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CALIFORNIA INSTITUTE OF TECHNOLOGY
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PROGRESS REPORT NO. 29
FOR A PROGRAM OF
THERMOELECTRIC GENERATOR TESTING
AND
RTG DEGRADATION MECHANISMS EVALUATION

Submitted to

The US Department of Energy
Division of Nuclear Research and Application
Washington, D.C.

Prepared by

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by

The Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

February 1979

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FOREWARD

This report is submitted to the Department of Energy covering work conducted under Interagency Agreement No. E(04-3)-959 by the Jet Propulsion Laboratory and documents all activities covering the period of November and December 1978 and January 1979 - performed under the technical direction of Mr. Patrick O'Riordan, Office of Technical Development and Special Projects of the DOE Division of Nuclear Research and Application.

The portion of the report covering the selenide thermoelectric material evaluation is jointly sponsored by DOE and NASA Galileo Project.

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I. SUMMARY

Thermal conductivity measurements of the P-type and N-type selenide alloys after 17000 hours and 4100 hours, respectively, are in good agreement with the 3M Co data.

Ingradient testing of N-legs after 6600 hours show comparable performance to the reported 3M data. Ingradient testing of P-legs at accelerated test conditions, have completed 3600 hours and performance shows reasonably correlation with accelerated temperature and current gradients.

N-type samples from both the Thermal Conductivity Tests and Ingradient Performance Tests were removed from test for examination. All samples were found to be severely cracked upon removal from the test fixtures. Metallurgical and X-ray diffraction analysis showed (1) extensive cracking had occurred in the lower half (~~cold end~~) of the legs and (2) a crystallographic phase change occurred in the upper half (hot end) of the legs from monoclinic to orthorhombic. It is postulated that the phase change that occurs on heating aggravates the micro-cracks that exist in the "as fabricated" leg. Improvement in the "as fabricated" N-type leg, possibly by hot pressing, and a thermal treatment to convert the N-leg to the high temperature crystalline form are techniques being considered to resolve this "cracking" problem.

The P-type legs of the new design with the Astroquartz slurry wrap, and no partition, have been received from the 3M Co for evaluation.

The remaining MMH generator, Q1-A, on test has accumulated 10,946 hours and performance remains stable.

An initial evaluation of the performance of the Voyager 1 and 2 RTG's after 12,000 hours of operation versus the DEGRA performance prediction code, shows excellent agreement.

II. SELENIDE TECHNOLOGY EVALUATION

A. Thermal Conductivity Tests

The long-term experiment of the p-type, singly partitioned legs, operated over a temperature gradient of $T_H = 800^\circ\text{C}$, $T_c = 400^\circ\text{C}$, has accrued approximately 17,000 hours of operation. The thermal conductivity values for the four legs on test were calculated and are shown in Figure 1 and normalized to the original value (k_0 - 100 hours) in Figure 2 as a function of operating time. Test calorimeter No. 4 was discontinued at 12,400 hours due to loss of "contact" between the sample and cold end heat sink. This was evidenced by an increase in the ΔT from 70°C to 230°C , between the copper block (T-2) and the silica heat flux meter (T-3), see Figure 3. Calorimeter No. 4 was disassembled and loss of "contact" or pressure on the p-type pellet as it became shorter was due to the hang-up on the molybdenum sleeve between the heater block and the copper base plate. On these earlier tests, a straight sided molybdenum cylinder was used, which was replaced on later tests by a molybdenum bellows cylinder, see Figure 3.

The thermal conductivity of the samples, except for No. 5 shows reasonably good agreement with the 3i Co's published values. The thermal conductivity after the first 4,000 hours has shown good stability, including sample No. 5. The testing of samples 1, 3, 5 and 6 will be continued.

Figure 1. TPM-217 (P-LEG) Thermal Conductivity Calorimeter 1 to 6 T_H 800°C T_C 400°C

Figure 2. TPM-217 (P-LEG) Thermal Conductivity $T_H = 800^\circ\text{C}$ $T_C = 400^\circ\text{C}$

Figure 3. Thermal Conductivity Test Fixture

The testing of the n-type legs has been continued, utilizing the same type of calorimeter set-up as used for the p-type legs, see Figure 4 with the exception that all of the calorimeters have the molybdenum bellows cylinders. The operating conditions are $T_H = 800^\circ\text{C}$ and a maximum $T_C = 250^\circ\text{C}$. This limitation of the cold end junction temperature is required because lead foil is attached to the silver sputtered end of the leg as the cold end contact (silver-lead eutectic- 304°C). During the testing cycle, the diffusion pump failed at 2200 hours and 4000 hours; the vacuum level was maintained in the low micron pressure range by the mechanical pump. At approximately 4100 hours the hot side measuring thermocouples (T-1) readings became erratic. The cold side measuring thermocouples, T-2, readings remained constant. The tests were operated with a constant heater power input. Prior to 4100 hours the thermal conductivity values for the six legs had remained stable and showed good agreement with the 311 Co's published values.

The thermal conductivity values for the six legs are shown in Figure 5 and normalized to the original value ($K_0 = 20$ hours) in Figure 6. As a function of operating time.

The tests were cycled to room temperature at 4113 hours and two of the N-legs, No. 1 and 2, were removed from their test stands for examination. The N-legs appeared intact prior to their removal from the test fixture, see Figure 7. Upon disassembly of the test fixtures both N-legs were found to be badly cracked. The sample from calorimeter No. 2 (Lot No. N2634-T3-6) was separated into two halves, see Figure 8. The sample from calorimeter No. 1 (Lot No. N2634-T3-13) was also cracked; particularly the lower half of the leg see Figure 9.

Figure 4. Thermal Conductivity Test Fixture

Figure 5. Thermal Conductivity Test N-Type Calorimeter 1 to 6 T_H 800°C T_C 240°C

Figure 6. Thermal Conductivity Test N-Type T_H 800°C T_C 240°C

FIGURE 7.

Thermal Conductivity Test
N-Type, 4000 Hrs
Calorimeter-2

FIGURE 8.

Thermal Conductivity Test N-type
4000 hours Calorimeter-2

FIGURE 9.

Thermal Conductivity Test
N-Type 4000 hrs Calorimeter-1

The sample from calorimeter No. 2 was subjected to metallographic analysis and electron-probe microanalysis. The sample from calorimeter No. 1 was sent to General Atomic Co. for x-ray diffraction analysis. Inspection of the test fixture showed that deposits had shorted the measuring thermocouples at the hot end, which accounts for the erratic readings that occurred prior to shut down of the test. A summary of the scan made with the electron-microprobe is given below:

<u>Sample Location</u>	<u>Gd (counts)</u>	<u>Se (counts)</u>
Sample at Edge	17944	37691
In From Edge A	19367	40462
In From Edge B	19049	42649
In From Edge C	19463	43675
In From Edge D	19403	44630
Middle at Crack E	18985	41853
Toward outer Edge F	19225	40309
Toward outer Edge E	19650	43306
Toward outer Edge H	18466	48197
Toward outer Edge I	19538	41191
Toward outer Edge J	19241	41582
Outer Edge K	18636	36277
Outer Edge L	18949	35540
Away from Edge	19254	44521

There is something at the edge which is lowering the counts; this could be an oxide. Unfortunately this analytical instrument cannot identify oxygen. Overall the composition variation is very small, based on this qualitative analysis. Metallographic analysis showed extensive cracking particularly in

the lower half of the leg toward the cold contact and at the outside edges of the leg. The results of the x-ray diffraction analysis conducted by General Atomic Co., showed a crystallographic inversion from monoclinic to orthorhombic at the hot end of the N-leg. Similar results were obtained by measurements made for JPL on an ingradient tested N-leg; see section B - Ingradient Tests. A history of the N legs used for thermal conductivity measurement is shown in Table 1. Some of these legs showed incipient cracks as received. It is evident that the N-legs as fabricated exhibit some "cracks" and the phase transformation during testing aggravates this situation. The testing of the four N-legs will be resumed during the next reporting period.

B. Ingradient Testing

Testing of the group of p-legs with rounded copper cold shoes (an earlier design) was continued during this reporting period. Two p-legs were operated at "reference" conditions, $T_H = 800^\circ\text{C}$, $T_C = 150^\circ\text{C}$ and a current of 4.8 amps; these test conditions were used for previous ingradient tests of p-legs. This current translates into a current gradient of 1.4 amps/cm for the upper (hot) segment and 7 amps/cm for the lower segment, which are nominal GDS design operating conditions. In an attempt to evaluate the effort of accelerated current gradients and temperatures at ingradient conditions the following test conditions were selected for the remaining three p-legs:

Sample No.	Temperature		Current		Total Acceleration
	T_H/T_C	Acceleration	Amps	Acceleration	
2,3	800°C/150°C	Reference	4.8	nominal	-
5	800°C/150°C	"	8.16	5X	5X
1	830°C/150°C	2X	6.72	2.5X	5X
4	870°C/150°C	5X	4.8	nominal	5X

Table 1. N-Type Elements

Lot N2634 Received November 4, 1977

Ten (10) N-type gadolinium selenide
thermoelectric elements for ingradient
thermal conductivity measurements

Sample No	Test				Station No.	Test History
T3-13 ¹	Thermal Conductivity Calorimeter #1				3	At 2200 hours diffusion pump failed; safety control shut off heaters at 1×10^{-4} torr vacuum level. Mechanical pump remained on; samples cooled to room temperature. At 4000 hours seconds failure of diffusion pump - vacuum system occurred. Shut down cycle repeated as above.
T3-6 ²	"	"	"	#2		
T3-9 ³	"	"	"	#3		
T3-16 ³	"	"	"	#4		
T3-17 ³	"	"	"	#5		
T2-12 ³	"	"	"	#6		
AD - 49 hrs	"	"	Set-Up Test		14	Used to debug test set-up for N-type calorimeter-vacuum ok.
Test 1- 120 hrs.	"	"	"		14	
Test 1A - 240 hrs	"	"	"		14	
T3-7	Ingradient	Set-up Test		2	-	Used to debug test set-up for ingradient tests - 260 hours vacuum ok during these tests.

- Notes: 1. Sample No. 1 (T3-13) sent to GA for x-ray diffraction analysis.
2. Sample No. 2 (T3-6) metallographic section made; 1/2 to Caltech electron microprobe analysis, the other 1/2 for metallographic analysis.
3. Remaining four (4) samples on test.

Approximately 3600 hours of operation have been accumulated and the performance has not yet stabilized, see Figures 10 through 12.

The Seebeck voltage of the p-legs appears reasonable, see Figure 10, the reference samples No. 2 and 3 are approximately 208 $\mu\text{V}/^\circ\text{C}$. Sample No. 4 with the largest ΔT has the highest Seebeck voltage 230 $\mu\text{V}/^\circ\text{C}$ and Samples 1 and 5 with higher current gradient have lower Seebeck voltages, 196 $\mu\text{V}/^\circ\text{C}$ and 185 $\mu\text{V}/^\circ\text{C}$, respectively. The resistivities, see Figure 11, appear reasonable for the specific test conditions and appear to be reasonably stable. The calculated output power in Figure 12 shows these corresponding effects noted in the Seebeck voltage and resistivity measurements. This test is continuing.

Ingradient testing of the n-type GdSe legs has been continued utilizing the same set-up designed for the p-type samples. The only difference being that a disc of gadolinium foil had been inserted between the molybdenum heater block and the hot end of the n-type sample.

The n-legs are operated at a constant hot side of 800°C and a cold side temperature of 150°C in a hard vacuum environment. A total current of 3.7 amps, nominal GDS design operating conditions, was applied to the n-legs which are surrounded by Fiberfrax insulation. The n-legs have accumulated 6600 hours of operation and the performance has reasonably stabilized. The Seebeck coefficient, resistivity, open circuit voltage and power as a function of operation time, are shown in Figures 13 through 16, respectively, and show reasonable agreement with the published data. At 5100 hours sample No. 5 was removed from the test station and submitted for x-ray diffraction analysis. The results of the analysis concur with the General Atomic Co's finding that a phase transformation occurs at the hot end from monoclinic to orthorhombic. This sample was cracked upon removal from the test fixture and is typical of all the samples removed from test to date.

Figure 10 SEEBECK VOLTAGE VS TIME

"P" TYPE T/P/M 217

20/1 m = 5

VACUUM BAFFLED

SAMPLE	1	$T_h = 830^\circ\text{C}$	$T_c = 150^\circ\text{C}$	$I = 6.72$	AMPS
"	2	$T_h = 800^\circ\text{C}$	"	"	$I = 7.8$
"	3	$T_h = 800^\circ\text{C}$	"	"	"
"	4	$T_h = 870^\circ\text{C}$	"	"	"
"	5	$T_h = 800^\circ\text{C}$	"	"	$I = 8.26$

Figure 11. Resistivity Vs Time "p" Type TPM 217

RESISTIVITY VS TIME

"p" TYPE TPM 217

VACUUM BAKED

SAMPLE 1 $T_H = 850^\circ\text{C}$, $T_L = 150^\circ\text{C}$, $I = 6.12 \text{ AMPS}$ " " 2 $T_H = 800^\circ\text{C}$, " " $I = 4.10$ "" " 3 " " " " $I = 4.10$ "" " 4 $T_H = 870^\circ\text{C}$, " " $I = 4.10$ "" " 5 $T_H = 800^\circ\text{C}$, " " $I = 8.16$ "

Figure 12 - POWER VS TIME
 "P" TYPE TPM 217

VACUUM BAKED
 SAMPLE 1 $T_f = 830^\circ\text{C}$; $T_c = 150^\circ\text{C}$; $I = 6.72$ AMPS
 " 2 $T_f = 800^\circ\text{C}$; " " ; $I = 4.8$ AMPS
 " 3 $T_f = 800^\circ\text{C}$; " " ; $I = " "$
 " 4 $T_f = 870^\circ\text{C}$; " " ; $I = " "$
 " 5 $T_f = 800^\circ\text{C}$; " " ; $I = 8.16$ AMPS

Figure 12. Power Vs Time "P" Type TPM 217

FIGURE 13.

SEEBECK VOLTAGE VS. TIME

"N" TYPE Gd Se

$T_H = 800^\circ\text{C}$

$T_C = 150^\circ\text{C}$

VACUUM BAFFLED

CURRENT = 3.7 AMPS.

FIGURE 14.

RESISTIVITY VS TIME
 "N" TYPE Gd Se

$T_H = 800^\circ\text{C}$

$T_C = 150^\circ\text{C}$

VACUUM BAFFLED

CURRENT = 3.7 AMPS

FIGURE 15.

OPEN CIRCUIT VOLTAGE (EOC) VS TIME

'N' TYPE Gd Se

$T_H = 800^\circ\text{C}$

$T_C = 150^\circ\text{C}$

VACUUM BAKED

CURRENT = 3.7 AMPS

FIGURE 16.

POWER VS TIME
"N" TYPE Gd Se

$T_H = 800^\circ\text{C}$

$T_C = 150^\circ\text{C}$

VACUUM BAFFLED

CURRENT = 3.7 AMPS

A history of the N-legs used for ingradient testing is given in Table 2.

This test is continuing.

C. Thermophysical Properties and Compatibility Tests

The testing of N-type samples, unbaffled in a vacuum environment was resumed during this reporting period. The samples have accumulated 5263 hours of operation time; the isothermal weight rates versus time at 800°C, 900°C and 1000°C are plotted in Figure 17 through 19, respectively. These samples were tested for long time intervals, approximately 1000, 2500 and 1800 hours because of the low sublimation rate of the n-type material and to minimize potential oxidation of the samples. The n-type sample at 800°C after 3500 hours has begun to show a weight loss, although the overall weight change still shows a slight weight gain see Figure 17. The n-type samples at 900°C and 1000°C continue to show an increase in weight loss. The weight loss rate vs temperature of the n-type material is plotted in Figure 20, and is approximately three decades lower than the p-type material. This test is continuing.

Ten P-type-TPM217 thermoelectric elements with the astroquartz fiber wrap with a Min-k slurry coating were received from the 3M Co at the end of this reporting period. These P-type elements have a 0.030-inch thick copper foil bonded to the cold end and a 0.020-inch thick Tungsten/rhenium alloy cap bonded to the hot end. There is no partitioning foil. Several of these p-type elements will be run at the same ingradient test condition as the 3M Co, hot junction at 900°C with the cold junction at 150°C, and the results compared. Other p-type elements will be run at test condition used for samples prepared by JPL and the results compared. Testing will be initiated during the next reporting period.

Table 2. Test Status N-Type Elements

Lot 2640 Received March 1978

Ten (10) N-type gadolinium selenide thermoelectric elements for ingradient performance testing.

Sample No.	Test				Station No.
T4-10 ¹	1	Ingradient Performance - Position -1			2
T4-14		"	"	#2	
T4-21R		"	"	#3	
T5-24		"	"	#4	
T4-25		"	"	#5	
T4-21R ³	2	"	"	#1	
T4-13 ³		"	"	#2	
T4-18 ³		"	"	#3	
T4-23 ³		"	"	#4	
T5-25 ²		"	"	#5	

Samples were cracked after 78 hours of test; removed 3/23/78. Test set-up refurbished; new samples installed. Second group placed on test have accumulated 6099 hours as of 12/19/78. Sample No. T5-25R removed from test 11/10/78 after 5163 hours to check physical condition. Was found to be cracked. Vacuum level ok during entire test cycle; approximately 10^{-6} - 10^{-7} torr range.

Note: 1. Sample No. T4-10 sent for x-ray diffraction analysis.
 2. Sample No. T5-25R sent for x-ray diffraction analysis.
 3. Remaining four (4) samples on test.

Figure 12. Isothermal Test N-Type (No Baffle) Test Temp - 800°C

Figure 18. Isothermal Test N-Type (No Baffle) Test Temp - 900°C

Figure 19. Isothermal Test N-Type (No Baffle) Test Temp - 1000°C

Figure 20 WEIGHT LOSS RATE OF
N-MATERIAL IN VACUUM - UNBAFFLED

D. Accelerated Resistance "Module" Tests

At the end of the last reporting period it was noted that most of the Test Fixture construction members were made of copper, which provided an "infinite" sink for sublimed selenium and therefore this test set-up could produce erroneous results.

The test was interrupted and the test fixture refurbished with stainless steel construction members, see Figure 21. All of the test conditions remained the same as delineated in report No. 26.

The basic objective of this experiment is to determine whether the electrical resistance of the ceramic insulator in the "cold current strap assembly" deteriorates as a result of either material sublimation or is shorted by copper whisker growth. A dense 94% alumina ceramic, molybdenum-manganese metallized (.020 in-thickness) was used in the test set-up. The reference design specifies a beryllia ceramic because of its high thermal conductivity. For purposes of this test, the potential effect of deposits on the insulator's edge surfaces, the use of dense alumina will yield valid results. An unpartitioned TPM 217 p-type leg was used for this experiment. Resistance measurements are made between the copper electrical connector strap (-) and the copper base plate (+) while the module is operated at T_H -850°C and a T_C of 150°C. The cold junction temperature is controlled at 150°C $\pm$ 5°C by the back-heater placed between the sample and the water cooled base plate. In this test an acceleration factor of approximately 6X was selected as reasonable compared to 33X used in previous tests. It was felt that this acceleration would reasonably duplicate the shortening rate of the pellet and dispersion of the copper at the cold junction. The insulation resistance of the alumina insulator versus time is plotted in Figure 22. After 2100 hours the insulator resistance remains stable at 10^9 ohms and shows no degradation. This test is continuing.

Figure 21. Accelerated resistance module test of "Cold Current Strap Assembly"

Figure 22. Insulator Resistance

E. Degradation Modeling

During this past quarter, a number of potential improvements have been examined for adding to the DEGRA2 computer code. The three fold goal was to enhance graphic assessments of unicouple degradation, provide more accurate temperature modeling and allow additional capabilities to be included in the basic code.

Graphical output capability for hard copy demand terminals was programmed and verified. This capability allowed immediate evaluation at the terminal of temperature profiles especially at the interface junctions for partitions. More accurate temperature modeling involved modifying the call sequences such that the temperatures and property data near both extremes of the (temperature-property) table could be more accurately evaluated. The final improvement in DEGRA2 during this time was overlaying the code in core so that DEGRA2 and additional capabilities (enhancements) could be included. Just prior to developing this segmentation structure, DEGRA2 was too large to fit into core at one time. A scaled drawing of the D bank (data bank) and the I bank (instruction bank) is shown in Figure 23. It is abundantly clear that DEGRA2 is largely DBANK, ie., 25,996₁₀ words D Bank to 13,515₁₀ I BANK. From this we may conclude the version of DEGRA (~40k) will allow 24k words additional capability to be included before we are confronted again with storage problems on the Univac 1108 machine.

Production calculations were also performed with DEGRA2 with this newer version. DEGRA2 was used to conduct a study on the Galileo baseline. The data listed in Table 3 were used as input data for DEGRA2. The input data in Table 4 and the 3M summary of results were based on the June 78 3M presentation. A limited number of DEGRA results are listed in the lower right hand side of Table 4 for comparison. The approximate error in the DEGRA results relative to

ISANK DRAWN TO SCALE: 200 WORDS DECIMAL PER DASH

MAINONE (4959)

PLOTALL* (8556)

OPTIMUM* (2616)

TRPROPERTY* (5901)

INITIAL* (1509)

DSANK DRAWN TO SCALE: 300 WORDS DECIMAL PER DASH

MAINONE (22624)

PLOTALL* (3372)

OPTIMUM* (1447)

TRPROPERTY* (1576)

INITIAL* (479)

SYSS*RLIBS. LEVEL 72 02
END MAP

Figure 23. Scaled Drawing Illustrating the Segmentation of DEGRA2 on the JPL UNIVAC 1108

Table 3. DEGRA Input Data for the Galileo Baseline. This sample input was used for the 90,000 hour run in the Appendix.

```

1. NO
2. $INDEX
3.   ICAP=4, ILCAP=4
4.   IA=4, IC=4,
5.   IR= 48, ID= 48,
6.   ITERN= 40, ITMAX=25, JCAP= 49, MCAP= 49, ISTOP=6
7.   MNRO=-4
8. $END
9. $INDATA
10.  DELT=700., AS=4.80, EMISS=.865, IAREA='ND', LTOTN=.762, LTJTP=.762
11.   QP=7.3214, AR=48.7, CPLM=.001, ANSH=5*.4683, ANSC=5*.4683, ANS=5*.4683
12.   AP5H=5*.3269, AP5C=5*.3269, AP5C=5*.3269, AP5=5*.3269, LK5=5.30E-4
13.   LKNSH=5*5.E+6, LKPSH=5*5.E+6, CC=.01
14.   TYPE=2, SIGTEN=6.8, SIGTEP=6.8
15. $END
16. $LGAREA
17.   AN=300*.4683, AP=300*.3269
18. $END
19. $RSTST
20.   RF=.000, R9=1.E+7
21.   RHONCC=1.E-5, RHONCH=1.E-5
22.   RHONSC=5*1.E-7, RHONSH=5*1.E-7
23.   RHOPCC=1.E-5, RHOPCH=1.E-5
24.   RHOPSC=5*1.E-7, RHOPSH=5*1.E-7
25.   RHONS=5*1.E-7, RHOP5=5*1.E-7
26. $END
27. $LOADV
28.   ELOAD=30*.17857
29. $END
30. NO      NO      NO      NO      NO      NO      CONSX  DEBUY  VAR      YSTDZ
31. $MUE
32.   XMUENC=1.6E-4, XMUENH=1.6E-4
33.   XMUEPC=1.6E-4, XMUEPH=1.6E-4
34. $END
35. $TCON
36.   LKNCH=50.0, LKNCC=50.
37.   LKPC=50., LKPC=50.
38.   LKNSH=5*1.E+8, LKNSC=5*1.E+8
39.   LKPSH=5*1.E+8, LKPCS=5*1.E+8
40.   LKNS=5*1.E+8, LKPS=5*1.E+8
41. $END
42. $THICK
43.   LTNS=5*1.E-6, LTPS=5*1.E-6, TS=2.
44.   LN(1)=.1905, LN(2)=.1905, LN(3)=.1905, LN(4)=.1905
45.   LP(1)=.1905, LP(2)=.1905, LP(3)=.1905, LP(4)=.1905
46. $END
47. $STDYTA
48.   RTTEST=.04128, ETTEST=.295, PARTST=.5096
49. $END
50. THIS IS A TEST CASE FOR DEGRA2 USING..
51. SELFNO DATA **GALILEO GEOMETRY**.

```

3M experimental results is listed in Column 3 of Table II. These small errors may be too encouraging, that is to say, we still need to include the current dependence modifications in DEGRA before we can reasonably represent the SIG on Galileo but the trend illustrated in Table II is certainly in the correct direction.

Because of our need to examine DEGRA predictions closely, the Galileo baseline configuration was run out to 90,000 hours. These results are included in Tables 5 thru 8 for preliminary type of information only. The uncouple responses will clearly change when the current effect is included in the property characteristics and weight loss calculations.

Table 4. Comparisons of 3M Galileo Results with DEGRA Predictions

Input Data To DEGRA			
E/Couple	= 0.17857		
Q Total	= 7.3214 watts/couple		
RE	= 0.0		
Areas:	AN = 0.4683	Lengths:	LN = 0.762
	AP = 0.3269		LP = 0.762
Output Results			
	<u>3M</u>	<u>DEGRA</u>	<u>Approximate Error %</u>
Q Insulation (watts/couple)	1.025	1.056	3.0
R Total (M /couple)	34.6	35.37	2.2
T Hot (°C)	860.0	858.3	.2
T Cold (°C)	160.0	160.0	.0
Output Power (watts/couple)	.6875	.6919	.6

TABLE 5

PRELIMINARY DEGRA PREDICTIONS OF GALILEO RESULTS FOR
LONG OPERATING TIMES (OUT TO 90,000 HRS)

```

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
X          THIS IS A TEST CASE FOR DEGRA2 USING..                      X
X          SELENIDE DATA  **GALILEO GEOMETRY**..                      X
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

```

```

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
X  WEIGHT LOSS AND DIMENSIONAL CHARACTERISTICS  X
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

```

TIME (HOURS)	CUMULATIVE WT-LOSS N LEG	CUMULATIVE WT-LOSS P LEG	TOTAL CUMULATIVE WT-LOSS	TOTAL LENGTH N-LEG	TOTAL LENGTH P-LEG
0.	0.000	0.000	0.000	.7620	.7620
10.	1.397-09	6.878-08	7.016-08	.7620	.7620
100.	1.386-08	6.875-07	7.013-07	.7620	.7620
500.	6.895-08	3.426-06	3.495-06	.7620	.7620
1000.	1.373-07	6.832-06	6.969-06	.7620	.7620
1500.	2.050-07	1.022-05	1.043-05	.7620	.7620
3000.	1.995-07	1.001-05	1.021-05	.7620	.7620
5000.	4.550-07	2.310-05	2.355-05	.7620	.7620
10000.	1.047-06	5.419-05	5.523-05	.7620	.7620
15000.	1.594-06	8.374-05	8.533-05	.7620	.7620
20000.	2.098-06	1.118-04	1.139-04	.7620	.7619
25000.	2.564-06	1.385-04	1.411-04	.7620	.7619
30000.	3.034-06	1.655-04	1.685-04	.7620	.7619
35000.	3.464-06	1.910-04	1.945-04	.7620	.7619
40000.	3.861-06	2.153-04	2.191-04	.7620	.7619
45000.	4.227-06	2.383-04	2.425-04	.7620	.7619
50000.	4.563-06	2.601-04	2.647-04	.7620	.7619
55000.	4.873-06	2.808-04	2.857-04	.7620	.7619
60000.	5.158-06	3.004-04	3.056-04	.7620	.7619
65000.	5.419-06	3.191-04	3.245-04	.7620	.7619
70000.	5.659-06	3.367-04	3.424-04	.7620	.7618
75000.	5.880-06	3.535-04	3.594-04	.7620	.7618
80000.	6.082-06	3.694-04	3.754-04	.7620	.7618
85000.	6.267-06	3.844-04	3.907-04	.7620	.7618
90000.	6.437-06	3.987-04	4.051-04	.7620	.7618

TABLE 6.

PRELIMINARY DEGRA PREDICTIONS OF GALILEO RESULTS FOR
LONG OPERATING TIMES (OUT TO 90,000 HRS)

XX
X THIS IS A TEST CASE FOR DEGRA2 USING.. X
X SELENIDE DATA **GALILEO GEOMETRY** X
XX

XX
X ELECTRICAL PERFORMANCE CHARACTERISTICS. X
XX

TIME (HOURS)	CURRENT (AMPERES /COUPLE)	OPEN CIRCUIT VOLTS-N LEG (V/COUPLE)	OPEN CIRCUIT VOLTS-P LEG (V/COUPLE)	OPEN CIRCUIT VOLTS-TOTAL (V/COUPLE)	OUTPUT POWER (W/COUPLE)
0.	3.870+00	1.477-01	1.677-01	3.154-01	6.910-01
10.	3.828+00	1.478-01	1.677-01	3.155-01	6.836-01
100.	3.827+00	1.478-01	1.677-01	3.155-01	6.834-01
500.	3.825+00	1.477-01	1.677-01	3.154-01	6.831-01
1000.	3.823+00	1.476-01	1.676-01	3.152-01	6.826-01
1500.	3.820+00	1.476-01	1.675-01	3.151-01	6.822-01
3000.	3.813+00	1.474-01	1.673-01	3.147-01	6.808-01
5000.	3.802+00	1.471-01	1.671-01	3.142-01	6.790-01
10000.	3.777+00	1.465-01	1.664-01	3.130-01	6.745-01
15000.	3.752+00	1.459-01	1.658-01	3.117-01	6.699-01
20000.	3.726+00	1.453-01	1.652-01	3.105-01	6.654-01
25000.	3.701+00	1.447-01	1.645-01	3.092-01	6.608-01
30000.	3.622+00	1.437-01	1.635-01	3.072-01	6.468-01
35000.	3.598+00	1.430-01	1.627-01	3.057-01	6.425-01
40000.	3.573+00	1.424-01	1.621-01	3.044-01	6.380-01
45000.	3.548+00	1.417-01	1.614-01	3.031-01	6.335-01
50000.	3.523+00	1.411-01	1.608-01	3.019-01	6.291-01
55000.	3.498+00	1.405-01	1.601-01	3.006-01	6.247-01
60000.	3.473+00	1.399-01	1.595-01	2.993-01	6.202-01
65000.	3.448+00	1.392-01	1.588-01	2.980-01	6.158-01
70000.	3.424+00	1.386-01	1.581-01	2.968-01	6.114-01
75000.	3.399+00	1.380-01	1.575-01	2.955-01	6.069-01
80000.	3.374+00	1.374-01	1.569-01	2.943-01	6.025-01
85000.	3.349+00	1.368-01	1.562-01	2.930-01	5.981-01
90000.	3.325+00	1.362-01	1.556-01	2.918-01	5.937-01

TABLE 7.

PRELIMINARY DEGRA PREDICTIONS OF GALILEO RESULTS FOR LONG OPERATING TIMES (OUT TO 90,000 HRS)

```

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
X          THIS IS A TEST CASE FOR DEGRA2 USING..                      X
X          SELENIDE DATA **GALILEO GEOMETRY**..                      X
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

```

```

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
X          ELECTRICAL RESISTIVITY CHARACTERISTICS..                    X
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

```

TIME (HOURS)	N-TYPE RESISTANCE (COLD J.)	N TYPE RESISTANCE (HOT J.)	TOTAL N TYPE	P TYPE RESISTANCE (COLD J.)	P TYPE RESISTANCE (HOT J.)	TOTAL P TYPE	TOTAL RESISTANCE (N+P)
0.	1.7126-02	1.3185-04	1.7257-02	1.8220-02	1.4467-04	1.8365-02	3.5372-02
10.	1.7094-02	1.3185-04	1.7226-02	1.8248-02	1.4468-04	1.8393-02	3.5770-02
100.	1.7093-02	1.3185-04	1.7225-02	1.8248-02	1.4468-04	1.8392-02	3.5771-02
500.	1.7089-02	1.3183-04	1.7221-02	1.8244-02	1.4466-04	1.8388-02	3.5763-02
1000.	1.7085-02	1.3181-04	1.7216-02	1.8239-02	1.4464-04	1.8383-02	3.5754-02
1500.	1.7080-02	1.3179-04	1.7212-02	1.8234-02	1.4462-04	1.8379-02	3.5745-02
3000.	1.7066-02	1.3173-04	1.7197-02	1.8219-02	1.4456-04	1.8364-02	3.5716-02
5000.	1.7047-02	1.3165-04	1.7178-02	1.8200-02	1.4448-04	1.8344-02	3.5679-02
10000.	1.7000-02	1.3146-04	1.7131-02	1.8151-02	1.4429-04	1.8295-02	3.5585-02
15000.	1.6952-02	1.3126-04	1.7084-02	1.8102-02	1.4408-04	1.8246-02	3.5492-02
20000.	1.6905-02	1.3106-04	1.7036-02	1.8053-02	1.4387-04	1.8197-02	3.5399-02
25000.	1.6858-02	1.3086-04	1.6989-02	1.8003-02	1.4366-04	1.8147-02	3.5306-02
30000.	1.6774-02	1.3052-04	1.6905-02	1.7975-02	1.4331-04	1.8118-02	3.5504-02
35000.	1.6727-02	1.3029-04	1.6857-02	1.7921-02	1.4306-04	1.8064-02	3.5339-02
40000.	1.6680-02	1.3007-04	1.6810-02	1.7869-02	1.4283-04	1.8012-02	3.5226-02
45000.	1.6634-02	1.2986-04	1.6763-02	1.7818-02	1.4260-04	1.7960-02	3.5111-02
50000.	1.6587-02	1.2964-04	1.6717-02	1.7766-02	1.4236-04	1.7908-02	3.4996-02
55000.	1.6540-02	1.2942-04	1.6670-02	1.7714-02	1.4213-04	1.7857-02	3.4880-02
60000.	1.6494-02	1.2920-04	1.6623-02	1.7663-02	1.4189-04	1.7805-02	3.4763-02
65000.	1.6447-02	1.2898-04	1.6576-02	1.7611-02	1.4164-04	1.7753-02	3.4647-02
70000.	1.6401-02	1.2876-04	1.6530-02	1.7560-02	1.4140-04	1.7701-02	3.4529-02
75000.	1.6355-02	1.2854-04	1.6483-02	1.7508-02	1.4115-04	1.7649-02	3.4412-02
80000.	1.6309-02	1.2832-04	1.6437-02	1.7456-02	1.4090-04	1.7597-02	3.4294-02
85000.	1.6263-02	1.2809-04	1.6391-02	1.7404-02	1.4065-04	1.7545-02	3.4176-02
90000.	1.6217-02	1.2787-04	1.6345-02	1.7353-02	1.4040-04	1.7493-02	3.4057-02

TABLE 8.

PRELIMINARY DEGRA PREDICTIONS OF GALILEO RESULTS FOR
LONG OPERATING TIMES (OUT TO 90,000 HRS)

```

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
X      THIS IS A TEST CASE FOR DEGRA2 USING..      X
X      SELENIDE DATA **GALILEO GEOMETRY**..      X
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

```

```

XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
X      TEMPERATURE CHARACTERISTICS..      X
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

```

TIME (HOURS)	N TYPE HOT JUNCTION TEMPERATURE	P TYPE HOT JUNCTION TEMPERATURE	N TYPE COLD JUNCTION TEMPERATURE	P TYPE COLD JUNCTION TEMPERATURE	AVERAGE RADIATOR TEMPERATURE	INPUT HEAT (WATTS)
0.	1131.30	1131.17	433.12	433.12	408.12	7.3214
10.	1134.41	1134.28	433.33	433.33	408.33	7.3213
100.	1134.39	1134.26	433.32	433.32	408.32	7.3207
500.	1134.19	1134.06	433.29	433.29	408.29	7.3181
1000.	1133.95	1133.82	433.24	433.24	408.24	7.3149
1500.	1133.70	1133.57	433.20	433.20	408.20	7.3116
3000.	1132.97	1132.84	433.07	433.07	408.07	7.3018
5000.	1131.99	1131.86	432.90	432.90	407.90	7.2888
10000.	1129.56	1129.43	432.47	432.47	407.47	7.2563
15000.	1127.14	1127.01	432.04	432.04	407.04	7.2240
20000.	1124.72	1124.60	431.61	431.61	406.61	7.1918
25000.	1122.32	1122.20	431.18	431.18	406.18	7.1598
30000.	1123.24	1123.11	430.96	430.96	405.96	7.1279
35000.	1120.62	1120.49	430.52	430.52	405.52	7.0961
40000.	1118.17	1118.05	430.09	430.09	405.09	7.0645
45000.	1115.72	1115.60	429.66	429.66	404.66	7.0330
50000.	1113.28	1113.16	429.23	429.23	404.23	7.0017
55000.	1110.85	1110.73	428.80	428.80	403.80	6.9705
60000.	1108.42	1108.30	428.37	428.37	403.37	6.9394
65000.	1105.99	1105.88	427.94	427.94	402.94	6.9085
70000.	1103.57	1103.46	427.52	427.52	402.52	6.8777
75000.	1101.16	1101.05	427.09	427.09	402.09	6.8471
80000.	1098.76	1098.64	426.67	426.67	401.67	6.8166
85000.	1096.36	1096.24	426.24	426.24	401.24	6.7862
90000.	1093.96	1093.85	425.82	425.82	400.82	6.7560

III. THERMOELECTRIC GENERATOR TEST AND EVALUATION

Thermoelectric generators, representing recent and advanced technology, assembled with lead telluride, TAG-85 and silicon-germanium materials are being tested at JPL. These generators are: The HPG (PbTe), and the Ring Converter (P-side PbSnMnTe/BiSbTe, N-side 2N-PbTe). Also, generator Q1-A (SiGe), representative of the MHW type generators, was on test during this reporting period.

A. High Performance Generator HPG S/N2

This generator has operated for a total time of 39,473 hours. During the test 1,796 hours operation the generator power has decreased by 1.4 watts, to its present value of 132.7 watts. During the same period of operation, the generator open circuit voltage and internal resistance has also slightly decreased. ($E_{oc} = 25.34 \text{ volts} \pm 0.05 \text{ volts}$, $R_{int} = 1.16 \text{ ohms} \pm 0.05 \text{ ohms}$). The generator hot junction temperature and cold junction temperature were $AVGT_H = 1012^\circ\text{F} \pm 5^\circ\text{F}$ $AVGT_C = 362^\circ\text{F} \pm 3^\circ\text{F}$.

The generator degradation rate for the last 5000 hours of operation was 0.51%/1000 hours. The generator history is illustrated in Figure 24.

B. Ring Converter

This generator has operated for a total accumulated time of 35,105 hours. During the last 1827 hours of operation the generator output power has remained the same at 12.38 watts. The generator open circuit voltage, internal resistance, hot and cold junction temperatures has also remained practically the same during that period of operation.

($E_{oc} = 4.09 \text{ volts} \pm 0.05 \text{ volts}$, $R_{in} = 329 \text{ milliohms} \pm 5 \text{ milliohms}$, $AVGT_H = 447^\circ\text{C} \pm 5^\circ\text{C}$ and $AVGT_C = 169^\circ\text{C} \pm 3^\circ\text{C}$)

In the last 5000 hours of operation there was no change in the generator performance characteristics. The generator history is illustrated in Figure 25.

C. MHW Generator Q1-A

This generator has operated for a total time of 10,946 hours. During the last 2,060 hours of operation the generator output power has decreased by 1.30 watts, to its present value of 138.6 watts. In that source period of operation the generator open circuit voltage and internal resistance was slightly increased. ($E_{oc} = 56.80 \text{ volts} \pm 0.05 \text{ volts}$, $R_{int} = 5.79 \text{ ohms} \pm 0.05 \text{ ohms}$)

The generator heat source and case temperature has remained the same.
 $AVG T_H = 1037^\circ\text{C} \pm 5^\circ\text{C}$, $AVG T_C = 263^\circ\text{C} \pm 3^\circ\text{C}$)

The generator degradation rate for the last 5000 hours of operation was 0.47%/1000 hours. The generator performance history is illustrated in Figures 26 and 27.

IV. IHW Flight Performance

A. Power Performance Comparisons for LES 8 and 9 RTGs

This information is furnished by Lincoln Laboratories on a quarterly basis. The power output of the four LES 8 and 9 RTGs has been compared with the calculated output of DEGRA up to a mission time of 24,366 hours. The comparison is shown in Figures 28 and 29. For details of the DEGRA calculations, the reader is referred to Progress Report No. 23, September 1977. Based on the initial performance of these RTGs, the BOI age of RTG-1 on LES-8 and RTGs-1 and 2 on LES-9 was 1500 hours and the BOI age of RTG-2 on LES-8 was 500 hours. The degradation rate of RTG-1 on LES-8 and RTG-2 on LES-9, see Figure 28, show excellent agreement with the DEGRA calculation using a silicon nitride coating lifetime of 100,000 hours. RTG-1 on LES-9 has a slightly higher degradation rate, but still shown reasonably good agreement with the 100,000

FIGURE 25.

FIGURE 26.

HISTORY OF MHW, ETG, Q1-A

ORIGINAL Q_{IN} 2400 WATTS E_{OUT} 30 VOLTS

FIGURE 27.

FIGURE 28.

Comparison of LES 8/9 RTG Power with DEGRA

Figure 29.

Comparison of LES 8 RTG Power with DEGRA

hours coating lifetime curve. RTG-2 on LES-8, see Figure 29, shows excellent agreement with the DEGRA calculation using a silicon nitride coating of 100,000 hours.

B. Power Performance of Voyager 1 and Voyager 2 Flight RTG's

This information is provided by the Voyager Flight Project at JPL. The six thermoelectric generators which provide the power for the Voyager spacecraft are of the same type and design as are used on the LES-8 and LES-9 spacecraft. A comparison of the Voyager RTG's power output versus that predicted by DEGRA has been made. For details of the DEGRA calculations the reader is referred to Progress Report No. 23, September 1977. Based on the initial performance of the RTG's on both Voyager 1 and 2, the Beginning Of Mission (BOM) age of all the RTGs was determined to be 1500 hours. The ratio of the output power to the original power at launch (P/P_o) of the RTG's on Voyager 1 and Voyager 2 is compared to the DEGRA data normalized to a Beginning Of Mission (BOM) "age" of 1500 hours, in Figures 30 and 31. The output data of the RTGs has been taken from a best "hand" fit curve of the actual data. During the next reporting period, a computer analysis of the "curve fit" of the actual data will be undertaken. The degradation rate of the three RTG's on Voyager 1 shows excellent agreement with the DEGRA calculations using a silicon nitride coating lifetime of 100,000 hours, see Figure 30. The degradation rate of the two RTG's on Voyager 2 also show excellent agreement with the DEGRA calculations using a silicon nitride coating lifetime of 100,000 hours, see Figure 31. For information the plots of the "raw" data versus time, as previously reported, for Voyager 1 and Voyager 2 are shown in Figures 32 and 33. The accrued time and power output of the RTG's is listed on the following page:

Voyager 1 - 12,093 hours (Δ hours - 2832)

RTG-1	F-8	148.5 watts
RTG-2	F-6	149.3 watts
RTG-3	F-9	151.2 watts
RTG's Total		449.0 Watts

Voyager 2 - 12,624 hours (Δ hours - 2832)

RTG-1	F-10	153.0 watts
RTG-2	F-12	151.8 watts
RTG-3	F-11	Telemetry - Not Operating

FIGURE 30.

COMPARISON OF VOYAGER-1 RTG POWER WITH DEGRA

FIGURE 31.

COMPARISON OF VOYAGER-2 RTG POWER WITH DEGRA

FIGURE 32.

FIGURE 33.