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PROGRESS REPORT NO 39
FOR A PROGRAM OF
THERMOELECTRIC-GENERATOR TESTING
AND
RTG DEGRADATION-MECHANISMS EVALUATION

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January 1981

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RTG DEGRADATION-MECHANISMS EVALUATION

Submitted to

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Washington D.C.

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FOREWORD

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-December 1980 performed under the technical direction of Mr. Patrick O'Riordan Power Systems Branch, Space and Terrestrial Systems Division of the DOE Office of Advanced Nuclear Systems and Projects.

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SECTION I

SUMMARY

Two neodymium selenide n-type legs and two new p-type Cu-Se legs have been setup for testing.

Weight loss measurements for coated Si-Ge material produced by G.E. are reported. The coating on the n-type Si-Ge legs and the n-type side of the Si-Mo hot shoes has disappeared. The coating on the p-type side of the Si-Mo hot shoes has almost completely degraded. It is unlikely that the G.E. coatings have ever been effective. Thermal conductivity measurements are in agreement.

The remaining MHW generator on test, Q1-A, has accumulated 28,600 hours and performance remains stable. The performance of the 18 couple modules remains stable. The S/N-1 module has accumulated 30,000 hours and the S/N-3 module has reached 27,300 hours.

Telemetry data indicate no changes in the trends of degradation of LES 8 and 9 and the Voyager RTGs.

SECTION II

SELENIDE TECHNOLOGY EVALUATION

A. INGRADIENT TESTING

Two neodmium selenide n-type legs have been setup for test together with two new p-type Cu-Se legs. The refurbishment of the instrumentation for the p-legs already tested for 8,500 hours will be accomplished in the next reporting period.

SECTION III

SILICON GERMANIUM MATERIALS TECHNOLOGY

A. SUBLIMATION OF Si-Ge PRODUCED BY GE

The samples of early silicon-germanium production submitted by GE are continuing under test for verification of their thermoelectric and physical properties. Sublimation data for Si_3N_4 coated components is presented in this report. The weight loss results for the uncoated 78-22% Si-Ge at 1150°C is presently undergoing analysis. Figures 1 and 2 show the weight loss results for two samples each of 78-22% Si-Ge, n and p type legs respectively. Each of these samples have undergone testing at 1000°C for 2,357 hours. The corresponding loss rates for the last 1,627 hours are shown in Figure 3. This rate was 3.7×10^{-7} mg/cm²-hr for both the n-type samples. The data shows that the coating on the n-type material has come off while that of the p-type material remains intact. This was confirmed when the samples were removed from the furnace for weight measurements.

The data presented in Figures 1 and 2 show that all sample outgassing has essentially occurred within approximately the first 50 hours of testing. The average loss rate of 1.5×10^{-7} mg/cm²-hr for the n-type samples from 50 hours to 730 hrs is about six times higher than previous tests conducted on RCA material for a corresponding length of time. This says that the coating was only partially intact during this period. The intermittent manner in which weight loss measurements are made prevents the exact determination of the time when the coating became completely ineffective, but this is most likely between 700 and 800 hours.

Figure 1. Sublimation, Silicon Nitride Coated Legs N-Type

Figure 2. Sublimation, Silicon Nitride Coated Legs, P-Type

Figure 4 shows the weight loss results for three Si_3N_4 coated SiMo hot shoes at 1200°C, 1150°C, and 1100°C for 2,771 hours. The corresponding loss rates for the last 1,416 hours are shown in Figure 5. These rates are 3.9×10^{-5} , 2.3×10^{-5} , and 9.1×10^{-6} mg/cm-hr for 1200°C, 1150°C, and 1100°C respectively. The coating on all three samples is observed to have lost its effectiveness. This was confirmed when the samples were removed from the furnace for weight loss measurements. The coating on the n-doped half of each hot shoe had completely come off. The coating on the p-doped half of the 1150°C and 1100°C samples was observed to have visibly deteriorated. The coating on the p-doped half of the 1200°C sample was essentially intact. This is the reason that the measured loss rate is about 0.4 that of uncoated SiMo; a half-coated hot shoe will produce a loss rate which is about 0.5 of the uncoated rate. During the last 400 hours of testing the maximum furnace temperature achieved was 1190°C for the 1200°C sample. An "expected" actual loss was therefore used in calculating the loss rate since no deviation from the weight loss trend from the last period was observed for the other two samples.

Since the coating on the p-doped side of the 1200°C hot shoe was more intact than that of either of the lower temperature samples, this would imply that the material preparation process is inconsistent at some stage. In addition, Figure 5 shows that the average loss rates for the first 730 hours are significantly higher than those measured for RCA material. This would seem to say that either the weight loss characteristics of the GE material are not as good as the RCA material or that the coating on the GE material has never been completely effective. Testing has been discontinued on these hot shoe samples.

Figure 4. Sublimation, Silicon Nitride Coated SiMo Hot Shoes

Figure 5. SiMo Loss Rate, Silicon Nitride Coated Hot Shoes

B. THERMAL CONDUCTIVITY TESTS

Thermoconductivity measurements are continuing on 78-22% n- and p-type Si-Ge samples. Present tests have been conducted for over 2,500 hours at $T_H = 750^\circ\text{C}$ and $T_C = 450^\circ\text{C}$. The data from this test is presented in Figure 6. There continues to be no deviation from the trends measured for the earlier RCA material.

Figure 6. Thermal Conductivity, P-, N-Type SiGe, 78% Si, vs Time

SECTION IV

THERMOELECTRIC GENERATOR TEST AND EVALUATION

Thermoelectric generators, representing recent and advanced technology, assembled with lead telluride, TAGS-85, and silicon-germanium materials have been tested at JPL. At present one generator, the Q1-A(SiGe), representative of the MHW type generators, is on test. Three 18 couple modules (S/N-1, S/N-2, S/N-3) that were extensively tested at RCA were received for JPL evaluation in support of the Galileo Program. Both the S/N-1 and the S/N-3 generators were on test during this reporting period.

A. MHW GENERATOR Q1-A

This generator has operated for a total time of 28,521 hours. During the last 1,724 hours of operation there has been no significant change in the generator power out. Presently the generator power out is 129.6 watts. The open circuit voltage and internal resistance also show no significant change. Presently these values are 57.20 volts and 6.30 ohms. The generator heat source temperature has increased from $\text{AVG } \bar{T}_H = 1024^\circ\text{C}$ to $\text{AVG } \bar{T}_H = 1028^\circ\text{C}$. The case temperature is no longer measured due to an instrument malfunction.

The shunt resistance history is presented in Figure 7. The present trend in the value of the shunt resistance has remained consistent.

The maximum power output which would occur without the loss due to the shunt conductance between the module and the insulating foil is shown in Figure 8. The maximum power output is that which would occur with zero electrical

Figure 7. Shunt Resistance History, Generator Q1-A

Figure 8. Shunt Resistance Power Loss, Q1-A

leakage to the insulating foil. The power ratio is also present in the same figure. The present calculated $P_{\max}$ is 131.2 watts compared to an actual power out of 129.6 watts. This continues to represent a one percent loss in power.

The generator life history is illustrated in Figures 9 and 10. The generator degradation rate for the last 5,000 hours of operation was 0.26 percent/1,000 hours. The corresponding generator degradation rate obtained using the DEGRA2 RTG degradation model for uncoated unicouples is 0.27 percent/1,000 hours for the same period of operation. The Q1-A generator and the DEGRA2 code are in excellent agreement. Figure 11 shows power output versus $\sqrt{\text{time}}$. Parametric test results are shown in Figure 12. The present operating point is observed to be approximately 1% below the maximum producible power level.

B. 18 COUPLE MODULES S/N-1, 3

Module S/N-1, has operated for a total time of 29,994 hours. The last 10,578 hours of operation have been at JPL. During the last 1,485 hours of operation the module power out has not significantly changed. Presently the module output power is 9.48 watts. There has been no significant change in the value of either the open circuit voltage or the internal resistance ($E_{oc} = 7.57$ volts and $R_{int} = 1.51$ ohms).

The hot junction temperature is not measured since the hot shoe thermocouples were not functional at the start of the present test. The module cold junction temperature has remained essentially the same at $\text{AVG } \bar{T}_C = 306^\circ\text{C}$.

The shunt resistance between the 18-couple circuit and the thermal insulating foil is shown in Figure 13. This value is presently 2,440 ohms and does

Figure 9. Q1-A History

Figure 10. Q1-A History

Figure 11. Q1-A Power Out Versus $\sqrt{\text{Time}}$

Figure 12. Parametric Test of Q1-A

Figure 13. S/N-1 Shunt Resistance, Module to Foil

not noticeably affect the power loss as shown in Figure 14 where the calculated maximum power output without shunt losses is compared to the actual power output. There continues to be no significant power loss due to shunt resistance.

The module life history is illustrated in Figure 15. The present performance is stable and the degradation rate for the last 5,000 hours of operation was 0.37 percent/1,000 hours. Parametric test results are shown in Figure 16. These results show that the module is operating approximately 2% below its maximum producible power level.

Module S/N-3 has operated for a total time of 27,292 hours. The last 5,485 hours of operation have been at JPL. During the last 1,681 hours of operation the power output has decreased by 0.19 watts to its present value of 8.06 watts. The open circuit voltage and the internal resistance have shown a slight change. Their present values are $E_{oc} = 6.84$ volts and $R_{int} = 1.45$ ohms. The cold junction temperature was stable during this period and had the value $AVG \bar{T}_C = 284^{\circ}C$.

The shunt resistance between the 18-couple circuit and the thermal insulating foil is shown in Figure 17. This value is presently 106,800 ohms and has no significant effect on the power loss as is observed from Figure 18 where the calculated maximum power output without shunt losses is compared to the actual power output.

The module life history is illustrated in Figure 19. The present performance is essentially stable. The generator degradation rate for the last 5,000 hours of operation was 0.49 percent/1,000 hours although the rate for the last 1,000 hours was less than 0.10 percent. Parametric test results are shown

Figure 14. S/N-1 Shunt Resistance Power Loss

Figure 15. 18 Couple Module S/N-1 Test History

Figure 16. 18 Couple Module S/N-1 Parametric Test

Figure 17. S/N-3 Shunt Resistance, Module to Foil

Figure 18. S/N-3 Shunt Resistance Power Loss

Figure 19. B Couple Module S/N-3 Test History

in Figure 20. The present operating point is observed to be about 1 percent below the maximum producible power level.

Figure 20. 18 Couple Module S/N-3 Parametric Test

SECTION V

MHW FLIGHT PERFORMANCE

The power output of both the LES 8 and 9 spacecraft MHW generators continue to follow the performance trend predicted by the DEGRA2 code as presented in the July 1980 report. Both Voyager spacecraft MHW generators show no significant change in performance. The life histories of both Voyager spacecraft generators are presented in Figures 21 and 22.

Figure 21. Voyager I Power, Normalized to BOM

Figure 22. Voyager II Power, Normalized to BOM