assembly. Hence, $t_{g \text{ max}}$ actual is 0.46 in.

We require t_i and t_g be equal to or greater than 0.060 in. Then t_g may be made to vary from 0.060 in. to 0.454 in. by simply moving the capsule centers along the diagonals.

The variations in the safety index with respect to variations in t_g are as shown in Figure III-5. The total heat source weight is that computed for the required twenty modules. This modification produces no change in weight. It is seen that variations in exterior graphite thickness of from 0.2 to 0.454 inch produce a change in the safety index of about 0.8. Graphite thickness directly affects the mean failure velocity $\bar{v}_f$ and the source term, $\bar{Q}$. The latter decreases by a factor of about 2.4 as t_g increases from 0.2 in. to 0.46 in. ($\Delta S.I.$ of 0.4). The balance of the change is attributed to increased $\bar{v}_f$ and hence decreased capsule failure probability.

At this point we note a possible design deficiency. The safety index formulation does not consider inter capsule protection. We have allowed the inter-capsule 3D graphite thickness between capsules to be reduced to the point where the impact protection is negligible. Since the block orientation at impact is essentially random, the likelihood of capsule-capsule interaction at impact is high. A reasonable approach would be to provide as much interior as exterior graphite protection, i.e., $t_i \approx t_g$ (point x in Figure III-5). This criterion will be imposed on future designs.

As demonstrated by the data of Figure III-5, graphite protection has a significant effect on the safety index. For optimal protection, a more general design (differing x, y, z module dimensions) requires $t_{g_x} = t_{g_y} = t_{g_z} = t_i$. This may be accomplished by sizing the fuel capsule appropriately, e.g., finding the "optimum" L/D ratio for the capsule for a given number and orientation of the capsules. The resulting capsule must, however, be within reasonable bounds (as discussed below).

FIGURE III-5
EXTERIOR GRAPHITE THICKNESS VARIATION

The next parameter considered was the capsule clad thickness. Using the same four-capsule design, weight-safety index variation is as shown in Figure III-6. The selection of $t_g = 0.4$ inch was arbitrary; the shape of the curve would have been essentially the same for any graphite thickness which still allows room to increase the clad thickness. To interpret these results we compare the results to a selected "slope of significance; that of an increase in the safety index by 0.5 for a corresponding total weight increase of five pounds (as shown in the figure). (This corresponds to a factor of 3.2 increase in impact safety protection). For slopes less than the prescribed criterion, the modification is deemed worthwhile. Larger values are unacceptable. It is seen that only minimal values of the clad thickness (~10 mils) produce an acceptable result. In consideration of the limitations imposed on the safety index model by the available test data, we must reject clad thicknesses of less than 20 mils as outside the range of credibility. Hence, increased clad thickness is shown to produce unacceptable results.

We next consider the effect of weight and safety index of the number of capsules per heat source module. For the purposes of this study, the module size was fixed at 2 x 4 x 4 inches and the clad thickness was fixed at 0.020 inch.

In the analytical process, the goal, previously discussed, of matching t_g and t_i was used. To this end for each number of capsules (2, 4, or 9) considered, the appropriate graphite thickness and resulting capsule dimensions were solved for under the condition of constant fuel volume and consistency of cumulative piece-part and gap dimensions with the external dimensions of the block.

FIGURE III-6
CLAD THICKNESS VARIATION

The dimensional characteristics of these three configurations are tabulated below.

Number of Capsules per Heat Source	Capsule Inventory (watts)	Fuel L/D	t_g (in.)	Capsule Axis Orientation (with respect to the 2 inch dimension)
2	117.0	3.3	0.43	perpendicular
4	58.4	0.74	0.39	parallel
9	26.0	1.70	0.30	perpendicular

Results of the safety/weight analysis are plotted in Figure III-7. It is seen that total difference in weight among the three configurations is only about 4 pounds, while the safety index varies by about 0.4. All configurations, from a practical point of view, are essentially equivalent. Note that the dashed line shows the essential equivalence of the 2 and 9 capsule arrays according to our measure of performance ($0.1 \text{ S.I./lb} = \text{equivalence}$).

Proper review of any derived results must consider limitations of the current approximate model. It is seen from the above data that to physically achieve the 9 capsule design it is necessary to use a fuel L/D of 1.7. We must keep in mind that the experiment used for normalization of the safety model (FSA spherical configuration) is most applicable to cylindrical capsules with an L/D of about one. As we move significantly away from this value, failure mechanisms other than those observed in the FSA experiment may become prevalent. A quantitative measure of the effect of capsule shape is not available but is planned to be obtained in future heat source development tests.

FIGURE III-7
VARIATION IN THE NUMBER OF FUEL CAPSULES

This study has tended to demonstrate the criteria for deriving near optimal heat source designs consistent with imposed constraints and a given heat source volume. Specifically:

- (1) Heat source designs must obviously fall within bounds imposed by system requirements: overall volume length, modularity, heat transfer area, total thermal inventory. These requirements tend to fix certain dimensions and module thermal inventory.
- (2) Fuel capsule dimensions must be within acceptable bounds. Fuel capsule L/D ratios of about 1.0 conform most closely with the experimental basis for the safety model.
- (3) Inter-capsule 3D graphite must be provided according to the $t_i = t_g$ criterion. This criterion tends to dictate the remaining free dimensions of the module for a given number of capsules per module. These criteria form the basis for a systematic procedure now employed for design safety-weight comparisons.

We have also considered the effects of uncertainty in the present impact safety index model. Consider first the reference terminal velocity drag coefficient of 1.2. The experimental data show a range for this parameter of about (1.0, 1.4). If we had selected either of these extremes and applied them to the basic design for this study, the resultant decrease or increase in impact velocity leads to a change in safety index of about 0.3 as shown below.

$C_{d_{\text{impact}}}$	v_i	$\Delta S.I.$
1.0	158	- .32
1.2	144	0
1.4	133	+ .36

This corresponds to a factor of >3 change and hence is significant. Our program should include tests adequate to establish the nominal impact velocity and minimize the associated uncertainty.

An even more dramatic effect is associated with the error in the failure velocity. The current model assigns a standard deviation of $\sigma_f = 0.2 \bar{v}_f$ to this parameter. With adequate testing, we may hope to establish the failure velocity to within 10%, i.e., $\sigma_f = 0.1 \bar{v}_f$. Should this be the case, the failure probability of the basic design would be reduced from about 10^{-2} to less than 10^{-4} corresponding to an increase of >2 in the impact safety index.

It should be recalled that the impact safety index formulation is only an approximate working model and will receive continual revision as a function of test data availability. Studies of this nature are useful in demonstrating the significance of the parameters and pointing to the areas which require future critical evaluation.

C. THE IMPACT SAFETY INDEX

The following provides a more detailed explanation of the safety index formulation with respect to the impact events as outlined in Section IV (TES-SNSO-3-25). Specifically, we elaborate on the formulation as given in Table IV-4 of that report.

As shown in the table, the impact safety index is comprised of a summation over four impact events:

$$S.I. = \log_{10} \left(I \sum_{j=1}^4 p_{a_j} p_{f_j} \bar{Q}_j \right)$$

The four events along with a derivation of their associated accident probabilities, p_a , were identified in Table IV-5.

The failure probability, p_f , is determined from the distribution functions of the impact velocity, v_i , and the single capsule failure velocity, v_f . These velocities are assumed normally distributed, i.e.,

$$v_i \text{ from } \eta(v_i, \sigma_i)$$

$$v_f \text{ from } \eta(v_f, \sigma_f)^*$$

A new variable, x , is defined as

$$x = \frac{v_f - v_i}{\sigma} \quad \text{where } \sigma = \sqrt{\sigma_i^2 + \sigma_f^2}$$

*Since a mechanical process is involved the v_f distribution is probably somewhat other than normal (log normal, Weibull).

Note that x is inherently related to failure. Failure occurs when v_f is less than v_i . Since v_i and v_f are normally distributed and x is a linear function of v_i and v_f , then x is normally distributed with a mean $\bar{x} = \frac{1}{\sigma} (\bar{v}_f - \bar{v}_i)$ and a variance of unity. The conditional (given impact) failure probability is

$$p_f = \frac{1}{2\pi} \int_{-\infty}^{-\bar{x}} e^{-\frac{u^2}{2}} du = \frac{1}{2\pi} \int_{\frac{\bar{x}}{\sigma}}^{\infty} e^{-\frac{u^2}{2}} du$$

$$= 1 - \Phi(\bar{x})$$

where Φ is the cumulative density function of the standard normal distribution.

The mean impact velocity (sea level) is computed from the weight and aerodynamic characteristics of the heat source module as

$$\bar{v}_i = 29 \sqrt{\frac{W}{1.2 A}} \quad (\text{ft/sec})$$

where

W is the weight of the module (lb)

and A is the reference area (ft^2), taken to be the area of the broadest face of the heat source module.

The terminal velocity drag coefficient, 1.2, was derived from drop tests of bodies with similar shapes (see Appendix E, ESD-SNSO-3-11, November 15, 1974).

Uncertainty associated with the impact velocity is related to the drag coefficient which, on the basis of the test data examined, was assigned an absolute standard deviation of 0.2. In terms of the impact velocity this corresponds to a fractional standard deviation of

$$\sigma_i = 0.08 \bar{v}_i$$

The nominal failure velocity is derived from a proportionment of the total kinetic energy of the impacting body at a failure condition:

$$\text{kinetic energy} = c \left[\text{clad strain energy} + \text{graphite strain energy} + \text{fuel absorption energy} \right].$$

Specifically,

$$\bar{v}_{\text{fail}} = \sqrt{\frac{\sigma_{u_c} \cdot \epsilon_c \cdot t_c + \sigma_{u_g} \epsilon_{u_g} t_g + \frac{1}{2\epsilon_c} (\sigma_u \cdot \epsilon_c \cdot t_c)}{k (W/A)_c}} \quad (\text{ft/sec})$$

where

σ_u is the ultimate tensile strength (psi)

ϵ_u is the strain to failure (psi)

$(W/A)_c$ is the ratio of the fuel capsule weight (fuel + clad material) to the exterior surface area of the capsule (lb/in^2)

Subscripts c refers to clad

g refers to graphite

t is the material thickness, clad or graphite (in.)

k is a normalization constant $\frac{\text{sec}^2 \text{ in.}}{\text{ft}^2}$

In the above equation, the first term in the numerator under the radical is the clad strain energy per unit area. Similarly, the second term is the graphite strain energy per unit area. The third term, written in terms of the clad properties, is an approximation for the fuel energy absorption per unit area.

The graphite thickness, t_g , used for evaluation of $\bar{v}_f$, is the minimum "exterior" graphite thickness. That is, for any heat source design, the minimum dimension from the pyrolytic graphite surface to the exterior surface of the block is used. Although pyrolytic graphite is present in the heat source, it is assumed not to contribute significantly to energy absorption.

The graphite, to date, is unspecified except that it be of the woven fiber, impregnated type "3D". We have assigned the following properties for evaluation of heat source designs.

$$\begin{aligned} \sigma_{u_g} &= 20,000 \text{ psi} \\ \epsilon_{u_g} &= 0.045 \\ \text{or } \sigma_{u_g} \cdot \epsilon_{u_g} &= 900 \text{ psi} \end{aligned}$$

This value is assumed to hold for all graphite impact temperatures.

Clad strength properties $(\sigma_{u_c}, \epsilon_c)$ are evaluated at the actual clad temperatures at impact. Data used in the analysis is given in Figure III- 8. The ultimate tensile strength curve presented in this figure is derived from measurements performed on aged material (8000 hours at 1100°C in the presence of PuO_2 and graphite) at ORNL. All data are from measurements performed at slow strain rates. The clad temperature at impact is derived from aerothermal analysis summarized in Appendix B, TES-SNSO-3-25. The clad impact temperature varies with extensive graphite thickness, t_g , hypersonic continuum ballistic coefficient and heating factor; the latter two are as defined in the appendix.

The fuel energy absorption term was derived from a model based on the assumptions that (1) structural deformation energy is negligible and (2) energy is absorbed in the process of compressing fractured fuel. The steps in developing the model were:

- (1) Calculate the hydrostatic pressure in fractured fuel required to produce tensile failure in an impacted capsule (at 90° from impact point).

$$\text{Result: } P_f = \frac{\sigma_{u_c} t_c}{r}, \quad r = \text{capsule radius.}$$

FIGURE III-8
MECHANICAL PROPERTIES OF PT-3008

- (2) Calculate ratio of fuel energy of compression to capsule strain energy at failure.

$$\text{Result: } E_{\text{fuel}} / E_{\text{clad}} = \text{const.} \cdot \frac{P_f}{\sigma_u \epsilon_u \frac{t_c}{r}} = \text{const.} \cdot \frac{1}{\epsilon_u}$$

- (3) Normalization was done by observing in the MHW case (as noted herein) that $E_{\text{fuel}} / E_{\text{clad}} \sim 5$. Since, in that case $\epsilon_c \sim 0.1$ the normalization factor was $1/2$.

The $\bar{v}_f$ equation was normalized using MHW FSA test data and the above stated graphite properties for the GIS. Specifically:

	<u>Granite Impact at ~2500°F</u>	
	<u>Iridium (2500°F)</u>	<u>Graphite</u>
σ_u	26,000	20,000
ϵ_u	0.50	0.045
t (in.)	0.024	0.46
	Capsule area (PICS)	8.0 in. ³
	Weight (fuel + iridium)	0.64 lbs.
	$\bar{v}_{\text{fail}} = 280 \text{ ft/sec}$	
Then K =	$0.154 \frac{\text{sec}^2 \text{-in.}}{\text{ft}^2}$	

The computed failure velocity applies to granite impact (assumed to be the hard surface for evaluation of the reentry impact situations). For the launch complex targets (steel, concrete), a correction factor is applied to the computed failure velocity. The correction factors were derived from an acoustic impedance model by comparing graphite/granite and graphite/other targets. Additionally, nominal impact velocities for

launch pad accidents are lower than the terminal velocity. Corrections, based on rigorous analysis of launch pad accidents for the Viking flights, are applied to the nominal terminal velocities. These corrections are summarized as follows:

Target	<u>Launch Complex Impacts</u>	
	Mean Impact Velocity (factor of terminal velocity)	Target correction factor. Multiplies the computed failure velocity.
Concrete	0.6	1.1
Steel	0.7	0.9

Consistent with the multitude of uncertainties including application of FSA test data to LCHPG designs and graphite properties, we have assigned a substantial uncertainty to the failure velocity. In fractional form

$$\sigma_f = 0.20 \bar{v}_f$$

The source term, $\bar{Q}$, is derived in two parts: the first defines the fraction of fines (fuel particles of less than 4 microns) produced by the impact event and the second defines that portion of the fines available which are released given capsule failure. Fines production is assumed proportional to the impact energy or equivalent to v_i^2 . For the released fines given failure, we have assumed a relative function which is proportional to the excess of the energy required to fail the capsule. Combining the two relationships

$$\bar{Q} \sim f(v_i, v_f) = \begin{cases} v_i^2 \left[\left(\frac{v_i}{v_f} \right)^2 - 1 \right] & \text{for } v_i > v_f \\ 0 & v_i \leq v_f \end{cases}$$

Since v_i and v_f are distributed quantities, we must solve an integral of the form

$$\bar{Q} = \frac{L}{p_f} \int_{-\infty}^{\infty} p(v_i) dv_i \int_{-\infty}^{\infty} f(v_i, v_f) p(v_f) dv_f$$

where $p(v_i)$ and $p(v_f)$ are the respective normal probability density functions already defined and L is a normalization factor. Inclusion of the factor $1/p_f$ yields source terms which are conditional on failure. No closed form solution for the above integral exists. A Monte Carlo technique was used for evaluation of $\bar{Q}$ parametrically. For a given set $\bar{v}_i, \bar{v}_f, \sigma_i, \sigma_f$ the game is as follows:

1. Pick v_i from $\eta(\bar{v}_i, \sigma_i)$.
2. Pick v_f from $\eta(\bar{v}_f, \sigma_f)$.
3. If $v_f > v_i$ end history (no failure). Otherwise proceed to Step 4.
4. Evaluate the source Q for this history using $f(v_i, v_f)$.
5. Add Q from Step 4 to ΣQ (initially ΣQ is set to zero).

An estimate of the desired source Q is $L\Sigma Q/(p_f N)$ where N is the total number of histories.

Normalization is accomplished by once again using MHW FSA test data. A function fit of data available at the time indicated that the fractional fines production for impact temperatures less than about 1250°C is about 7.5×10^{-4} , i.e., this fraction of the total fuel per capsule would be converted to fines for impacts at about 280 ft/sec. An estimate of the fraction of fines released given an impact failure was derived from the following test data* (all impacted at velocities of about 280 ft/sec).

*Additional test data contained in the "Fairchild Correlation" were not available when this model was formulated.

FSA Sample	Grams of fuel released per gram of fuel
MHFT-03	0.0027
MHFT-04	0.00006
MHFT-12	0.0056

MHFT-12 was subjected to a heat pulse prior to impact. MHFT-03 appears to be in the same category, hence the two values were averaged to yield a value of 4.2×10^{-3} .

Assuming that the fines released per fines available for release is proportional to total fine release per fuel available for release and further assuming that the heat pulse was characteristic of the atmospheric reentry event, then this fraction is applicable to impacts following reentry as the fraction of fines released to those available.

The normalization constant L was evaluated by performing a special Monte Carlo run in which an impact velocity $\bar{N}_i = 280$ ft/sec (assumed to be known precisely, $\sigma_i = 0$) was used. The normal failure velocity for this run was $\bar{v}_f = 280$ ft/sec with a reduced standard deviation of $\sigma_f = 0.067 \bar{v}_f = 19$ ft/sec. A normalization factor of $L = 3.4 \times 10^{-10}$ was found to produce the desired result of $\bar{Q} = 7.5 \times 10^{-4} \times 4.2 \times 10^{-3} = 3.2 \times 10^{-6}$ curies of fines produced per curie of fuel.

The remaining experiment, MHFT-04, was not thermally pulsed prior to impact. This was assumed typical of a launch complex impact. Accordingly, in evaluation of launch pad impact events, the source term as computed for reentry events was reduced by a factor of $4.2 \times 10^{-3} / 6 \times 10^{-5} = 70$.

A summary of source terms derived by the above methods used in heat source evaluation is given in the following table as a function of $\bar{v}_i$ and p_f . To obtain these results, the Monte Carlo results were plotted and "smoothed" in an attempt to relieve some apparent statistical fluctuations.

TABLE III-2
IMPACT SOURCE TERMS

Reentry Events*

Exterior Graphite Thickness $t_g = 0.46$ in.

Mean impact velocity $\bar{v}_i$ ft/sec	$\bar{Q} \left(\frac{\text{curies of fines released}}{\text{curie inventory}} \right)$					
	Failure probability, p_f					
	0.5	0.1	0.05	0.01	0.005	0.001
50	5.3×10^{-7}	4.4×10^{-7}	3.9×10^{-7}	3.7×10^{-7}	4.3×10^{-7}	8.2×10^{-7}
100	2.2×10^{-6}	1.7×10^{-6}	1.6×10^{-6}	1.5×10^{-6}	1.3×10^{-6}	1.8×10^{-6}
150	4.8×10^{-6}	3.9×10^{-6}	3.4×10^{-6}	3.3×10^{-6}	3.5×10^{-6}	5.0×10^{-6}
200	8.6×10^{-6}	7.0×10^{-6}	6.2×10^{-6}	5.8×10^{-6}	5.7×10^{-6}	8.0×10^{-6}
250	1.4×10^{-5}	9.8×10^{-6}	9.2×10^{-6}	1.1×10^{-5}	1.2×10^{-5}	1.5×10^{-5}
300	2.0×10^{-5}	1.7×10^{-5}	1.5×10^{-5}	1.4×10^{-5}	1.6×10^{-5}	2.2×10^{-5}

*For launch complex impacts, divide the tabular values by 70.

In actual heat source evaluation, the values of this table were interpolated to find the proper source term.

One other factor is applied to the source term. Impact analyses performed by Marshall Eck (Fairchild Industries) have shown the ratio of energy absorbed in the graphite, fuel and clad to be about 80%, 16% and 4%, respectively for an FSA impact. Assuming the same relative proportions in the fuel and clad, the absence of graphite would produce an 80%, 20% fuel, clad energy apportionment. Consistent with the assumed energy dependence of fines production, this apportionment is expressed approximately as

$$4.8 e^{-3.41 t_g}$$

where t_g is the aforementioned exterior graphite thickness (inches). For a graphite thickness of 0.46 in. (FSA) this factor is unity, whereas for no graphite the value is 4.8. This factor is evaluated and multiplies the nominal $\bar{Q}$ from Table III-2.

The safety index formulation as described herein is realized to be only approximate model and is subject to continual updating as pertinent test data and analysis becomes available. Constructive criticism is invited. At the time of this writing, certain inadequacies are known to exist. Specifically, the energy absorption term for the fuel in the $\bar{v}_f$ equation may be too optimistic. A more realistic model will be derived as a function of fuel strength properties. Similarly, an attempt will be made to update the graphite energy absorption term using information forthcoming from Battelle Columbus Laboratory analysis and experimentation and from Air Force and Navy graphite data which we have just begun to receive. Revisions are planned for the October-December 1975 period.

Current heat source design analysis considers the use of the granular fuel form. Once again, we question the fuel energy absorption in computation of $\bar{v}_f$. Current thinking is that fuel energy absorption is mainly due to breaking up of the solid fuel form. The granular form may be hydrostatic in nature; on impact, the fuel is free to move and hence absorb very little of the impact energy. Accordingly, for heat sources using granular fuel we have dropped the fuel energy absorption term in the $\bar{v}_f$ equation. The result is a lower $\bar{v}_f$, higher p_f and hence a reduced impact safety index. For "typical" LCHP heat source designs the reduction in the safety index is about 0.6 corresponding to an increase in the failure probability of about a factor of 4.

The results of fuel capsule impact tests planned at LASL utilizing three fuel forms will also be integrated into the impact model.

IV. COMPONENT DEVELOPMENT STATUS AND TEST

A. LIAISON WITH 3M COMPANY

Technical liaison was continued with the 3M Company during this 3 month period by the following efforts:

1. Trips to 3M on July 9 and September 4, 1975
2. Numerous telephone conversations
3. Final briefing to ERDA with 3M in attendance on July 15, 1975

Topics currently being evaluated are:

1. Generator assembly approach

In general, 3M will assemble the T/E module which includes the cold end hardware and TES will complete the generator assembly.

2. The effect of the 110 °C P-element selenide phase change on the cold junction temperature design point.
3. Fibrous insulation outgassing requirements and generator overall leakage criterion for a sealed (i. e. , non-pumped) generator.
4. Use of a graphite thermopile hot side face sheet to alleviate any axial thermal expansion problem.
5. Use of Min-K in T/E module with an annular stuffing of Fiberfrax around each element.
6. Trade-offs involved in using 3M lightweight square follower cold end hardware versus TES flexible sleeve cold end hardware.
7. Additional performance calculations by 3M that include the effects on thermopile weight and efficiency of non-zero extraneous resistance. These calculations will be performed over the range in cold junction temperature of 100 °C to 150 °C.

B. HEAT SOURCE COMPATIBILITY AND VENT PERFORMANCE MODULES

The initial heat source module went on test at the Los Alamos Scientific Laboratory during September for a period of six months minimum. The purpose of the test program is to evaluate material compatibility and vent performance. The module as depicted in Figure IV-1 consists of a Pt-3008 capsule ($t = .020''$) encapsulating three 25 watt(t) PuO_2 fuel pellets. This particular capsule includes the TES vent and hemispherical end fillers of yttria stabilized ZrO_2 . The capsule temperature over the duration of the test is 1000°C in a helium environment.

Temperature readings as of October 2, 1975 were as follows:

Capsule side wall	999°C
Capsule dome	970°C
Graphite	973°C
Outer can (stainless steel)	906°C

The remaining heat source assemblies as shown in Figure IV-2 are scheduled to go on test during the last quarter of 1975.

C. 3D CARBON/CARBON AIR OXIDATION TESTING

With the purpose of furthering the characterization of candidate heat shield graphite materials, specimens of 3D carbon/carbon composite were tested during August and September to determine its air oxidation behavior as a function of temperature, pressure and air flow rate. This data is useful to support planned aerothermal studies since oxidation is the primary mode of surface recession during reentry. These experiments were conducted utilizing both a Marshall tube furnace and a du Pont thermogravimetric analyzer (TGA).

FIGURE IV-1

75 W(t) HEAT SOURCE TEST MODULE

75 W(t)
Teledyne Vent
1000°C Helium

25 W(t)
LASL Vent
1000°C Helium

25 W(t)
LASL Vent
1000°C Vacuum

25 W(t)
LASL Vent
1000°C Vacuum
"Control"

50 W(t)
LASL Vents
1100°C Vacuum

50 W(t)
LASL Vents
1100°C Helium

FIGURE IV-2
HEAT SOURCE MODULE CONFIGURATIONS

In addition to the 3D carbon/carbon, POCO AXF-Q1 specimens were also tested to correlate with results of previous experimentation conducted during the Pioneer heat source program (Ref. 5).

The test specimens of 3D carbon/carbon were of both cylindrical and rectangular parallelepiped configurations. The material, identified as billet S/N 483B1, was obtained from Fiber Materials, Inc., of Biddeford, Maine. The Thornel 400 yarn bundles consisted of two yarns per bundle in each of the three orthogonal directions where the Z spacing between bundles was 0.030 inch. The material density was 1.90 gms/cc.

The experiments were conducted with the following ranges of variables:

Temperature	900 - 1600 °F
Pressure	0.1 and 1.0 atmospheres
Air flow rate	0.1 - 5 liters/minute
Time	1-1/2 - 360 minutes

All test data is provided by mass flux rate as a function of the inverse of temperature. Figure IV-3 provides the reaction rate for the POCO-AXF-Q1 and incorporates the data per Ref. 5 in addition to the new data. Figures IV-4 and -5 delineate the reaction rates for the 3D carbon/carbon, the former associated with the tube furnace experimentation and the latter associated with the TGA. The test results indicate that the mass flux rate for both materials is rather insensitive to test time. The new AXF-Q1 specimens were tested over a wide range from 60 to 360 minutes. However, one specimen was tested at three time intervals with an increase in rate for each successive test which raises the question of relative surface condition. Three mechanisms are suggested:

FIGURE IV-3

MASS FLUX RATE VS. RECIPROCAL OF TEMPERATURE FOR POCO AXF-Q1

FIGURE IV-4

MASS FLUX RATE VS. RECIPROCAL OF TEMPERATURE FOR 3D CARBON/CARBON

FIGURE IV-5

MASS FLUX RATE VS. RECIPROCAL OF TEMPERATURE FOR 3D CARBON/CARBON

- (1) The specimen surface was roughened by selective oxidation thus presenting a greater surface area than can be measured.
- (2) Surface spalling due to cycling thermal stresses.
- (3) Each successive test begins with some absorbed oxygen in the specimen since the specimens are not outgassed between runs.

One noticeable difference in the furnace results of Figure IV-4 and the TGA results of Figure IV-5 is the slope of the data as a function of specimen shape. All TGA specimens were cylindrical, whereas the furnace specimens were rectangular with the exception of three specimens. The slope for the data for these latter three specimens compares closely with the TGA slope results. The final test report for these studies has recently been released (Ref. 6).

D. COLD END HARDWARE DEVELOPMENT

The development effort to assemble and test flexible sleeve cold end hardware was continued during the period. The status of major items as of September 30, 1975 has been shown in the table below. The shift from aluminum to copper as a foil material has permitted the production of consistently satisfactory flex-sleeves with existing tooling.

<u>Tooling/Facilities</u>	<u>Status</u>	<u>Remarks/Disposition</u>
Pre-plating ribbon wrapping test	complete	in use
Sleeve wrapping tool	complete	in use
Sleeve punching tool	rework	in use
Sleeve forming tool	in mfg.	scheduled
Cleaning baths Cu and Al	operational	in use

<u>Tooling/Facilities (cont.)</u>	<u>Status</u>	<u>Remarks/Disposition</u>
Electroless plating bath, zincate	complete	in use on Al parts only
Electroless plating bath, Ni-410	complete	Al parts only - not used at present
Electroless plating bath, Cu	complete	in use on Al parts only
Electroplating facility, Cu	complete	in use on Al parts only
Electroplating facility, Sn	complete	in use on Cu foil
Electroless plating bath, Sn	complete	in use on Al foil
Rinse baths	complete	in use on Cu foil and Al parts
<u>Test Fixtures</u>		
Cold end hardware module test fixture	details complete; awaiting assembly	see sleeve availability below
<u>Cold End Hardware Components</u>		
Sleeves - Al	held for future development	current effort complete
Sleeves - Cu	under development	parts being fabricated for installation development
Springs	complete	in stock
Cap	complete	in stock
Dielectric wafers	complete	in stock
Cap assembly	in mfg.	under development for bond
Flex-sleeve assembly	in mfg.	under development for bond
Flex-sleeve installation	in mfg.	under development for bond

The cold end hardware ΔT test for verification of the thermal analysis for this design is scheduled for November 1975.

E. COMPONENT DEVELOPMENT PLANNING EFFORT

Major components and procedures of the LCHPG GDS which require either development or evaluation tests to demonstrate capability of reliable performance have been tabulated below. Scheduling to be consistent with program needs and projected resources is in progress.

<u>Item/Topic</u>	<u>Effort/Task</u>
Electrical Feed-Thru*	Identify connectors which may be hermetically sealed into housing through vendor search and test.
Electrical Heat Source*	Vendor/programs search for proven reliable high temperature heater technology. Heater selection and acceptance testing.
Insulation*	Characterization of candidate insulations for in-module and non-module use through vendor search and test.
Cold End Hardware*	Demonstration of manufacturing techniques and performance.
Bi-Metallic Ring*	Develop and demonstrate a reliable joint between Al housing and bellows.
Support Ring Brazed Joint	TZM attachment to Pt-30 Rh isolation hot frame will be demonstrated to design requirements.
Bellows Development*	IHF-to-housing bellows design and fabrication.
Bellows/Bimetallic Ring Fusion Weld	Demonstrate reliable weld technique between selected candidate thin sheet (.010"-.020"), dissimilar metals.
IHF Can Material Property Evaluation*	Confirm Pt-30 Rh properties to be consistent with IHF and converter design objectives.
Z-93 Emissive Coating	Characterize coating in support of design objectives.
Converter Final Seal*	Develop a seal and sealing procedure for the evacuated LCHPG converter section.
Fueling/Defueling Friction Tests*	Evaluate anticipated frictional loads during fueling, defueling.

* Note: Items marked by an asterick are active, or have been activated during the 3-month reporting period.

V. MISSION APPLICATIONS

During the three-month interval represented by this addendum report, three missions were evaluated for potential application of the selenide technology: (1) NASA/ESA Out-of-the-Ecliptic mission, (2) AFSATCOM mission, and (3) a GPS mission. Each of these design efforts is summarized independently in the following pages. Various design options were exercised such as thermoelectric module arrangements and number of heat rejection fins to maximize the specific power and efficiency of the systems. The three studies explore units in size from 60 to 600 watts electrical. In general, the larger power units are more efficient and have higher specific powers.

In the study of the NASA/ESA Out-of-the-Ecliptic Mission, the selenide generator designs are compared to existing SNAP 19 technology. This comparison will give the reader an appreciation for the performance improvements to be obtained through the use of LCHPG systems.

A. NASA /ESA OUT-OF-THE-ECLIPTIC STUDY

The recommended radioisotope thermoelectric generators for the NASA /ESA Phase A Out-of-the-Ecliptic mission study are the LCHPG and SNAP 19 type systems. The LCHPG converters utilize a selenide base thermoelectric material providing over 10% efficiency and are currently being developed for early 1980 mission application. A ground demonstration system is scheduled to be operating in July 1977. The SNAP 19 thermoelectric materials are already space qualified (Pioneer and Viking Programs) and utilize a telluride thermoelectric material which yields efficiencies up to 7-1/2 percent. Both systems are fueled with plutonium-238 oxide heat sources. The converter designs are modular to allow various power level packages to be assembled without requalification of components such as the thermoelectric couple designs or heat source modules.

An LCHPG unit of 500 W(e) is shown in the accompanying photo and cut away drawing for reference. The NASA/ESA Out-of-the-Ecliptic mission application requires less power and thus the converter would be smaller. The SNAP 19 converters would use the same geometry, heat source configurations and fabrication techniques. However, they would be slightly larger and heavier due to the lower efficiencies of the telluride thermoelectric modules.

The selenide system is modularized at a BOL unit size of 65 W(e) and the telluride referred to as TAGS/2N at a BOL unit size of 75 W(e). The difference in BOL power is to accommodate differences in the performance characteristics over a mission lifetime, i.e., both systems will provide 60 W(e) at the end of a 5 year mission. Two each are required to supply the total mission requirements of 120 W(e).

A detailed summary of the selenide RTG and TAGS/2N RTG, as designed for the NASA/ESA Out-of-the-Ecliptic mission, follows.

500 W(e) LCHPG Modular Generator

<p>PERFORMANCE SUMMARY</p> <p>SELENIDE RTG</p>
--

Output power (watts)

• BOL	65
• 5 years	60

Load voltage, volts 3.7

Specific power (watts/pound), BOL 3.0

Steady state temperatures, BOL (°C)

Sink	-79
Radiator	90
Cold junction	125
Hot junction	900
Isolation hot frame	930
Inboard capsule	1060

Efficiencies, BOL (%)

Overall	10.2
Thermoelectric	12.6
Thermal	81.0

Fuel inventory (watts(t)) 636

SIZE/WEIGHT SUMMARY SELENIDE RTG

<u>Component</u>	<u>Weight (pounds)</u>
Isolation hot frame	2.0
Thermoelectric elements	0.7
Straps + cold end hardware	0.8
Insulation	2.6
Heat pipes	0.6
Heat pipe saddles	0.2
Fin (web)	1.0
Housing/covers	3.8
Ribs	1.0
Emissive coating	0.5
Fuel (PPO)	3.5
Clad	0.9
Heat shields	3.7
	<hr/>
Total	21.3
RTG height (inches)	17.0
Fin tip-to-tip, diagonally (inches)	29.0
Housing cross-section (inches)	5.9 x 6.3

<p>CONFIGURATION/MATERIAL SUMMARY</p> <p>SELENIDE RTG</p>

<u>Item</u>	<u>Material</u>	<u>Configuration</u>
Fuel	PPO	Right circular cylinder, 35.3 watts/pellet, L/D = 1
Encapsulating Member	Pt-3008	Right circular cylinder, 0.020 in. thick, 9 per heat shield
Heat Shield	Graphite, 3D Type	Parallelepiped, 2 per RTG
Reentry Insulator	Pyrolytic Graphite	Sleeve plus end caps; surrounds group of 3 capsules
Compliant Pad	Graphite Felt	Disc
Spacer for Capsules	POCO Graphite	Tube; axially separates capsules
Isolation Hot Frame	Pt-30 Rh	Rectangular can open at ends, 1.8 x 4.5 x 9 in.
Bellows	Pt-30 Rh	Oval, 0.010 in. thick
Hot Frame Flanges	TZM at fueling end; Pt-30 Rh at other end	Transition pieces from square can to oval bellows
Seal Ring	Al/St. Steel	Transition piece from bellows to housing; explosively bonded
Hot Side Dielectric	BeO or Al_2O_3	Either sprayed on straps or separate sheet
Hot Straps	Molybdenum	Sculptured; 0.070 in. thick
Thermoelectric P-leg	Copper-Silver Selenide, Partitioned	Length = 0.3 in. Diameter = 0.314 No. = 44
Thermoelectric N-leg	Current Standard Gadolinium Selenide	Length = 0.3 in. Diameter 0.417 No. = 44
Cold Straps	Copper	0.010 in. thick; 2 string parallel circuit
Cold End Hardware	Copper BeO Dielectric 17-7 PH Steel Spring	Flexible sleeve type 15 one-mil wraps; helical, round wire compression type spring
Converter Insulation	Min-K TE 1400	Min-K 20 lbs/ft ³

<u>Item</u>	<u>Material</u>	<u>Configuration</u>
Eng Plug Insulation	Min-K TE 1400 or Min-K 2000	2 in. thick
Blank Side Insulation	Min-K TE 1400 or Min-K 2000	2 in. thick
Housing	Aluminum	Rectangular section, 0.050 in. min.
Fins	Aluminum	0.020 in., 11.0 x 12.0 in., 4 per RTG
Heat Pipes	Copper/Water	Internal axial grooves; 10 L-pipes per RTG; 0.196 in. O.D.
Housing Rib	Aluminum	Module Side- 1.9 in. high, 0.03 in. thick Non-module Side- 1.2 in. high, 0.02 in. thick
Fin Rib	Aluminum	Tapered from root-to-tip; 0.020 in. thick
Electrical Receptacle (power output)	TBD	Hermetically sealed to housing
Emissive Coating	ZnO + K ₂ SiO ₄ binder (IITRI Z-93)	0.005 in. thick
Controlled Leak Device	TBD	Located in one end cover
Heat Source Cavity Gas Fill	Helium	Few psi up to 1/2 atm.
Converter Gas Fill	Vacuum	Leak-tight

SELENIDE MODULE CONFIGURATION (22 couples)

<p>PERFORMANCE SUMMARY</p> <p>TAGS/2N RTG</p>

Output Power (watts)

• BOL	75
• 5 years	60

Load voltage, volts	6.1
---------------------	-----

Specific power (watts/pound), BOL	2.3
-----------------------------------	-----

Steady state temperatures, BOL (°C)

Sink	-79
Radiator	120
Cold junction	145
Hot junction	520
Isolation hot frame	550
Inboard capsule	690

Efficiencies, BOL (%)

Overall	7.5
Thermoelectric	8.4
Strap	95
Thermal	93

Fuel Inventory (watts(t))	1000
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<p>SIZE/WEIGHT SUMMARY</p> <p>TAGS/2N RTG</p>

<u>Component</u>	<u>Weight (pounds)</u>
Isolation hot frame	1.7
Thermoelectric elements	2.7
Straps + cold end hardware	2.3
Insulation	4.0
Heat pipes	0.8
Heat pipe saddles	0.3
Fin (web)	1.2
Housing/covers	4.3
Ribs	1.7
Emissive coating	.7
Fuel (PPO)	5.5
Clad	1.4
Heat shields	6.0
	<hr/>
Total	32.6
RTG height (inches)	19.5
Fin tip-to-tip, diagonally (inches)	29.1
Housing cross-section (inches)	8.6 x 4.0

<p>CONFIGURATION/MATERIAL SUMMARY</p> <p>TAGS/2N RTG</p>
--

<u>Item</u>	<u>Material</u>	<u>Configuration</u>
Fuel	PPO or Shards	Right circular cylinder, 37.0 watts/pellet, L/D = 1
Encapsulating Member	Pt-3008	Right circular cylinder, 0.020 in. thick, 9 per heat shield
Heat Shield	Graphite, 3D Type	Parallelepiped, 3 per RTG
Reentry Insulator	Pyrolytic Graphite	Sleeve plus end caps; surrounds group of 3 capsules
Compliant Pad	Graphite Felt	Disc
Spacer for Capsules	POCO Graphite	Tube; axially separates capsules
Isolation Hot Frame	Haynes-188	Rectangular can open at ends, 1.8 x 4.5 x 13.5 in.
Bellows	Haynes-188	Oval, 0.010 in. thick
Hot Frame Flanges	Haynes-188	Transition pieces from square can to oval bellows
Seal Ring	Al/St. Steel	Transition piece from bellows to housing; explosively bonded
Hot Side Dielectric	BeO or Al ₂ O ₃	Either sprayed on straps or separate sheet
Hot Straps	Molybdenum	Sculptured; 0.070 in. thick
Thermoelectric P-leg	TAGS-85	Length = 0.5 in. Diameter = 0.270 in. No. = 128
Thermoelectric N-leg	2N	Length - 0.5 in. Diameter = 0.377 in. No. = 128
Cold Straps	Copper	0.010 in. thick; 2 string parallel circuit
Cold End Hardware	Aluminum BeO Dielectric, 17-7 PH Steel Spring	Flexible sleeve type; 20 one-mil wraps; helical, round wire compression type spring
Converter Insulation	Min-K TE 1400	Min-K 20 lbs/ft ³

<u>Item</u>	<u>Material</u>	<u>Configuration</u>
Eng Plug Insulation	Min-K TE 1400 or Min-K 2000	2 in. thick
Blank Side Insulation	Min-K TE 1400 or Min-K 2000	2 in. thick
Housing	Aluminum	Rectangular section, 0.050 in., min.
Fins	Aluminum	0.020 in., 9.6 x 16.5 in. height, 4 per RTG
Heat Pipes	Copper/Water	Internal axial grooves; 12 L-pipes per RTG; 0.173 in. O.D.
Housing Rib	Aluminum	{ Module Side- 1.9 in. high; 0.04 in. thick Non-module side- 1.4 in. high; 0.03 in. thick
Fin Rib	Aluminum	Tapered from root-to-tip; 0.020 in. thick
Electrical Receptacle (power output)	TBD	Hermetically sealed to housing
Emissive Coating	ZnO + K ₂ SiO ₄ binder (IITRI Z-93)	0.005 in. thick
Controlled Leak Device	TBD	Located in one end cover
Heat Source Cavity	Helium	Few psi up to 1/2 atm.
Converter Gas Fill	Argon	Leak-tight

 $D_N = .377$
 $D_P = .270$
 $Spc = .550$
 $T_{COLD} = 295^{\circ}F$
 $T_{HOT} = 970^{\circ}F$
 $T_H, \text{ aged} = 1000^{\circ}F$
 $V = 1.5 \text{ volts/module}$
 $P_{BOL} = 18.8 \text{ watts/module}$

TAGS/2N PIONEER-VIKING COUPLE (64 COUPLES/SIDE) 2 SIDES/RTG

B. AFSATCOM MISSION STUDY

Included in this section are summaries of the LCHPG designs for the AFSATCOM mission. Mission requirements were provided by Rockwell International, Downey, California.

The AFSATCOM LCHPG's evaluated are four-fin units operating at power levels of 200, 400 and 600 watts electrical in order to provide the parametric power requirements needed by the user.

Basic design constraints for this study were:

1. current standard selenides with zero percent extraneous resistance,
2. a 900°C hot junction temperature,
3. a GPO fuel form,
4. an unobstructed view of space.

Results of the analysis indicate efficiencies in the range of 10.5 to 10.8% are achievable with specific powers in the range of 3.3 to 3.5 watts per pound over the unit range of 200 to 600 watts electrical.

Performance data sheets are presented in the following four pages.

AFSATCOM
PERFORMANCE SUMMARY
SELENIDE RTG

Output power (watts) at BOL	200	400	600
Load voltage, volts	11.2	22.4	33.6
Specific power (watts/pound), BOL	3.27	3.48	3.53
Steady state temperatures, BOL (°C)			
Sink	-79	-79	-79
Radiator	90	90	90
Cold junction	125	125	125
Hot junction	900	900	900
Isolation hot frame	930	930	930
Inboard capsule	1035	1035	1035
Efficiencies, BOL(%)			
Overall	10.5	10.7	10.8
Thermoelectric	12.6	12.6	12.6
Thermal	83.1	85.0	85.7
Fuel inventory (watts(t))	1908	3727	5546

SIZE/WEIGHT SUMMARY
SELENIDE RTG

<u>Component</u>	<u>Weight (pounds)</u>		
	<u>200 W(e)</u>	<u>400 W(e)</u>	<u>600 W(e)</u>
Isolation hot frame	4.2	6.2	8.8
Thermoelectric elements	2.0	4.1	6.1
Straps + cold end hardware	5.0	10.0	15.0
Insulation	8.1	11.6	15.0
Heat pipes	3.6	8.2	13.0
Heat pipe saddles	1.1	2.4	3.8
Fin (web)	3.6	7.6	11.7
Housing/covers	4.7	7.3	9.8
Ribs	2.8	6.2	9.5
Emissive coating	1.6	3.2	4.8
Fuel (GPO)	10.6	20.6	30.7
Clad	2.7	5.3	8.0
Heat shields	11.2	22.4	33.7
Total	61.2	115.1	169.9
RTG height (inches)	22.0	38.0	54.0
Fin tip-to-tip, diagonally (inches)	55.7	62.5	65.7
Housing cross-section (inches)	6.8 x 5.5	6.8 x 5.5	6.8 x 5.5

CONFIGURATION/MATERIAL SUMMARY
SELENIDE RTG

TES-3075-43

<u>Item</u>	<u>Material</u>	<u>Configuration</u>		
		200 W(e)	400 W(e)	600 W(e)
Encapsulating Member	Pt-3008	Right circular cylinder, 0.020 in. thick, 4 per heat shield		
Reentry Insulator	Pyrolytic Graphite	Sleeve plus end caps; surrounds each capsule		
Compliant Pad	Graphite Felt	Disc		
Bellows	Pt-30 Rh	Circular 0.010 in. thick		
Hot Frame Flanges	TZM at fueling end; Pt-30 Rh at other end	Transition pieces from square can to circular bellows		
Seal Ring	Al/St. Steel	Transition piece from bellows to housing, explosively bonded		
Hot Side Dielectric	BeO	Either sprayed on straps or separate sheet		
Hot Straps	Molybdenum	Sculptured; 0.070 in. thick		
Cold Straps	Copper	0.010 in. thick; 2 string parallel circuit		
Cold End Hardware	Copper, BeO Dielectric 17-7 PH Steel Spring	Flexible sleeve type 15 one-mil wraps; helical, round wire compression type spring		
Converter Insulation				
T/E Module	Fiberfrax 660-H paper	12 lbs/ft ³		
T/E Module Periphery	Min-K TE 1400	20 lbs/ft ³		
End Plug Insulation	Min-K TE 1400 or Min-K 2000	2 in. thick		
Blank Side Insulation	Min-K TE 1400 or Min-K 2000	1.5 in. thick		
Housing	Aluminum	Rectangular section, 0.050 in. min.		
Electrical Receptacle (power output)	TBD	Hermetically sealed to housing		
Emissive Coating	ZnO + K ₂ SiO ₄ binder (IITRI Z-93)	0.005 in. thick		

V-17

Item	Material	Configuration		
		200 W(e)	400 W(e)	600 W(e)
Controlled Leak Device	TBD	Located in one end cover		
Heat Source Cavity Gas Fill	Helium	Few psi up to 1/2 atm.		
Converter Gas Fill	Vacuum	Leak-tight		
Fuel	GPO	Right circular cylinder, 59.6 watts/capsule L/D = .862	Right circular cylinder, 58.2 watts/capsule, L/D=.862	Right circular cylinder, 57.8 watts/capsule, L/D = .862
Heat Shield	Graphite	Parallelepiped, 8 per RTG	Parallelepiped, 16 per RTG	Parallelepiped, 24 per RTG
Isolation Hot Frame	Pt-30 Rh	Rectangular can open at ends, 3.732 x 3.732 x 16 in	Rectangular can open at ends, 3.732 x 3.732 x 32	Rectangular can open at ends, 3.732 x 3.732 x 48
Thermoelectric P-leg	Copper-Silver Selenide, Partitioned	Length = 0.3 in. Diameter = 0.314 in. No. = 128	Length = 0.3 in. Diameter = 0.314 in. No. = 256	Length = 0.3 in. Diameter = 0.314 in. No. = 384
Thermoelectric N-leg	Current Standard Gadolinium Selenide	Length = 0.3 in. Diameter = 0.417 in. No. = 128	Length = 0.3 in. Diameter = 0.417 in. No. = 257	Length = 0.3 in. Diameter = 0.417 in. No. = 384
Fins	Aluminum	0.020 in., 24.3 x 19.0 in. 4 per RTG	0.020 in., 27.7 x 35.0 in., 4 per RTG	0.020 in., 29.3 x 51.0 in., 4 per RTG
Heat Pipes	Copper/Water	Internal axial grooves; 6 L-pipes per RTG fin pair; 0.265 in. O.D.	Internal axial grooves; 12 L-pipes per RTG fin pair; 0.277 in. O.D.	Internal axial grooves; 17 L-pipes per RTG fin pair; 0.282 in. O.D.
Housing Rib	Aluminum	Module Side - 2.0 in. high, 0.03 in. thick Non-module Side - 1.5 in. high, .02 in. thick	Module Side - 2.0 in. high, .03 in. thick Non-module Side - 1.5 in. high, 0.02 in. thick	Module Side - 2.0 in. high, 0.03 in. thick Non-module Side - 1.5 in. high 0.02 in. thick
Fin Rib	Aluminum	Tapered from root-to-tip; 0.025 in. thick	Tapered from root-to-tip; 0.030 in. thick	Tapered from root-to-tip; 0.030 in. thick

C. GLOBAL POSITIONING SATELLITE

Three power levels have been evaluated for the GPS mission; 100, 200 and 500 watts electrical. The 100 and 500 watt electrical units are based on a four-fin array, but the 200 watt electrical unit is a two-fin array designed to facilitate close packaging in the launch vehicle shroud with eventual deployment similar to that of solar panels.

The mission power and configuration requirements were based on input from Rockwell International, Downey, California.

The basic design constraints for the GPS study are identical to those listed in Section B, AFSATCOM Mission Study.

The results for the GPS sizing and performance study yielded system efficiencies from 10.1 to 10.8% at specific powers of 2.9 to 3.5 watts per pound.

Performance data sheets are presented in the following pages.

100 W(e): 4-FIN
PERFORMANCE SUMMARY
SELENIDE RTG

Output power (watts) at BOL	100
Load voltage, volts	5.6
Specific power (watts/pound), BOL	2.9
Steady state temperatures, BOL (°C)	
Sink	-79
Radiator	90
Cold junction	125
Hot junction	900
Isolation hot frame	930
Inboard capsule	1035
Efficiencies, BOL (%)	
Overall	10.1
Thermoelectric	12.6
Thermal	79.7
Fuel inventory (watts(t))	994

100 W(e): 4-FIN
 SIZE/WEIGHT SUMMARY
 SELENIDE RTG

<u>Component</u>	<u>Weight (pounds)</u>
Isolation hot frame	3.5
Thermoelectric elements	1.0
Straps + cold end hardware	2.5
Insulation	6.4
Heat pipes	1.5
Heat pipe saddles	0.5
Fin (web)	1.7
Housing/covers	3.2
Ribs	1.1
Emissive coating	0.8
Fuel (GPO)	5.4
Clad	1.4
Heat shields	5.6
	<hr/>
Total	34.6
RTG height (inches)	15.0
Fin tip-to-tip, diagonally (inches)	45.8
Housing cross-section (inches)	6.8 x 5.5

100 W(e): 4-FIN
CONFIGURATION/MATERIAL SUMMARY
SELENIDE RTG

<u>Item</u>	<u>Material</u>	<u>Configuration</u>
Fuel	GPO	Right circular cylinder, 62.1 watts/capsule, L/D=.862
Encapsulating Member	Pt-3008	Right circular cylinder, 0.020 in. thick, 4 per heat shield
Heat Shield	Graphite	Parallelepiped, 4 per RTG
Reentry Insulator	Pyrolytic Graphite	Sleeve plus end caps; surrounds each capsule
Compliant Pad	Graphite Felt	Disc
Isolation Hot Frame	Pt-30 Rh	Square can open at ends, 3.732 x 3.732 x 8 in.
Bellows	Pt-30 Rh	Circular, 0.010 in. thick
Hot Frame Flanges	TZM at fueling end; Pt-30 Rh at other end	Transition pieces from square can to circular bellows
Seal Ring	Al/St. Steel	Transition piece from bellows to housing; explosively bonded
Hot Side Dielectric	BeO or Al ₂ O ₃	Either sprayed on straps or separate sheet
Hot Straps	Molybdenum	Sculptured; 0.070 in. thick
Thermoelectric P-leg	Copper-Silver Selenide, Partitioned	Length = 0.3 in. Diameter = 0.314 in. No. = 64
Thermoelectric N-leg	Current Standard Gadolinium Selenide	Length = 0.3 in. Diameter = 0.417 in. No. = 64
Cold Straps	Copper	0.010 in. thick; 2 string parallel circuit
Cold End Hardware	Copper BeO Dielectric 17-7 PH Steel Spring	Flexible sleeve type 15 one-mil wraps; helical, round wire compression type spring

100 W(e): 4-Fin (cont.)

<u>Item</u>	<u>Material</u>	<u>Configuration</u>
Converter Insulation		
T/E Module	Fiberfrax 660H paper	12 lbs/ft ³
T/E Module Periphery	Min-K TE 1400	20 lbs/ft ³
End Plug Insulation	Min-K TE 1400 or Min-K 2000	2 in. thick
Blank Side Insulation	Min-K TE 1400 or Min-K 2000	1.5 in. thick
Housing	Aluminum	Rectangular section, 0.050 in. min.
Fins	Aluminum	0.020 in., 19.8 x 11.0 in., 4 per RTG
Heat Pipes	Copper/Water	Internal axial grooves; 4 L-pipes per RTG fin 0.246 in. O.D.
Housing Rib	Aluminum	Module Side- 1.9 in. high, .025 in. thick Non-module Side- 1.4 in. high, .020 in. thick
Fin Rib	Aluminum	Tapered from root-to-tip; .020 in. thick
Electrical Receptacle (power output)	TBD	Hermetically sealed to housing
Emissive Coating	ZnO + K ₂ SiO ₄ binder (IITRI Z-93)	0.005 in. thick
Controlled Leak Device	TBD	Located in one end cover
Heat Source Cavity Gas Fill	Helium	Few psi up to 1/2 atm.
Converter Gas Fill	Vacuum	Leak-tight

GPS
200 W(e); 2 Fin
PERFORMANCE SUMMARY
SELENIDE RTG

Output power (watts) at BOL	200
Load voltage, volts	11.2
Specific power (watts/pound), BOL	3.2
Steady state temperatures, BOL (°C)	
Sink	-79
Radiator	90
Cold junction	125
Hot junction	900
Isolation hot frame	930
Inboard capsule	1035
Efficiencies, BOL (%)	
Overall	10.5
Thermoelectric	12.6
Thermal	83.1
Fuel inventory (watts(t))	1908

GPS
200 W(c): 2 Fin
SIZE/WEIGHT SUMMARY
SELENIDE RTG

<u>Component</u>	<u>Weight (pounds)</u>
Isolation hot frame	4.2
Thermoelectric elements	2.0
Straps + cold end hardware	5.0
Insulation	8.1
Heat pipes	5.4
Heat pipe saddles	1.4
Fin (web)	2.5
Housing/covers	4.4
Ribs	3.1
Emissive coating	1.2
Fuel (GPO)	10.6
Clad	2.7
Heat shields	11.2
	<hr/>
Total	61.8
RTG height (inches)	22.0
Fin tip-to-tip, diagonally (inches)	74.3
Housing cross-section (inches)	6.8 x 5.5

GPS
200 W(e); 2 Fin
CONFIGURATION/MATERIAL SUMMARY
SELENIDE RTG

<u>Item</u>	<u>Material</u>	<u>Configuration</u>
Fuel	GPO	Right circular cylinder, 59.6 watts/pellet, L/D = .862
Encapsulating Member	Pt-3008	Right circular cylinder, 0.020 in. thick, 4 per heat shield
Heat Shield	Graphite, 3D Type	Parallelepiped, 8 per RTG
Reentry Insulator	Pyrolytic Graphite	Sleeve plus end caps; surrounds each capsule
Compliant Pad	Graphite Felt	Disc
Isolation Hot Frame	Pt-30 Rh	Square can open at ends, 3.732 x 3.732 x 16 in.
Bellows	Pt-30 Rh	Circular, 0.010 in. thick
Hot Frame Flanges	TZM at fueling end; Pt-30 Rh at other end	Transition pieces from square can to circular bellows
Seal Ring	Al/St. Steel	Transition piece from bellows to housing; explosively bonded
Hot Side Dielectric	BeO or Al ₂ O ₃	Either sprayed on straps or separate sheet
Hot Straps	Molybdenum	Sculptured; 0.070 in. thick
Thermoelectric P-leg	Copper-Silver Selenide, Partitioned	Length = 0.3 in. Diameter = 0.314 in. No. = 128
Thermoelectric N-leg	Current Standard Gadolinium Selenide	Length = 0.3 in. Diameter = 0.417 in. No. = 128
Cold Straps	Copper	0.010 in. thick; 2 string parallel circuit
Cold End Hardware	Copper BeO Dielectric 17-7 PH Steel Spring	Flexible sleeve type 15 one-mil wraps; helical, round wire compression type spring

200 W(e): 2 Fin (cont.)

<u>Item</u>	<u>Material</u>	<u>Configuration</u>
Converter Insulation		
T/E Module	Fiberfrax 660H paper	12 lbs/ft ³
T/E Module Periphery	Min-K TE 1400	20 lbs/ft ³
End Plug Insulation	Min-K TE 1400 or Min-K 2000	2 in. thick
Blank Side Insulation	Min-K TE 1400 or Min-K 2000	1.5 in. thick
Housing	Aluminum	Rectangular section, 0.050 in. min.
Fins	Aluminum	0.020 in., 33.6 x 19.0 in., 2 per RTG
Heat Pipes	Copper/Water	Internal axial grooves; 9 L-pipes per RTG fin 0.315 in. O.D.
Housing Rib	Aluminum	Module Side- 1.8 in. high, .022 in. thick Non-module Side- 1.3 in. high, .020 in. thick
Fin Rib	Aluminum	Tapered from root-to-tip; .030 in. thick
Electrical Receptacle (power output)	TBD	Hermetically sealed to housing
Emissive Coating	ZnO + K ₂ SiO ₄ binder (IITRI Z-93)	0.005 in. thick
Controlled Leak Device	TBD	Located in one end cover
Heat Source Cavity Gas Fill	Helium	Few psi up to 1/2 atm.
Converter Gas Fill	Vacuum	Leak-tight

500 W(e): 4 Fin
PERFORMANCE SUMMARY
SELENIDE RTG

Output power (watts) at BOL	500
Load voltage, volts	28.0
Specific power (watts/pound), BOL	3.5
Steady state temperatures, BOL (°C)	
Sink	-79
Radiator	90
Cold junction	125
Hot junction	900
Isolation hot frame	930
Inboard capsule	1035
Efficiencies, BOL (%)	
Overall	10.8
Thermoelectric	12.6
Thermal	85.4
Fuel inventory (watts(t))	4647

500 W(e) : 4 Fin
SIZE/WEIGHT SUMMARY
SELENIDE RTG

<u>Component</u>	<u>Weight (pounds)</u>
Isolation hot frame	7.4
Thermoelectric elements	5.1
Straps + cold end hardware	11.5
Insulation	14.6
Heat pipes	10.3
Heat pipe saddles	3.5
Fin (web)	9.8
Housing/covers	8.1
Ribs	7.7
Emissive coating	4.1
Fuel (GPO)	28.0
Clad	6.6
Heat shields	25.7
	<hr/>
Total	142.4
RTG height (inches)	47.0
Fin tip-to-tip, diagonally (inches)	65.1
Housing cross-section (inches)	6.8 x 5.5

500 W(e): 4 Fin
CONFIGURATION/MATERIAL SUMMARY
SELENIDE RTG

<u>Item</u>	<u>Material</u>	<u>Configuration</u>
Fuel	GPO	Right circular cylinder, 58.1 watts/capsule, L/D=.862
Encapsulating Member	Pt-3008	Right circular cylinder, 0.020 in. thick, 4 per heat shield
Heat Shield	Graphite	Parallelepiped, 20 per RTG
Reentry Insulator	Pyrolytic Graphite	Sleeve plus end caps; surrounds each capsule
Compliant Pad	Graphite Felt	Disc
Isolation Hot Frame	Pt-30 Rh	Square can open at ends, 3.732 x 3.732 x 40 in.
Bellows	Pt-30 Rh	Circular, 0.010 in. thick
Hot Frame Flanges	TZM at fueling end; Pt-30 Rh at other end	Transition pieces from square can to circular bellows
Seal Ring	Al/St. Steel	Transition piece from bellows to housing; explosively bonded
Hot Side Dielectric	BeO	Either sprayed on straps or separate sheet
Hot Straps	Molybdenum	Sculptured; 0.070 in. thick
Thermoelectric P-leg	Copper-Silver Selenide, Partitioned	Length = 0.3 in. Diameter = 0.314 in. No. = 320
Thermoelectric N-leg	Current Standard Gadolinium Selenide	Length = 0.3 in. Diameter = 0.417 in. No. = 320
Cold Straps	Copper	0.010 in. thick; 2 string parallel circuit
Cold End Hardware	Copper BeO Dielectric 17-7 PH Steel Spring	Flexible sleeve type 15 one-mil wraps; helical, round wire compression type spring

500 W(e): 4 Fin (cont.)

<u>Item</u>	<u>Material</u>	<u>Configuration</u>
Converter Insulation		
T/E Module	Fiberfrax 660H paper	12 lbs/ft ³
T/E Module Periphery	Min-K TE 1400	20 lbs/ft ³
End Plug Insulation	Min-K TE 1400 or Min-K 2000	2 in. thick
Blank Side Insulation	Min-K TE 1400 or Min-K 2000	1.5 in. thick
Housing	Aluminum	Rectangular section, 0.050 in. min.
Fins	Aluminum	0.020 in., 29.0 x 43.0 in., 4 per RTG
Heat Pipes	Copper/Water	Internal axial grooves; 20L-pipes per RTG fin 0.281 in. O.D.
Housing Rib	Aluminum	Module Side- 2.0 in. high, .030 in. thick Non-module Side- 1.5 in. high, .020 in. thick
Fin Rib	Aluminum	Tapered from root-to-tip; .000 in. thick
Electrical Receptacle (power output)	TBD	Hermetically sealed to housing
Emissive Coating	ZnO + K ₂ SiO ₄ binder (HTRI Z-93)	0.005 in. thick
Controlled Leak Device	TBD	Located in one end cover
Heat Source Cavity Gas Fill	Helium	Few psi up to 1/2 atm.
Converter Gas Fill	Vacuum	Leak-tight

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