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AEC RESEARCH AND
DEVELOPMENT REPORT

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GA-8928, Pt. II

UC-33, Propulsion

Systems and Energy

Conversion

RADIOISOTOPE SPACE POWER GENERATOR

ANNUAL SUMMARY REPORT

FOR THE PERIOD JULY 1, 1967 THROUGH JUNE 30, 1968

By

J. E. Cruver, R. G. Shevlin, R. L. Leedy, E. J. Steeger, F. L. Unmack

Prepared under
Contract AT (29-2)-2564
for
Albuquerque Operations Office
U. S. Atomic Energy Commission

December 1969

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SUMMARY

A 25 to 32-watt (BOL) generator design (nominally called the 30-watt generator) has been developed using ISOTEC technology: 400°C PbTe elements in a lightweight panel configuration. The modular construction of the ISOTEC generator has such flexibility that major components (thermoelectric panels and structural members) can be used directly to assemble generators with rated outputs ranging from 20 to 100 watts. The application toward which the 30-watt generator design was directed was the NAVSAT (20-watt EOL) navigational satellite, where high reliability for five year life and output greater than 2-watts per lb were important. Development of test generators to verify design calculations began in July, 1967, and the first test generator (GC01) had been completed and performance tested by the following June. GC01 exceeded the predicted values of both output power and thermal efficiency by about 10%. Additional test generators are being built and tested in a continuing development program.

TABLE 1

DESIGN GOALS

-
1. 20-watt electrical output, EOL
 2. Reliability of generator producing > 20 watts to be > 0.995
 3. Lifetime goal of generator ~ 5 years
 4. Performance goal of generator is > 2 watts/lb (complete)
 5. ISOTEC PbTe element technology ($T_{\text{hot junction}} 400^{\circ}\text{C}$)
 6. Fuel capsule design flexibility for variations in sizes and shapes
 7. Capsule support structure releases fuel capsule on reentry at 1000°C
 8. Fuel capsule loaded and unloaded into generator on launch pad
 9. Thermal input (~ 60 thermal watts) to the spacecraft
 10. Generator structure can support an antenna (~ 5 lb)
 11. Generator structure capable of Scout missile launch environment
 12. Orbit ~ 600 n mi, gravity gradient stabilized
 13. The electrical circuit should have magnetic symmetry
-

1. GENERATOR DEVELOPMENT

In this reporting period detailed design and fabrication of the first ISOTEC NAVSAT development generator GC01 was completed. Other major developments include:

- Static structural analysis and preliminary dynamic tests on thermoelectric panel and a structural mock-up.
- Two thermal insulation tests; one to obtain data on insulation joint designs, and one to obtain data on two types of thermal insulation surrounding the elements.
- Two test panels fabricated and put on accelerated life test at 450°C.

Figure 1 shows the development schedule.

1.1 DESIGN AND ANALYSIS

The material properties that determine the theoretical performance of thermoelectric couples are (ρ), the electrical resistivity; (k), the thermal conductivity, and (α) the Seebeck coefficient. The material properties of "N" and "P" lead telluride as published by 3M are shown in Figs. 2, 3, and 4, while the material properties for the processed and bonded material as used in the ISOTEC couples are shown in Figs. 5, 6, and 7.

The electrical resistivity and the Seebeck coefficient for the "as bonded" material was determined experimentally; while the thermal k of the "P" material, which is shown as 1.33 times the 3M value, was inferred from calorimetric tests of ISOTEC panels. The decrease of "P" material resistivity and the increase of the thermal conductivity are due to the use of gold foil in the bonding process.

The selection of the thermoelectric element length of 0.165", the "N" element diameter of 0.128", and "P" element diameter of 0.104" has been

	July 1967	Jan 1968	July 1968
1. Design Review	1		
2. Panel (PC01) - Fabrication Development	2		
3. Insulation test - joint comparison	3		
4. Preliminary thermal analysis		4	
5. Mechanical Mock-up (MU-1) Mech. Assembly Test		5	
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Fig. 1 ISOTEC/NAVSAT summary development schedule

Fig. 2 3M data for the Seebeck Coefficient of lead telluride

Fig. 3 PbTe thermal conductivity 3M data

Fig. 4 3 M data for lead telluride

Fig.5 Experimentally determined Seebeck Coefficient

Fig. 6 Lead telluride thermal conductivity

Fig. 7 Experimental values of lead telluride resistivity

previously reported.¹ The radiator and collector areas ($13.725 \text{ cm}^2/\text{couple}$) and the number of couples (360) for a nominal 30 watt generator were also reported earlier.¹

1.2 GENERAL THERMOELECTRIC DESIGN METHOD

In order to determine the operational points of a generator which is made of an array of ISOTEC couples, those factors introduced by the design and by the local environment must be taken into consideration. The following is a list of the major factors which perturb the ideal thermoelectric performance:

I. Thermal Bypass Losses

- a) Loss through insulation of active areas
- b) Losses at insulation joints
- c) Losses at annular space around elements
- d) Losses through heat source supports that penetrate the insulation
- e) Effect on insulation conductance of elements acting as penetrations
- f) Loss through inactive areas

II. Generator Circuit Resistance

- a) Circuit resistance of element to element connectors
 1. Element bond
 2. End caps
 3. Grommets
 4. Radiators
 5. Collectors
- b) Circuit resistance of panel to panel connectors

III. Surface Properties of Radiator

- a) ϵ and α for earth and solar flux
- b) Fraction of generator exposed to earth and solar flux

The variation of physical properties with time, the changes of thermal power with time and the consideration of couples failing during the generator life time are not considered for this analysis so that only beginning of life performance will be estimated.

The basic equation for thermoelectric performance must be written to consider the variables affecting performance and a heat balance must be made to determine the generator operating point.

The performance equation can be stated as:

$$\text{Heat arriving at the radiator} - \text{power generated} = \text{heat radiated to space} \quad (1)$$

$$\begin{aligned} &\text{Peltier heat} + \text{Fourier heat} - \text{one-half joule heat} + \text{thermal bypass losses} - \text{power generated} + \text{solar flux adsorbed by radiator} + \text{earth flux adsorbed by radiator} = \text{heat radiated to space} \quad (2) \end{aligned}$$

$$\begin{aligned} &\frac{\frac{2}{\alpha} T_1 (T_1 - T_o)}{r (m+1)} + K(T_1 - T_o) - \frac{\frac{1}{2} \frac{2}{\alpha} (T_1 - T_o)^2}{r(m+1)^2} + \text{Bypass Loss/couple} \\ &- \frac{\frac{2}{\alpha} (T_1 - T_o)^2_m}{r(m+1)} + A\phi_s \alpha + A\phi_e \epsilon = \sigma A\epsilon_r T_o^4 \quad (3) \end{aligned}$$

To avoid complications in the solution of (3) for the radiator temperature (T_o) some of the variables can be lumped. The electrical losses which affect the Peltier heat and P_o can be considered as an addition to the couple resistance (r) and the bypass losses can be included by increasing the couple conductance (K). Rewriting (3) and rearranging so that the left hand side of the equation is the heat arriving at the radiator from the collector yields

$$\frac{\frac{2}{\alpha} T_1 (T_1 - T_o)}{r (m+1)} + K (T_1 - T_o) - \frac{\frac{2}{\alpha} (T_1 - T_o)^2}{2r (m+1)^2} (1 + 2m) = A\epsilon_r \sigma T_o^4 - (A\phi_e \epsilon + A\phi_s \alpha) \quad (4)$$

The radiator equilibrium temperature for a selected hot junction temperature is then found at the intersection of plots of both sides of equation (4).

1.3 GCOL DESIGN

For the ISOTEC GCOL design the following assumptions were made:

1. Thermal bypass losses are 10% of the total heat input plus 73.7 watts for the aluminum whiskers around the elements.

2. Circuit resistance is 20% of the couple resistance.

3. The radiator is considered to have $\epsilon = 0.8$ and $\alpha_s = 0.1$.

4. One-fourth of the earth flux and solar flux is impinging on the entire radiator surface.

5. For space chamber operation, the radiator is considered to have $\epsilon = 0.85$ with no back radiation.

Using the material properties as previously noted and using the ELEGEN computer code to obtain $\bar{\alpha}$, $\bar{\rho}$, $\bar{k}$, the radiator temperature of 164°C was calculated as is shown in Fig. 8.

The intersection of the two curves determines a radiator temperature which is equal to the cold junction temperature (100% fin efficiency). Since there is a finite temperature difference between the cold junction and the effective radiator temperature, the cold junction and radiator temperatures are shown for a ΔT of 30°C at the element cold cap. This ΔT has been determined experimentally for 0.005 mil iron and nickel caps with nickel grommets.

The generator power output at the cold junction temperature determined by Fig. 8 is

$$P_o = \frac{\bar{\alpha}^2 (T_1 - T_o)^2 m \times \text{No. of couples}}{r(m+1)} \quad (5)$$

The generator efficiency is the ratio of the power generated to the total heat input

$$\eta_o = \frac{P_o}{Q_t} \quad (\text{Fig. 9})$$

$$\text{where } Q_t = \left[\frac{\bar{\alpha}^2 T_1 (T_1 - T_o)}{r(m+1)} + K(T_1 - T_o) - \frac{\bar{\alpha}^2 (T_1 - T_o)^2}{2R(m+1)^2} \right] \times \text{No. of couples} \quad (6)$$

Design trade-off studies were reported in Reference 1. A detailed design was completed and Fig. 10 shows the final assembly drawing for GC01.

$T_H = 400^\circ\text{C}$
 ρ and α , experimental values
 $k_n = 3M$, $k_p = 1.33 \times 3M$
 20% circuit resistance
 thermal bypass = 10% - 73.7 watts

Fig. 8 Generator heat balance

Fig. 9 Generator efficiency
(predicted and actual performance of GC01)

The weight breakdown for the generator as fabricated was:

1. Side panels	3.05 lb.
2. Top and bottom covers	1.76
3. Posts, shear ring, hardware	0.68
4. Heat source support (stainless steel)	0.50
	<u>5.99</u> lb.

1.4 ANALYSIS OF GCO1 PERFORMANCE DATA

Figures 11 through 13 compare the predicted with the actual performance of GCO1. The generator produced 26.8 watts at $T_h = 400^\circ\text{C}$ and $T_c = 164^\circ\text{C}$. Complete tests results and procedures are presented in Section 3.

Examination of the figures reveal that GCO1 produced more power than predicted and also had a greater thermal efficiency than predicted. Since generator power is a function of $\bar{\alpha} \Delta T^2 / r$ and the load voltage is a function of $\alpha \Delta T$ and r , the difference can be assigned to one or all the variables $\bar{\alpha}$, ΔT and r . The generator resistance (r) as measured under load is within 1% of the predicted value as shown in Fig. 13, so that the difference must lie in the $\bar{\alpha}$, ΔT product. If the average cold junction temperature is actually lower than determined by test, then the total bypass losses would be close to 10% of the total heat input. This is very unlikely, since thermal tests of the insulation and alumina whiskers show a loss of about 20%.

Assuming a Seebeck coefficient equal to the value supplied by 3M, the predicted performance of generator GCO1 is shown in Fig. 14 through 18. The actual voltage and current fall almost on the predicted points.

The efficiency, which is a strong function of the lead telluride thermal conductivity and the bypass losses, was higher than predicted. This indicates that either the thermal conductivity of the "P" material is less than 1.33 times the 3M conductivity or that the bypass loss is much less than estimated. The tests of generator GCO2 where the alumina whiskers are replaced by tantalum opacified paper washers will help to determine bypass losses more accurately.

Fig. 11 Thermal input to generator
(predicted and actual for GC01)

Fig. 12 Voltage and current for 360 couples of four series string (predicted and actual for GC01)

Fig 13 Generator resistance as a function of T_c

Fig. 14 GC01 generator efficiency

Fig. 15 GC01 heat balance - space chamber

Fig. 16 GC01 generator output

Fig. 17 GC01 generator current and voltage

Fig. 18 GC01 thermal input as a function of T_c

1.5 GENERATOR GCO2 AND NAVSAT GENERATOR CALCULATIONS

Based upon the performance test results of GCO1, calculations were made for test generator GCO2 and the NAVSAT generator. Generator GCO2 incorporates the following insulation improvements over GCO1:

1. Insulation blanket increased by 50%.
2. Alumina whisker insulation replaced by tantalum opacified washers.

The calculated performance for GCO2 is listed in Table II.

The NAVSAT generator incorporates the GCO2 design plus replacing the spot weld end caps on the cold side with laser welded caps. This improvement allows a reduction in the number of couples from 360 to 304 (8.25 panels) to meet the 20-watt EOL design power. Table III indicates the ISOTEC NAVSAT generator calculations.

1.6 THERMAL ANALYSIS

Thermal analyses on two thermoelectric generator design configurations were performed. A spherical and a cylindrical heat source were investigated for the first configuration, 6" x 10" panels. In the GCO1 configuration only a spherical heat source was considered. Results of the study are presented in Reference 2.

One-eighth of the generator was divided into discrete nodes for the thermal model. The computer codes CONFAC I and SCRIPT F were used to determine the view factors and the overall radiation interchange. Steady-state temperature distributions in the analytical model were calculated on the digital computer using a thermal analyzer program.

Results indicated that for the same heat dissipation the heat source geometry has little effect on collector temperature. The calculated maximum collector temperature variation on the GCO1 configuration was only 17°C, while for the other configuration the collector temperature variation was 29°C. Experimental temperature measurements on GCO1 indicated a maximum collector difference of only 11°C. The detailed experimental results are presented in Section 3.

1.7 STATIC STRUCTURAL ANALYSIS

A static stress analysis was performed on the generator and heat source

TABLE II

PERFORMANCE OF GC01 AND GC02

	GC01 Test Results	GC02 Calculated
Hot junction temperature ($^{\circ}\text{C}$)	398 $^{\circ}$	400 $^{\circ}$
Cold junction temperature ($^{\circ}\text{C}$)	164 $^{\circ}$	155 $^{\circ}$
Power to load (watts)	26.83	28.8
Efficiency (%)	3.73	4.45
Load voltage (volts)	4.30	4.66
Load current (amps)	6.24	6.18
Thermal input (watts)	719.	646.

TABLE III

ISOTEC NAVSAT GENERATOR (BASED ON GC01 OPERATION)

	Beginning of Life	End of Life
Temperature (Hot junction) ($^{\circ}\text{C}$)	400.0	386.0
Power output (watts)	27.0	22.4
Thermal power of capsule Pu-238 (watts)	561.0	538.0
Efficiency (%)	4.8	-----
Thermal input to satellite (watts)	50.0	47.0
Voltage (load at max. eff.) (volts)	4.0	3.9
Current (load at max. eff.) (amps)	6.8	5.7
Power allocation		
Output to NAVSAT (watts)	20.0	20.0
Pu-238 decay (8%)	2.0	-----
TE degradation (10%)	2.7	-----
Redundancy (5%)*	1.0	1.0
Contingency (5%)	<u>1.3</u>	<u>1.4</u>
Total Power	27.0	22.4
Generator weight (lbs.)	5.7	-----
Fuel capsule weight (lbs.)	<u>6.9</u>	<u>-----</u>
Total weight (lbs.)	12.6	-----
Specific weight (w/lb)	2.14	-----

* Required for 0.96 reliability (0.9 confidence level) with 4 x 90 couple matrix.

support structure. Table IV summarizes the results. Acceleration loads of 30 g's and 36 g's are for the Scout and NAVSAT specifications. Also, there is a load due to a pressure differential across the converter during launch. The maximum ΔP was calculated to be 0.08 psi. Complete results are presented in Reference 3.

Table IV shows that an adequate margin of safety exists for all components except for the original flat design of the end panel beams. The end panel beams were strengthened by increasing the thickness of the center and by tapering to give a sufficient safety margin for Scout launch conditions.

1.8 OFF-DESIGN PERFORMANCE STUDIES

Several off-design parametric studies were conducted to determine generator performance effects. The most important off-design conditions were:

1. Generator view factor to insolation, albedo, and earth radiation
2. Changes in radiator surface properties
3. Variations in load impedance
4. Change in performance due to isotope decay
5. Failure of couples

1.8.1 Generator View Factor to Insolation, Albedo and Earth Reflection

The hot and cold junction temperatures of the generator when variations of earth and solar radiation occur can be determined by using the computer program CONFAC I and SCRIPT F.

For the worst case, assuming the non-equilibrium condition of no internal re-radiation, the cold junction and hot junction temperatures will be 148°C and 394°C with no solar or earth flux impinging on the radiator, and 172°C and 418°C with full solar and earth flux. These temperatures are for $\alpha = 0.1$ for the solar flux, $\alpha = \epsilon = 0.8$ for the earth radiation flux and $\epsilon = 0.8$. Since the difference in the re-radiation flux between 418°C and 394°C is greater than the flux through a panel, the internal re-radiation becomes very significant in smoothing collector temperatures.

1.8.2 Changes in Radiator Surface Properties

The generator cold junction temperature is not strongly influenced

TABLE IV
SUMMARY TABULATION OF STATIC STRESSES GENERATED IN THE
NAVSAT THERMOELECTRIC GENERATOR STRUCTURAL COMPONENTS

GENERATOR STRUCTURAL COMPONENT	CALCULATED LOADS			0.08 psi int.	ALLOWABLE STRESS OR BUCKLING LOAD	FACTORS OF SAFETY			
	30 g's AXIAL	36 g's AXIAL	5 g's LATERAL			CASE 1: 30 g's AX + 5 g's LAT	CASE 2: 36 g's AX + 5 g's LAT	CASE 3: 0.08 PSI + CASE 1	CASE 4: 0.08 PSI + CASE 2
END PANEL BEAMS (ORIGINAL DESIGN)									
Tensile Stress (psi)	9,600	11,500	---	5,900	25,000	2.6	2.18	1.61	1.44
Compression Stress (psi)	-17,500	-21,000	---	-10,700	-22,000	1.25	1.05	0.79	0.69
END PANEL BEAMS (REVISED DESIGN)									
Cross Beams-Comp.Stress(psi)	- 3,550	- 4,250	---	- 2,200	-22,000	6.2	5.2	3.8	3.4
Y Beams-Comp.Stress (psi)	- 8,000	- 9,500	---	- 4,900	-22,000	2.7	2.3	1.7	1.53
Center Beam-Comp.Stress (psi)	- 7,400	- 8,800	---	- 4,500	-22,000	3.0	2.5	1.85	1.65
END PANEL HONEYCOMB									
Tensile Stress (psi)	7,900	9,500	---	1,900	20,000	2.5	2.1	2.0	1.75
Compressive Stress (psi)	- 7,900	- 9,500	---	- 1,900	-17,700	2.2	1.86	1.81	1.55
END PANEL HONEYCOMB BOND									
Shear Stress (psi)	156	188	---	38	300	1.92	1.6	1.55	1.33
CORNER POSTS									
Tensile Stress (psi)	---	---	548	---	16,600	30.	30.	30.	30.
Compressive Stress (psi)	-2,460	-2,950	-548	---	-14,600	4.8	4.2	4.8	4.2
Axial Buckling Load (lbs)	71	85	12	---	185	2.6	2.0	2.6	2.0
SIDE PANEL HONEYCOMB									
Tensile Stress (psi)	---	---	---	1,900	20,000	---	---	10.5	10.5
Compressive Stress (psi)	---	---	---	- 1,900	-17,700	---	---	9.3	9.3
Shear Stress (psi)	51	61	350	---	3,800	9.5	9.2	9.5	9.2
SIDE PANEL HONEYCOMB BOND									
Shear Stress (psi)	5	6	162	38	300	1.8	1.79	1.47	1.46
HEAT SOURCE SUPPORT POSTS, T ₁ (304)*									
Tensile Stress (psi)	---	---	2,830	---	42,500 (10,000)	15 (3.5)	15 (3.5)	15	15
Compressive Stress (psi)	- 6,100	- 7,300	-2,830	---	-42,500(-10,000)	4.8 (1.12)	4.2 (0.99)	4.8	4.2
Axial Buckling Load	46	55	21	---	95 (190)	1.42 (2.8)	1.25 (2.5)	1.42	1.25
HEAT SOURCE SUPPORT RING*									
Tensile Stress (psi)	---	---	1010 (1350)	---	38,600 (9,300)	38 (6.9)	38 (6.9)	38	38
Compressive Stress (psi)	---	---	-295 (-590)	---	-38,600 (-9,300)	131 (16)	131 (16)	131	131
HEAT SOURCE SUPPORT STRAPS									
Tensile Stress (psi)	25,000	30,000	---	---	38,600	1.55	1.29	1.55	1.29

*Allowable stresses and safety factors based on 304 stainless steel are indicated in parenthesis, others assume titanium.

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by variations of emittance and absorptance of the radiator surface. For the GCOL design condition where it is assumed that one-fourth of the solar and earth radiation flux is impinging on the entire radiator surface, the equilibrium radiator temperature is expressed by,

$$T_{\text{RAD}} = \frac{\frac{\varphi}{A} + \frac{\varphi_s \alpha}{4} + \frac{\varphi_e \epsilon}{4}}{\epsilon \sigma} \quad (7)$$

Figure 19 illustrates how both α and ϵ must change to maintain a cold junction temperature of 154°C .

Figure 20 illustrates how the cold junction temperature varies with α varying and ϵ constant at 0.8, and ϵ varying and α constant at 0.1. The emissivity has the largest effect upon the cold junction temperature.

1.8.3 Variations of Load Impedance

At the generator maximum efficiency operating point of $m = 1.2$ (ratio of load resistance to generator internal resistance) the amount of heat pumped from the hot junction to the cold junction is about 25% of the total heat through the couples. Since the Peltier cooling of the hot junction is a function of the current through the couple, variation in the load resistance will affect the hot junction temperature. Figure 21 illustrates the theoretical hot junction temperatures for variations of the matching factor (m).

1.8.4 Change in Generator Performance Due to Isotope Decay

The decrease in thermal power of the generator heat source with time will reduce both the generator output and efficiency.

Assuming a beginning of life thermal power of 661 watts, the Pu-238 decay will result in thermal power change with time as shown in Fig. 22.

Since the thermal flux from the radiator is a function of T_R^4 , while the ΔT from the hot to cold junctions is a function of thermal flux, the change in the hot junction temperature is more marked than the change in the cold junction temperature as shown in Fig. 23. The changes in generator output power and efficiency resulting from the temperature changes are shown in Fig. 24 and 25.

Fig. 19 Trade-off of ϵ and α for 154°C cold junction temperature

Fig. 20 Cold junction temperatures with variable radiator surface properties

Fig. 21 Average hot junction temperature vs match fact for constant heat input

Fig 22. Variation of capsule thermal power with time approximate

Fig. 23 Hot and cold junction temperature history Pu_{238} decay

Fig. 24 Change in generator output power due to isotope decay

Fig. 25 Generator efficiency variation with isotope decay

1.8.5 Failure of Couples

The effect of open couples on the hot junctions of series and of parallel couples and the effect on the performance of the NAVSAT generator design was investigated.

The assumptions used in the calculation of couple failure are as follows:

1. A couple fails when one element failed; the electrical circuit of that couple is lost.
2. With one element failed, the remaining element of the couple can conduct heat to the radiator side.
3. The failures are random.

When one couple opens the thermal throughput is reduced by the loss of thermal conductance of that element plus the Peltier heat that was pumped to the cold side by the current through the couple.

$$Q_{\text{Fourier}} = K (\Delta \tau) \quad (8)$$

$$Q_{\text{Peltier}} = \alpha T_1 I \quad (9)$$

With one couple open in a row of four, the generator current must be divided between three couples instead of four so that both a voltage drop and current decrease occur because of the increased resistance of the current path.

When the generator current is reduced due to an increase in generator resistance, the amount of Peltier heat for all active couples is slightly reduced.

The generator resistance with open couples was calculated as follows:

1. Resistance for one row of four cross-connected couples

$$(R_4) = R_{\text{couple}}/4$$

2. The resistance of a row of couples with one failure

$$(R_3) = R_{\text{couple}}/3$$

The generator resistance with failed couples is:

$$R_{\text{gen}} = R_3 \times \text{no. couples failed} + R_4 \times (\text{no. of parallel with no open couple})$$

The total circuit resistance with a matching factor of $M = 1.2$ is then

$$R_{\text{circuit}} = R_{\text{gen}} + 1.2 R_{\text{o gen}} \quad (R_{\text{o gen}} \text{ is the greater resistance at start of life})$$

Since the open circuit voltage with random failures can be assumed to be constant and equal of $\bar{\alpha} \Delta \tau$. The generator current is expressed by

$$I = \frac{\bar{\alpha} \Delta \tau}{R_{\text{circuit}}} = \frac{\alpha \Delta \tau}{R_{\text{gen}} + 1.2 R_{\text{o gen}}} \quad (10)$$

The voltage drops across the generator and the loads are then:

$$R_{\text{gen}} = I R_{\text{gen}} \quad (11)$$

$$E_{\text{load}} = I 1.2 R_{\text{o gen}} \quad (12)$$

The power available at the load is:

$$P_{\text{load}} = I^2 1.2 R_{\text{o gen}} \quad (13)$$

Element failures and the reduced generator current both contribute to reducing the thermal conductance of the generator panels while the local increase in current through three couples in a row of four pumps additional heat from the hot to the cold side. Figure 26 illustrates the change in Q when failures occur if the ΔT across the panels is assumed to remain constant.

Figure 27 shows how the net average hot junction temperature would decrease with time due to the compensating temperature rise due to open failures and temperature decrease due to decay of the isotopic heat support.

Figure 28 shows the strong effect of the increased Peltier cooling in the parallel elements and the resulting temperature decrease with element failures.

Figures 29 and 30 show the effects on power, current, voltage, and matching factor (m) with couple failure.

(ΔT ACROSS PANELS ASSUMED CONSTANT)

Fig. 26 No. of element failures

Fig. 27 Hot junction temperature change with time

Fig. 28 Hot junction temperature change due to couple failure

Fig. 29 Power to load with open couples ($m=1.2$)

m = 1.2 AT BEGINNING OF LIFE

Fig. 30 Matching factor change due to open couples

Conclusions

1. The hot junction (in series with failure) within the generator rise 0.3°C with an element failure as an open.
2. The hot junctions (in parallel with failure) within the generator decrease 6.0°C with an element failure as an open.
3. The hot junctions within the generator decrease 1.8°C per year from decay of the Pu-238 heat source.
4. A failure rate of six elements/year would not increase the hot junctions within the generator above 400°C .
5. The observed failure rate from test is $\lesssim$ one element/year with the Type-C bond and no open failures have been observed with the Type-C M&M bond, hence, failures will not increase the hot junctions above 400°C .
6. The parallel elements to the failed one become significantly lower in temperature (6°C with one and 17°C with two failures) and, hence, more reliable.

2. FABRICATION DEVELOPMENT

Generator (GC01) with an electrical heat source and six test panels were fabricated during this report period. The manufacturing and assembly sequences are shown on Fig. 31 and 32. Fabrication quality control methods were initiated and largely developed during fabrication of GC01. They are discussed along with the fabrication techniques in this section.

2.1 COLLECTOR AND RADIATORS

The hot side collectors and the cold side radiators are formed from 0.002 inch thick silver foil. Then the parts are chemically cleaned and additional silver is diffusion bonded in a hydrogen furnace to thicken the area that is spot welded. Figure 33 shows a radiator assembly and Fig. 34 the collectors with elements.

Both the collector and radiators are coated to obtain high emissivity. The emissive coating, Pyromark, is applied with a spray gun and air dried. The coating contains volatiles which must be removed before use in the generator. The volatiles are removed from the radiator coating during the honeycomb vacuum outgassing. Collectors are baked out in vacuum at 525°C. The vacuum outgassing operation removes most of the Pyromark binder leaving a rather soft coating which at first was abraded during subsequent fabrication steps. Pyromark abrasion was reduced by coating assembly tooling with teflon.

2.2 WELDING

The thermoelectric generators are currently assembled using resistance welding on both the hot and cold sides. In addition to investigating new

FIG. 31--THERMOELECTRIC PANEL FABRICATION FLOW SHEET

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FIG. 32--THERMOELECTRIC GENERATOR FABRICATION FLOW SHEET

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Fig. 33 Thermoelectric panel radiator assembly

Fig. 34 Elements and collectors for a thermoelectric panel

welding processes, such as laser welding, a continuing program has been conducted to improve the quality of the resistance welding. Much improvement in welding consistency can be attributed to attention to weld machine qualifications.

A special welding head support was constructed for welding generator panels. This support allowed the panel to be conveniently positioned under the weld head and eliminated the bending forces applied to the cold side caps.

The resistance welding procedures and the materials of the hot side weld joint were improved over those used for panels previous to GC01 fabrication.

A 0.005-inch thick silver washer was diffusion bonded to the collector to strengthen the weld area. This washer had several beneficial results. Formerly, when the resistance spot welds were made between the 0.002-inch silver and the 0.005-inch end cap the silver often thinned around the edges of the weld. This left a weld with poor electrical, thermal and mechanical connections between the collector and element end cap. The additional silver provided by the bonded washer corrected this condition.

The weld between silver and nickel or iron requires an interface material to form a good joint. A 0.005-inch diameter gold wire was formerly used which could not be precisely located under the electrodes. This caused the resistance to vary resulting in different amounts of resistive heating during welding. This caused the 0.002-inch silver to melt, forming small holes.

The 0.002-inch gold washer interface material shown in Fig. 35 eliminated the variable joint resistance and has resulted in consistent welds. These welds have improved the electrical and thermal conductivities of the collector to hot side end cap joints. Figure 36 shows typical spot welds obtained in GC01 fabrication.

The strength of the collector welds for the generator has been increased by the materials and process changes. The n-element weld strength formerly averaged 3.7 lbs/weld and is now 15 lbs/weld. The p-element weld strength formerly averaged 2.8 lbs/weld and is now 15 lbs. A welding qualification

Fig. 35 Hot side weld joint for generator GC01

Fig. 36 Weld from generator GC01

procedures which states acceptable strength standards has been established.

2.3 HONEYCOMB

The generator structure is composed of a magnesium thorium frame stiffened with honeycomb. The phenolic honeycomb is bonded to the magnesium with epoxy at 180°C. A vacuum bag process is employed in bonding. The magnesium is coated with dichromate to improve bonding and to protect from corrosion.

Following bonding the honeycomb structure is vacuum outgassed at 180°C to remove the unreacted organic components and low molecular weight polymers from the epoxies and phenolics. The outgassing also removes water and volatiles from the dichromate conversion coating and machined holes in the magnesium frame.

2.4 INSULATION

The generator insulation consists of alternate layers of aluminum foil and aluminum opacified quartz paper. The opacified quartz portions of the Linde high vacuum insulation are outgassed at 450°C for a minimum of four hours at a pressure of 5×10^{-5} torr or less, prior to use in the generator.

Insulation on the top and bottom dead areas is secured by 0.002-inch diameter alumel alloy wires. Two needles are threaded with wire and passed through the insulation with both needles passing through the insulation towards the honeycomb. The two needle technique assures that the insulation is always pierced in compression which prevents tearing. Completed stitches are tied and the knot secured with epoxy resin on the cold side.

In the first six panels of GC01 the top layer of the insulation blanket was a sheet of quartz paper. It was used to prevent the collectors from electrically shorting to the first layer of aluminum foil. The quartz paper was found to be very fragile and it was difficult to prevent the collectors from shorting to the aluminum foil. Aluminum opacified paper is much stronger and abrasion resistant. The voltage breakdown of the opacified paper was checked and found to be greater than 300 volts under the pressure exerted by collectors. A double weight sheet of opacified

paper was substituted for the quartz paper on panel PE-08 and later panels. This greatly reduced the problem of electrical shorts.

2.5 PANEL ASSEMBLY

The panel assembly operation has been established in a semi-clean area. Final assembly of a panel is carried out in three steps:

1. The radiator assembly is placed over the 72 elements and the element cold caps slipped into the radiator grommets. To facilitate the cap-grommet mating the cap has been modified to slightly decrease its diameter where it first enters the grommet. This cap modification was not used on any of the PC, PG, and the first two PE panels. No broken elements were experienced on these panels, but the cap modification operation was made as an added precaution to reduce forces on the elements during assembly.
2. The second final assembly step is a tack-weld to temporarily fasten the cap to the grommet to permit the final welds to be made on a fixed-head resistance welder. The tack welds prevent the collector assemblies from dropping out of the radiator when the panel is moved from the final assembly fixture to the welder.
3. The last step secures the cap to the grommet with multiple resistance spot welds. This step is followed by a resistance check of panel continuity.

A resistance check between steps 2 and 3 will detect broken elements before the final welding is started.

Generator panel interconnections are made by soldering tabs of the silver radiator busses together. The panel connections were made with a nominal 100 watt soldering iron operated at 60 volts from a variable auto-transformer supply. The solder was 60/40 tin-lead solder fluxed with electronic grade mildly activated resin flux.

Tests were performed to determine if soldering of the electrical connections could damage the adhesive bond between the honeycomb structure and the radiator. The 0.007-inch silver radiator buss will rapidly conduct

the heat of soldering into the bond area and the radiator bond cannot sustain a temperature greater than 350°F. A test panel connection was made using two panels and a Teflon block bonded to a corner post. The temperature of the bond area was measured by welding 0.002-inch diameter thermocouples to the bonded side of the silver radiator. The temperature maximum while soldering was 331°F. To provide a safety factor, dry nitrogen was blown on the radiator between the solder joint and the bonded areas. This heat sinking method reduced the temperature to 177°F -- well below the range of potential adhesive softening or damage.

The connecting silver straps from the radiators must cross over the magnesium structure and must be insulated from the structure to prevent short circuits. Teflon insulators were selected for this use. It was treated with an etchant and adhesively bonded to the dichromated magnesium frames.

Bond tensile test samples were made, using 1/8" thick Teflon bonded to the dichromated HK38A magnesium alloy used for corner posts. The average bonded area was 0.65 in.². This is approximately the bond area available on the corner posts. For samples 2 and 5 the bond strength exceeded the strength of the Teflon and the test coupon elongated and parted.

<u>Sample</u>	<u>Max. Load-Lbs.</u>	<u>Tensile Strength (psi)</u>
1	153	245
2	170	250
3	176	260
4	162	245
5	172	275
6	156	235
7	153	245

The adhesive joint must only support the Teflon insulating block which will weigh less than 4 grams.

Figures 37 and 38 show the assembled generator GC01 with instrumentation and electrical heat source.

Fig. 37 Thermoelectric generator GC01

Fig. 38 Generator GC01 with electrical heat source

2.6 QUALITY CONTROL DEVELOPMENT

Concurrent with the development of the fabrication processes and assembly techniques, foundations were laid for a formal quality control program. Inspection and test procedures were developed to assure that the generators would be functional units. Quality control check points are indicated on Fig. 31 and 32.

One of the major areas of quality control development was in the element bonding processes. Each element receives a unique serial number identifying its material batch and various processing steps it has incurred. It is checked dimensionally and its electrical properties are measured. Destructive tests are performed on sample elements from each bonding run to measure the element tensile strength. At least two n-type elements and two p-type elements are randomly selected from the group of elements for each panel and placed in a test module to simulate generator operating conditions. Seebeck coefficients, resistance, and power output of these elements are measured. A process specification was prepared to describe the element processing and checking procedures.

Resistance welding requires constant attention to produce strong and consistent welds. The process is very sensitive to any electrical resistance changes between the welding electrodes. Resistance is in turn a function of the electrode condition, electrode geometry and part surface condition. Several specifications were prepared to instruct the welder operators in the proper welding machine set-up for each welding operation in the generator. The panel welding procedures also specify that weld test coupons be made and pulled to test weld quality. These samples are made for each weld set-up. If for some reason, such as changing the electrodes, the machine is changed during panel welding, the machine must be re-qualified before proceeding with part production.

Resistance checks of the panels during GC01 fabrication revealed several short circuits. Electrical shorts between the collectors and the first aluminum insulation foil and shorts occurring on the cold side between the elements and the last few aluminum insulation foils were observed.

The collector-to-foil shorts were cleared by straightening the collectors, thus removing the penetrations. Two techniques were used to clear the element-to-foil shorts. One method was to pass a thin metal strip between the honeycomb and the insulation. This raised the foils out of the hole in the honeycomb and compressed the Al_2O_3 baffle. The other technique was to press lightly and uniformly downward on the element causing the unsupported section of the foil surrounding the grommet to "oil can" outward. The end cap was removed from the source of trouble - contact with the foil.

Design changes were initiated to eliminate shorting on subsequent panels. Collector corners were rounded to prevent piercing of the top cover sheets of insulation. In addition, the top cover sheet of insulation was changed from quartz paper to a double thickness of aluminum opacified quartz. The latter was much more rugged.

Cold side shorts were eliminated by two design changes. First, tantalum opacified washers were selected to replace the alumina whisker insulation surrounding the elements. They prevented contact of the multifoil insulation with the element cold cap. In addition, the hole diameter of the last five aluminum foil insulation sheets were increased by 0.01-inch.

One hundred percent inspection of aluminum foil insulation holes insures that no burrs are left from the punching operation. One hundred percent inspection also is required on elements after bonding to determine if any sharp surfaces are present on the element or cap.

3. TESTING

Major tests conducted during the report period included insulation thermal bypass, shock and vibration testing of a panel and a mechanical mock-up, performance testing of quality control modules, and thermal plus performance mapping of GC01.

3.1 INSULATION TESTS

Thermal bypass of the ISOTEC NAVSAT generator is defined as the heat that flows from the source to the radiator without passing through the thermoelectric couples. Bypass heat flows through the following paths:

1. Linde super-insulation
2. Joints in insulation
3. Annular areas around elements
4. Heat source supports

Determination of heat bypass through the insulation hinges on the measurement of the effective conductivity of the insulation. Since the conductance of multi-layer vacuum insulation is affected by joints, penetrations, layer density, and boundary temperatures the analysis and test procedures are not straight-forward.

The basic thermal conductivity of aluminum foil-opacified paper insulation for the boundary temperatures of 400°C to 150°C has been reported by Linde to be 3.6×10^{-6} w/cm°C. Data on the effects of joints are very meager. However, some analytical work published by Linde using a two dimensional model indicates that a joint in a panel about the size of a generator panel will result in an increase of about 30% in thermal conductivity.

Position of insulation relative to a penetration may increase or decrease the insulation conductance by altering the temperature gradient through the insulation. Linde is currently using a computer analysis to determine if there is an optimum position of the insulation relative to the thermoelectric

elements.

Joint heat leak was determined experimentally using a mat of insulation with Geonetics heat meters at the joint and midway between the joint and the edge of the insulation. The type of joints investigated are shown in Fig. 39. The minimum heat leak occurred with a well laid-up butt joint. Since this type of joint is almost impossible to reproduce in a generator configuration, the butt-overlap joint was selected for use. The heat leak was determined to be about 0.02-watts per inch of length.

Generator GC01 was assembled with alumina whisker insulation in the annular areas around the elements. The heat leak for this type of insulation was determined by using a method similar to that used in determining the leak at joints. A mat of insulation was assembled with a 1/4" dia. hole at the center with the hole filled with alumina whiskers. A heat meter measured the flux at the cold side and this was compared to the flux without a hole. A second test was made using disks of tantalum opacified quartz fiber paper as the insulation in the hole. The heat leak for 720 annular spaces was computed to be 91.2 watts with the alumina whiskers and 17.5 watts with the tantalum opacified paper washers.

3.2 QUALITY CONTROL MODULES

Six QC modules were performance tested up to a hot junction temperature of 450°C. Each module contained two n-elements and two p-elements taken at random from bonding runs made during the fabrication of the NAVSAT Generator GC01. The pertinent data on each of these modules are given in Table V.

Additionally, modules QC-1, QC-2, and QC-4 were life tested and reported in the first section of this report. Module QC-4 was used as a specimen for irradiation tests, and the results are reported in Reference 4.

3.3 PANEL SHOCK AND VIBRATION TESTING

Panel PC02 was shock and vibration tested in accordance with "g" levels in the Scout launch specification (Table VI). It was tested both at room temperature and at a hot junction temperature of $160 \pm 5^{\circ}\text{C}$. This panel

Fig. 39 Results of insulation and joint tests

TABLE V

GC01 QUALITY CONTROL MODULE DATA

Module Power Output Normalized to $\Delta T = 244^{\circ}\text{C}$		Generator Output
QC-1	74.2 73.6	
QC-2	73.6 75.4	26.8 watts @ $\Delta T = 234^{\circ}\text{C}$ or
QC-3	76.7 75.3	29.2 watts @ $\Delta T = 244^{\circ}\text{C}$
QC-4	75.2	with
QC5A	79.4	358 couples total
QC5B	81.2 77.0	
Average = $76.2 \frac{\text{mw}}{\text{couple}}$		$81.5 \frac{\text{mw}}{\text{couple}}$
$1 \sigma = \pm 2.3 \text{ mw}$		

TABLE VI

SCOUT PROTOTYPE SINUSOIDAL VIBRATION SPECIFICATIONS

(Sweep Rate = 2 Octaves/Minute)

Frequency Range cps	Acceleration ($\pm$ g)
5 - 10	0.4" D.A.
10 - 50	2
50 - 500	6
500 - 2000	12

was dimensioned 6 x 10 inches and contained a larger honeycomb area than the generator panels. Internal resistance of the panel was monitored during all tests.

3.3.1 Mechanical Shock Test

Panel PC02 was shock tested in the direction normal to the collectors (Z axis) and at room ambient temperature. The test consisted of three shocks with each shock pulse approximately a half-sine with a peak amplitude of 30 g's and a duration of 11 ± 1 millisecond. Resistance prior to the shock test and after each drop is given in Table VII. Panel resistance remained constant within the accuracy of measurement.

3.3.2 Sinusoidal Vibration Tests

The panel was given a critical frequency search in the direction normal to the collectors (Z axis) while at ambient temperature. It was subjected to 2 g's (p-p) while sweeping the frequency linearly from 10 to 2000 cps at a rate of 44.2 cpm. Two major resonances were observed during the test and are listed in Table VIII. The panel resistance was monitored continuously during all vibration tests.

The panel was subjected to sinusoidal vibration in accordance with Table VI while maintaining a collector temperature of $160 \pm 5^{\circ}$. The radiator temperature was held at $100 \pm 6^{\circ}\text{C}$. Vibration direction was normal to the collectors (Z axis). Data on the resonances observed are presented in Table VIII.

3.3.3 Room Temperature Vibration

The panel was subjected to sinusoidal vibration while at room ambient temperature. Direction of vibration was normal to the collectors (Z axis), and the data on the observed resonances are presented in Table VIII.

Panel PC02 was also vibrated sinusoidally in a direction parallel to the collectors' largest dimension. It was subjected to the accelerations listed in Table VI except in the frequency range of 500 to 2000 cps. The vibration system was not capable of driving the slip table and fixture at ± 12 g's. Therefore, the panel was vibrated to ± 10 g's in the range of 500 to 2000 cps.

TABLE VII

PANEL RESISTANCE DURING SHOCK TEST

Remarks	Panel Resistance m Ω
Panel mounted in fixture	16.3 $\pm$ 0.2
Drop No. 1	16.4 $\pm$ 0.2
Drop No. 2	16.4 $\pm$ 0.2
Drop No. 3	16.3 $\pm$ 0.2
Resistance 30 minutes after test	16.5 $\pm$ 0.2

TABLE VIII
SINUSOIDAL VIBRATION TEST DATA

<u>Test</u>	<u>Resonance Frequency cps</u>	<u>± g Input</u>	<u>± g Panel</u>	<u>Amplification Factor</u>	<u>Approximate Bandwidth for 1/2 (f max)</u>
Resonance	140	2	13.6	6.8	40
Survey	195	2	7.0	3.5	20
(Z Axis)	350	2	8.6	4.3	70
	690	2	13.6	6.8	50
Hot Vibration	145 ± 5	6	20.0	3.3	60
(Z Axis)	615 ± 5	12	28.0	2.3	190
Cold Vibration	155 ± 5	6	14.0	2.3	35
(Z Axis)	650 ± 5	12	26.0	2.2	190] *
	725 ± 5	12	28.0	2.3	

* Two peaks on the resonance band

3.3.4 Resonance Dwell

The panel was vibrated for a period of 5 minutes at each of the frequencies (155, 650, and 725 cps). Input g-level was maintained in accordance with the frequency and g-level values listed in Table VI. Three tests were conducted while the panel was at ambient temperature and no damage was observed.

3.3.5 Discussion

Differences observed in the frequencies between the resonance search and the room temperature prototype vibration specifications may be attributed to one or both of the following:

1. The response curve is relatively flat at resonance, making it difficult to obtain the absolute maximum on the response curve.

2. The panel's response is similar to that of a structure with a variable stiffness (i.e., the resonance frequency is dependent upon driving force).

Resonance differences between the hot and cold vibration test appear to be significant. The panel responds as though it is slightly stiffer, structurally, when it is cold.

The panel resistance prior to all tests was $16.3 \pm 0.2 \text{ m } \Omega$. Based upon the resistance measurements and physical observations, no damage was done to the panel by the shock and vibration tests.

3.4 MOCK-UP GENERATOR SHOCK AND VIBRATION TESTING

A mechanical generator mock-up (MU-2) was fabricated and tested. It contained one thermoelectric panel and nine structural ("dummy") panels, which consisted of the frame and honeycomb structure only. Final assembly of MU-2 is depicted in Fig. 40. It was instrumented as shown in Fig. 41 and subjected to both shock and sinusoidal vibration.

The accelerometer locations were defined as follows:

1. Accelerometer No. 1 - measured the driver (input) response.
2. Accelerometer No. 2 - was mounted on the panel over the "L" shaped portion of the panel frame on one end.
3. Accelerometer No. 3 - was mounted on the panel over the "T" shaped

Fig. 40 Final assembly of mockup generator MU-2

Legend:

A = Panel containing thermo-electric elements (PS01)

• = Accelerometer location

○ = Accelerometer number

Fig. 41 Instrumentation for MU-2

portion on the panel frame near the center.

4. Accelerometer No. 4 - was mounted the same as No. 2 but on the other end.

5. Accelerometer No. 5 - was mounted on the solid portion of the blank end piece near the post adjacent to the panel.

6. Accelerometer No. 6 - was mounted in the center of one-half of the panel.

Resistance of the panel was monitored before and after each test since measurements during the test interfered with the accelerometer readings.

3.4.1 Shock Test

The mock-up was subjected to three shocks in one direction only with the thermoelectric panel mounted on top. The shock pulse had an amplitude of 30 g peak with a duration of 11 milliseconds, half sine wave. Test data are presented in Table IX. A visual examination upon completion of testing revealed no evidence of damage or deterioration to the generator as a result of the shock test. There was no change in panel resistance. See Table X.

3.4.2 Vibration Test

The mock-up was subjected to the following sinusoidal vibration tests in each of the three mutually perpendicular axes. The thermoelectric panel was first mounted on the top and then on the side of the mock-up. First, a low level resonance search was conducted. In this test the mock-up was swept at $\pm 0.5g$ through the frequency range from 10 to 2000 Hz at a linear rate in the "Z Vertical" axis only. Test time was 20 minutes. Tables XI and XII list the test data.

After completion of the resonance search, a prototype vibration test was performed. The mock-up was swept from 5-2000 Hz at two octaves per minute at the following levels:

<u>Frequency (Hz)</u>	<u>"Z Thrust" Axis</u>	<u>"Z Vertical" and "X" Axes</u>
5-10	0.4 inch dia.	0.2 inch dia.
10-50	2g peak	1g peak
50-500	6g peak	1.5g peak
500-2000	12g peak	2.5g peak

TABLE IX

SHOCK TEST DATA (PANEL MOUNTED ON TOP OF MU-2)

Accelerometer No.	Shock Test No. 1 g's	Shock Test No. 2 g's	Shock Test No. 3 g's
1	30	30	30
2	32	-	-
3	24	-	-
4	70	40	38
5	-	32	33
6	-	-	-

TABLE X

PANEL RESISTANCE DATA

Test Description	Panel Resistance m Ω Initial 22.4	Remarks
Shock # 1	22.4	No changes observed
Shock # 2	22.3	No changes observed
Shock # 3	22.3	No changes observed
Vibration Z-axis (panel top)		
Resonance search	22.3	No changes observed
Prototype	22.9	One p-element broken
Vibration X-axis (panel side)		
Resonance search	22.9	No changes observed
Prototype	22.9	No changes observed
Resonance dwell	27.9	Collector bent during test

TABLE XI

RESPONSE DATA FOR Z-AXIS VIBRATION TEST ON MU-2 (PANEL MOUNTED ON TOP)

<u>Resonance Search</u>	<u>67 Hz</u>	<u>185 Hz</u>	<u>519 Hz</u>	<u>560 Hz</u>	<u>850 Hz</u>	<u>1725 Hz</u>
<u>Accelerometer No.</u>	<u>g's</u>	<u>g's</u>	<u>g's</u>	<u>g's</u>	<u>g's</u>	<u>g's</u>
1	0.5	0.5	0.5	0.5	0.5	0.5
2	-	6.5	6.5	6.5	2.5	5.0
3	21.0	5.0	4.0	5.0	3.0	1.0
4	3.0	4.5	4.5	2.0	2.0	2.0
5	-	-	4.0	5.0	4.0	6.0
6	18.0	7.0	4.0	-	2.5	2.0
<u>Prototype Vibration</u>						
1	6.9	6.0	-	12.0	12.0	12.0
2	54.0	48.0	-	100.0	45.0	20.0
3	100.0	35.0	-	100.0	70.0	10.0
4	110.0	9.0	-	95.0	35.0	20.0
5	18.0	15.0	-	110.0	120.0	70.0
6	130.0	15.0	-	100.0	15.0	5.0

TABLE XI (continued)

<u>Resonance Search</u> Accelerometer No.	<u>15 Hz</u> <u>g's</u>	<u>108 Hz</u> <u>g's</u>	<u>410 Hz</u> <u>g's</u>	<u>625 Hz</u> <u>g's</u>
1	0.5	0.5	0.5	3.0
2	-	8.5	12.0	25.0
3	-	27.0	8.0	27.0
4	25.0	13.0	16.0	22.0
5	-	2.0	1.5	22.0
6	-	-	-	-
<u>Prototype Vibration</u>				
1		6.0	6.0	12.0
2		10.0	220.0	120.0
3		105.0	110.0	120.0
4		130.0	300.0	100.0
5		15.0	15.0	120.0
6		-	-	-

*
Response data on blank honeycomb panel

TABLE XII

RESPONSE DATA ON X-AXIS VIBRATION TEST ON MU-2 (PANEL MOUNTED ON SIDE)

<u>Resonance Search</u>			
Accelerometer No.	<u>119 Hz</u> <u>g's</u>		<u>625 Hz</u> <u>g's</u>
1	0.5		0.5
2	6.0		1.0
3	21.0		9.0
4	4.0		7.0
5	0.5		2.0
6	15.0		3.0

<u>Prototype Vibration</u>			
	<u>119 Hz</u> <u>g's</u>	<u>175 Hz</u> <u>g's</u>	<u>625 Hz</u> <u>g's</u>
1	1.5	1.5	2.5
2	15.0	5.0	6.0
3	50.0	7.0	5.0
4	10.0	15.0	3.0
5	2.5	10.0	7.0
6	35.0	18.0	9.0

A resonance dwell test was conducted after the prototype vibration test. The mock-up was vibrated for five minutes at the most severe resonant frequency, 67 Hz, in "Z Vertical" axis. One p-element broke and fatigue cracking in the collectors at the center of the panel was noted as a result of the resonance dwell.

3.4.3 Discussion

Shock and vibration tests indicated that the thermoelectric elements can withstand accelerations in excess of 100 g's. This is considerably above the highest acceleration of 36 g's proposed in the NAVSAT specification. The data also revealed that the MU-2 structure amplified the input accelerations at some frequencies and the panel resonance frequency was low. It corresponded to the high "g" frequency range of the NAVSAT vibration specification.

From this preliminary test a structural mock-up MU-3 is being designed and fabricated with the following changes:

1. Dummy panels will include the Ag radiators to more closely represent the stiffness of the completed panel.
2. The panel structural frames will be stiffened to raise the panel resonance frequency and decrease the "g" amplification.
3. Collector assemblies will be stiffened (as in PC02).

With the changes it is expected that generator design will meet all the shock and vibration specifications for the NAVSAT application.

3.5 GC01 Thermal and Performance Testing

Generator GC01 was tested in a space chamber at Gulf General Atomic Incorporated. Seventy-two 2-mil iron constantan thermocouples mapped temperatures on the generator and electrical heat source. Power output of the generator was 26.8 watts.

Before conducting the generator performance test the electrical heat source was placed in the space chamber to determine its operating characteristics. The heat source consisted of Ta-10w heater wire spirally wound on a cylindrical alumina mandrel. It was centered within a 7.31-inch OD

tantalum sphere coated with pyromark.

During the heat source performance test the space chamber shrouds were filled with liquid nitrogen. Thermal impedance of the generator was simulated by a Kaowool insulator supported on a wire cage. Figure 42 indicates the sphere and thermal simulator temperatures as a function of input electrical power. The sphere temperature varied only $\pm 10.5^{\circ}\text{C}$ at a power input of 707 watts.

Generator GC01 was instrumented with 103 thermocouples, of which 72 were monitored during the first performance test because of feedthrough limitations. Figure 43 shows GC01 mounted in the space chamber. A second performance test was scheduled for early FY '69. The test procedure is indicated below.

1. Measure room temperature panel and generator resistance after installing the generator in the space chamber.
2. Evacuate chamber down to 100 torr. in no less than 30 minutes.
3. Evacuate chamber down to 100 microns.
4. Start LN_2 trap and diffusion pump.
5. Measure room temperature panel and generator resistance.
6. Apply electrical power to the generator heater when the pressure is less than 5×10^{-5} torr. System pressure must be kept below 10^{-4} torr. during heat-up.
7. Continue to apply power to the generator heater until the cold junction temperature is between 100 and 150°C .
8. Slowly fill shrouds on space chamber with LN_2 .
9. Increase power input until the hot junction reaches approximately 325°C . The heat rate shall not exceed 2°C per minute.
10. Record data on all thermocouples and voltage probes (steady data conditions) at 325° , 375° , 400° , and 425°C hot junction temperature.

The performance test data are presented in Tables XIII and XIV. Thermal data are indicated in Reference 2 along with the predicted values.

Power input measurements were limited to $\sim \pm 5\%$ during this test due to instabilities in the power supply and inability to measure the AC RMS voltage accurately.

Fig. 42 Sphere and thermal simulator temperatures as a function of input electrical power

Fig. 43 Generator GC01 mounted in the space chamber

TABLE XIII

TEST GENERATOR GC01 PERFORMANCE TEST DATA

Test No. 1													
*(1)	*(2)												
$\overline{T}_h$ °C	$\overline{T}_c$ °C	$\overline{\Delta T}$ °C	I AMPS	V_L VOLTS	P_o WATTS	P_i WATTS	η %	η %	R_i m Ω	R_L m Ω	T_{source} °C	T_{3-5} °C	
424	178	246	6.561	4.524	29.68	798	3.72	3.79	--	689	576	579	
398	164	234	6.243	4.299	26.83	734	3.66	3.73	--	689	554	557	
393	160	233	5.694	4.580	26.08	722	3.64	3.69	--	685	547	550	
371	152	219	6.020	3.791	22.82	688	3.32	3.39	--	630	529	532	
320	135	185	5.737	2.969	17.03	636	2.68	2.74	--	518	488	490	

$$*(1) \text{ Average Hot Junction Temperature } \bar{T} = \frac{\bar{T}_{h_n} + \bar{T}_{h_p}}{2}$$

$$*(2) \text{ Average Cold Junction Temperature } \bar{T} = \frac{\bar{T}_{c_n} + \bar{T}_{c_p}}{2}$$

*(3) Power output delivered to generator load in column 8.

*(4) Measured power input uncorrected for lead losses.

*(5) Measured efficiency uncorrected for lead losses.

*(6) Efficiency corrected for 15 watts conducted through instrumentation leads.

*(7) Generator internal resistance computed from instantaneous measurements of open circuit voltage.

*(8) Generator load resistance.

*(9) Average heat source temperature based upon five thermocouple.

*(10) Average heat source temperature using two thermocouples 90° apart.

TABLE XIV

TEST GENERATOR GC01 PANEL LOAD VOLTAGES

<u>Test No. 1</u>											
<u>T_h</u> <u>°C</u>	<u>T_c</u> <u>°C</u>	<u>PE02</u> <u>mV</u>	<u>PE03</u> <u>mV</u>	<u>PE06</u> <u>mV</u>	<u>PE05</u> <u>mV</u>	<u>PE08</u> <u>mV</u>	<u>PE04</u> <u>mV</u>	<u>PE07</u> <u>mV</u>	<u>PE10</u> <u>mV</u>	<u>PE11</u> <u>mV</u>	<u>PE12</u> <u>mV</u>
424	178	488.2	424.8	453.4	444.4	473.6	446.6	460.2	449.2	452.9	448.5
398	164	464.1	397.6	433.1	420.5	452.3	422.5	440.3	422.0	428.9	425.5
393	160	489.2	441.2	458.0	449.2	480.4	450.1	468.2	449.1	453.9	451.5
371	152	404.5	361.0	378.8	368.0	399.1	369.0	387.7	393.7	380.5	378.8
320	135	321.4	284.8	301.4	288.8	318.8	286.9	308.5	287.1	290.7	289.7
<u>Generator GC01 Panel Open Circuit Voltages</u>											
454	166	1084.0	982.0	1039.0	1041.0	1083.0	1044.0	1061.0	1037.0	1044.0	1042.0
417	156	964.0	918.0	924.0	921.0	962.0	924.0	941.0	919.0	925.0	923.0
376	142	822.9	779.4	786.9	782.9	822.3	783.6	802.8	778.6	783.4	782.6

4. REFERENCES

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