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SILICON GERMANIUM (SiGe) RADIOISOTOPE THERMOELECTRIC GENERATOR (RTG) PROGRAM FOR SPACE MISSIONS

FIFTEENTH TECHNICAL PROGRESS REPORT
CONTRACT DE-ACO1-79ET-32043

PERIOD FROM 1 THROUGH 31 AUGUST 1980

space division

GENERAL ELECTRIC

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RADIOISOTOPE THERMOELECTRIC GENERATOR (RTG)
PROGRAM FOR SPACE MISSIONS**

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PERIOD FROM 1 THROUGH 31 AUGUST 1980

Prepared for

**DEPARTMENT OF ENERGY
ADVANCED NUCLEAR SYSTEMS AND PROJECTS
WASHINGTON, D.C.**

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30 September 1980

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SUBJECT: CONTRACT DE-AC01-79ET32043
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Sincerely,

A. R. Carrazzone
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FIFTEENTH MONTHLY PROGRESS REPORT
1 THROUGH 31 AUGUST 1980

SILICON GERMANIUM (SiGe)
RADIOISOTOPE THERMOELECTRIC GENERATOR (RTG)
PROGRAM FOR SPACE MISSIONS

CONTRACT DE-AC01-79ET-32043

1.0 INTRODUCTION

This report, submitted by the General Electric Company, describes work accomplished during the reporting period on the DOE Silicon Germanium RTG Program, Contract DE-AC01-79ET-32043. This program consists of the following three tasks:

Task 1 - Multi-Hundred Watt RTG for the Galileo Probe Mission

Task 2 - Reestablishment of Silicon Germanium Unicouple Capability

Task 3 - General Purpose Heat Source RTG for the International Solar Polar and Galileo Orbiter Missions.

Details of program progress for each task, including a milestone schedule and a discussion of current problem areas (if any) are presented in the following sections.

2.0 GALILEO PROBE RTG

2.1 PROGRAM MANAGEMENT AND CONTROL

The Quarterly Program Review was held at JPL on August 13 and 14 to review RTG program status.

DOE visited GE on August 14 and 15 to discuss program status. Major program emphasis continues to be placed on the qualification test program and preparations for converter assembly due to start in September.

Assembly of the Q-2, Qualification Test Module, was completed. The unit was installed in the thermal vacuum chamber and engineering tests of the ACS system started. The predicted average shell temperatures (using JPL flow rates) were not met. The cooling tube to fin fastening screws will be retorqued (to higher values) and additional testing will be conducted.

Component level testing was accomplished on the assembled PRD. Minor modifications to the design will be made in order to reduce pull force at the maximum misalignment actuation direction. The specification will also be modified to increase the maximum pull force from 2 to 5 pounds. Ames has concurred with this change.

The foil insulation area has been completed and the work started on the Galileo Probe end cap foils. (Figure 2.1-1.)

2.2 HEAT SOURCE LIAISON, INTERFACE AND HANDLING

During processing of two FWPF aeroshell end cap billets, an electric short occurred in the process oven heater. During cooldown after heater failure, pitch leaked from the container housing the billets. The billets were cleaned and inspected, and found to have no apparent degradation due to the process failure.

An AVCO inspection report No. 18336 was written and forwarded to the GE MRB. The Board concurred with AVCO's recommended processing instructions subject to the stipulation that the concurrence will be at no risk to GE (i.e., the material furnished in the performance of the Galileo Contract must meet all the requirements of GE-AEPD Specification NS0060-01-20, Rev. A).

2.3 JPL LIAISON AND INTERFACE

ARC was contacted and verbal agreement reached over the maximum pull allowed for actuation of the PRD. The GE request was for an increase to 5 pounds.

2.4 RTG DESIGN AND ANALYSIS

2.4.1 AUXILIARY COOLING SYSTEM (ACS)

Engineering performance testing in the thermal vacuum test facility revealed that insufficient conductance existed at the fin/coolant tube interface. Insufficient heat was absorbed by the coolant water, consequently the target average case surface temperature of 100°C was not met. These test results are discussed in Paragraph 2.12.2.

The original design of the ACS coolant tubes used Belleville washers to limit the bolt loads. The reason for limiting the bolt loads was to insure that sliding of the bolts could take place during thermal expansion. If the bolts were torqued at room temperature and the sliding prevented the resultant tension in the beryllium fin would be approximately 20,000 psi.

During testing, it was found that the clamping force, as limited by the Belleville washers, was not sufficient to provide adequate heat transfer. The bolt torque was then increased completely flattening the Belleville washers. At a bolt torque of 39 in-lbs (about 1380 pounds force), the heat transfer of the joint was satisfactory.

The original intent of the design to allow movement to account for differential thermal expansion cannot be assured with the high clamping force. Assuming no sliding of the aluminum with respect to the beryllium fin, a compressive stress in the beryllium during launch can be assured if the bolts are torqued at a temperature higher than that expected at launch. Therefore, the torquing procedure for the flight units will be:

- Torque bolts to 39 in-lbs at room temperature.
- After thermal vacuum testing and with the fins and coolant tubes at about 90°F hotter than launch, loosen the bolts (about 7-9 in-lbs of torque). Then, with the fins and coolant tubes maintained at this temperature, retorque the bolts to the 39 in-lbs.
- The spring washers will be deleted from the design.

With this procedure and assuming no motion due to differential thermal expansion, the maximum differential stress in the beryllium will not exceed 6000 psi in compression.

2.4.2 CONVERTER VENTING (PRD)

PRD performance tests were initiated. Nominal force of about one pound is required to actuate the PRD except in the lateral misalignment mode. At six to eight degree misalignment the force required reached about 5 pounds. The specification is 2 pounds maximum force. The PRD was de-accepted for engineering evaluation. The increased force was due primarily to physical interference of the actuation pin mechanism and the PRD housing and plunger tube. Some of the additional force is due to the sliding friction present when a lateral force component results from the misalignment.

The PRD design was slightly modified to provide adequate clearance for the actuation pin mechanism in all misalignment modes. The PRD was then reassembled and tested. Maximum

actuation force in the worst condition of eight degrees lateral misalignment was measured in the 3 to 4 pound range. The specification was changed, with the user's concurrence to allow a maximum force of 5 pounds.

At the end of this reporting period, the PDR was being inspected for reacceptance as the qualification unit.

2.4.3 INSTRUMENTATION CABLE ASSEMBLY

An engineering and manufacturing review was conducted to evaluate the manufacturing development needs for the instrumentation cable. Slight changes in the shield wrapping and end terminations were identified as improvements. The improved manufacturing techniques will be employed on the Qualification Module G2 configuration prior to dynamic testing.

2.4.4 PROOF TEST OF QUALIFICATION MODULE HEAT SOURCE END CAPS

Static load proof tests of the heat source end caps for the Qualification Module vibration tests have been successfully completed. The caps were tested for longitudinal loads up to 3000 pounds using the test configuration described in the previous progress report. The 3000 pound load condition provided a factor of safety of 2 for a longitudinal vibration response of 50 G's. The caps were subjected to an alcohol crack detection examination following the tests to verify that all surfaces were free of cracks.

2.4.5 ASSESSMENT OF SAFETY OF RTG CASE ON A PRESSURE VESSEL

A conservation analysis of the RTG case has been performed to determine if the case acting as a pressure vessel provides an adequate margin of safety to meet the STS safety requirements. NASA requires a minimum margin of safety of 0.4 on ultimate strength. Based on the most severe temperature and pressure differential conditions, the calculated margin of safety is 0.74, exceeding the NASA requirements.

2.5 SYSTEM TESTING AND RTG FUELING

An intermittent leak in the Loading Assembly Station (LAS) Gas Management System (GMS) caused by a hairline crack in the body of the flow meter in the oxygen analyzer was found. A new flow meter has been ordered.

The LAS Facility SI 249697 is being reviewed.

The Generator Shipping Container (GSC) SI 249229 and the ETG processing procedure are completed and being reviewed.

Changes to the Read Out Console (ROC) System checkout SI 249656 are in process.

The system test policy document (GESp7142) has been prepared. A draft is being readied for DOE.

2.6 GROUND SUPPORT EQUIPMENT

2.6.1 QUALIFICATION MODULE

The Qualification Module was placed in the thermal vacuum chamber in the Long Life Facility for general performance testing of the ACS. The Qual Module was configured as G1 of 47J305628.

2.6.2 IHS SIMULATOR

The IHS Simulator Loading Fixture was calibrated with a load cell in preparation for "setting" and preloading the IHS Simulator internal graphite components.

The IHS Simulator end caps were static load tested to 3,000 pounds per PIR 6221. The load tests were performed on an Instron machine at load application rate of 0.02 inch per minute. Inspection revealed no degradation due to the static load, and the end caps were deemed acceptable for the IHS Simulator which will be used in the Qualification Module for dynamic testing. The static load test results are documented in PIR 6229.

The IHS Simulator was then built up in accordance with PIR 6219, except the forward end cap had not been assembled at the end of this reporting period.

2.6.3 RTG SHIPPING CONTAINER (RTG-SC)

The envelope of the MHW RTG for the Galileo (GLL) Probe Mission has increased due to the auxiliary cooling system, the pressure relief device and the instrumentation connector. Accommodation of these changes has required a shift of the location of the cg of the RTG in the RTG shipping container and a reduction in the clearances between the RTG and the wall of this shipping container. The results of analysis of the allowable drop height of the resulting configuration indicate that the 18-inch drop specified in MIL SPEC 810 will result in impacting between the RTG and the shipping container. Allowing for a 10 percent margin of safety, the allowable drop height should be reduced to 13.7 inches. To avoid major redesign of the shipping containers, derating of the permissible drop height from 18 inches to 13.7 inches is being considered.

2.6.4 ACS COOLANT MANAGEMENT CONSOLE (ACS-CMC)

Fabrication of the ACS-CMC has been completed. An acceptance test was performed and the CMC did not pass, due primarily to flow meter variations, coolant leakage and safety interlock settings. However, all functional performance requirements were tested and met. Maximum coolant temperature supply of 375°F was achieved as well as a heat removal capability of the required 14,000 Btu/hr. The CMC is capable of supplying coolant up to 1.1 gpm with a pressure drop of 15 psi on the ACS.

The vendor is in the process of correcting the deficiencies noted.

2.7 MANUFACTURING

The following is a summary of the manufacturing activities during the reporting period:

- Assembly of F-13 Auxiliary Cooling System (ACS) was started.
- Hardware for the F-13 gas management valve was cleaned and deburred and submitted for C of I.
- Hardware for the F-13 Pressure Relief Device (PRD) was cleaned and deburred and submitted for C of I.
- Refurbishment of the F-13 Electric Heat Source (EHS) was started.
- Assembly of the IHS Simulator for qual module was started.

2.8 QUALITY ENGINEERING AND CONTROL

Engineering tests of the ACS cooling has been initiated on the Q-2 Module. Initial test results showed less-than-optimum heat transfer from the shell to the cooling loop. The cooling loop clamping devices are being tightened to correct this deficiency.

Initial tests of the Cooling Management Cart showed that additional modifications are required. There were leaks in the system and the operation of the regulator and temperature switch were not satisfactory.

Initial checkout of the 2nd Read Out Console has been completed. Some troubles were experienced with the data logger. A test of the 2nd Power Supply Console was completed.

Pressure decay tests and insulation resistance tests for F-1E Converter, following drilling of the ACS mounting holes, showed the unit was acceptable. Similar tests on F-13 showed a high leak rate - this is consistent with previous storage data.

Material Review Board activity is summarized in Table 2.8-1.

2.9 RELIABILITY ASSESSMENT

No work was planned or performed on this task in this reporting period.

2.10 SAFETY ASSESSMENTS

A request was placed to purchase 26 additional GIS's (i.e., 24 per HSA plus 2 spares) of the MHW/Galileo design for use in the heat source systems impact test. This was deemed necessary to preclude consideration by the vendor (HITCO) of closing out their production capability. HITCO is currently completing the final order from Mound for GIS's for the MHW/Galileo Probe RTG's.

Table 2.8-1. Galileo (Probe)

Nonconformance Report	Item	Discrepancy	Disposition
48574	Pressure Dome	1) Minor Dimensional Discrepancies 2) Cleanliness	Accept
48575	Bearing Sleeve	Minor Dimensions	Accept
48678	PRD Safety Pin	Dimensions	1) Rework 2) Accept
48679	Clamp	Dimensions	Accept
48683	Wafer	Minor Surface Defect	Accept
48693	Gas Mgmt. Assy.	Minor Weld Defect	Accept
48708	C-Seals	Failed Sample Adhesion Tests	Return to Vendor
48709	C-Seals	Failed Sample Adhesion Tests	Return to Vendor

2.11 FIELD AND LAUNCH SUPPORT

No effort planned or undertaken.

2.12 COMPONENT DEVELOPMENT AND RELIABILITY TESTING

2.12.1 PRD

As reported in Paragraph 2.4.2, the PRD Performance Tests (Specification NS 0010-13-26) resulted in actuation force above specification limit for the lateral 8-degree misalignment condition.

The PRD Actuation Pin Mechanism performance tests are conducted per SI 249709. The test configuration is a complete PRD component mounted in a fixture on a laboratory bench. The PRD is heated to $220^{\circ}\text{C} \pm 10^{\circ}\text{C}$. The actuation pin mechanism is pulled and the force measured by a calibrated dial force indicator.

The maximum force recorded in the nominal and longitudinal misalignment planes was 1.4 pounds. The specification limit of 2 pounds was exceeded, however, when the actuation pin mechanism was pulled in the 8-degree lateral misalignment mode.

The PRD was returned to Engineering for design modification, and is expected to be resubmitted for testing next month.

2.12.2 ACS

ACS engineering tests have been completed. Initial tests were conducted using JPL Interface Specification GLL ES 512280. Coolant flow rates of 5 ± 1 lb/min at inlet temperatures of 21°C and 30°C were test inputs. Average qual module shell temperatures in vacuum ranged from 113°C (6 lb/min at 21°C) to 122°C (4 lb/min at 30°C). These exceeded the required maximum average shell temperature of 100°C . Examination of the temperature distribution showed the main resistance to heat flow occurred at the fin/coolant tube interface. Shim softness was verified to be similar to those used in preliminary tests.

Improvement in heat transfer across this interface could be achieved by increasing the fin/tube clamping pressure. Torque on all ACS cooling tube screws was increased to 23 in-lbs, but performance improved only slightly. ACS flow was then terminated and qual module was permitted to reach steady state temperatures in vacuum with the EHS powered at 2300 watts. This was done to allow the coolant tube shins to "set" and simulate actual conditions seen during prime RTG fueling operations (without ACS operating).

Performance tests were then redone. Average shell temperature during worse case coolant inlet conditions (i.e., 4 lb/min at 30°C) fell from 122°C to 113°C .

After an analysis of screw and fin stresses it was determined that the cooling tube screw torque could be increased to 400 in-lbs. Also, the Ames Galileo Probe Specification JP-632 provides for the division of the allotted RTG coolant between two RTG's as opposed to the three specified in the JPL specification. This effectively increases the available coolant from 5 lb/min to 7.5 lb/min nominal. Applying a $\pm 5\%$ to the nominal value results in an allowable inlet coolant flow rate range of 7.125 lb/min (minimum) to 7.875 lb/min (maximum). The coolant inlet temperature remained at 21 to 30°C . The Belleville washers were removed since they performed no useful purpose at the higher screw torque values.

An average shell temperature of 100°C was achieved at the low flow, high coolant inlet temperature. Heat removal at these conditions was measured at 1720 watts.

Test data for various flow rates are plotted in Figure 2.12-1. Curves are interpolated between the 21 to 30°C values. As shown, the required average shell temperature is achieved with a minimum flow rate of 7.12 lb/min at a 30°C inlet coolant temperature. Required screw torque of 39 in-lbs and a high temperature "soaking" period was also required.

2.12.3 D5A MODULE

The D5A Module Test Plan was completed.

3.0 SiGe REESTABLISHMENT

3.1 PROGRAM MANAGEMENT

During this reporting period, the brazing problem in cold stack fabrication was resolved. Unicouple fabrication will commence in September. Pellet slicing and grinding are being worked in-house and approval for in-house operation will be sought by the review board in September. Overtime activity is continuing in selective areas, and completion of reestablishment activities is still targeted for October 31, 1980.

Converter 18-1 achieved operating conditions at a hot shoe temperature of 1035°C on August 14, 1980, and its power output was 9.02 watts. It is operating well and has a lower initial degradation rate than predicted.

The program has expanded this month to include technology maintenance activities directed at enhancing unicouple performance. Powder mesh sizes and processing variables are being used as parameters to achieve enhanced properties. Evaluation effort of gallium phosphide silicon germanium is also in progress.

A program review meeting was held with DOE personnel on August 15, 1980. Program schedules and the new technology maintenance tasks were discussed.

The schedule of the reestablishment program is presented in Figure 3.1-1 and program milestones are presented in Table 3.1-1.

3.2 SiGe UNICOUPLE FACILITATION

3.2.1 IDENTIFICATION OF REQUIRED EQUIPMENT

This phase of the program is complete.

3.2.2 EQUIPMENT ACQUISITION

No activity during this reporting period.

3.2.3 INSTALLATION AND CHECKOUT

This phase of the program is practically complete. Five air test stations were installed for testing of single uncouples. A modification of the yarn processing facility was completed this month which provides for a traversing spool on which to wind the yarn. Figure 3.2-1 shows this new coil winding machine as it was modified for our application.

	CY 79						CY 80						CY 81														
	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	
● VACUUM CASTING				F			TV		FTV					PR						Q							
● HOT PRESSING				F				TV						FTV						PR							
● T/E PARTS PREP				F										FTV						PR							
● 1ST BOND COUPLE				F																PR							
● Si ₃ N ₄ COATING				F					TV											FTV							
● 2ND BOND COUPLE				F																PR							
● COLD STACK ASS'Y				F																TV							
● COUPLE PRE-ASS'Y				F																FTV							
● UNICOUPLE ASS'Y				F																TV							
● WRAPPED U/C ASS'Y				F																FTV							
● VERIFICATION MODULES				F																PR							
																				SPD-1							
																				18-1							
																				18-3							
																				18-4							
																				18-5							

Table 3.1-1. Program Milestones

Ident. No.	Description	Completion Date		Comments
		Planned	Actual	
2.1	Complete SiGe Reestablishment Program	11/1/80		
2.1A	Issue Detailed Management Plan	1/20/80	1/20/80	Revision Submitted 2/27/80
2.2	Complete SiGe Unicouple Facilitation	12/31/79	12/31/79	Facilitation for TV Completed
2.3	Complete Technology Verification	10/31/80		
2.3A	Initiate Vacuum Casting Technology Verification	9/1/79	8/20/79	
2.3B	Initiate Test of 18-Couple Converter 18-1 (TV-1)	4/30/80	7/23/80	
2.3C	Complete MHW Unicouple Technology Verification	6/1/80	6/30/80	
2.4	Complete Production Readiness	11/1/80		
2.4A	Initiate Production Readiness for Vacuum Casting	12/1/79	2/5/80	
2.4B	Completion Production Readiness for Vacuum Casting	6/30/80	7/7/80	
2.4C	Initiate 18-Couple Converter 18-3 (SP-1) Test	7/31/80		Revised per Latest Program Revision to 11/80
2.4D	Initiate 14-Couple Dynamic Module SPD-1 Test	8/31/80		
2.4E	Initiate 18-Couple Converter 18-4 (SP-2) Test	9/30/80		Revised per Latest Program Revision to 12/80
2.4F	Initiate 18-Couple Converter 18-5 (SP-3) Test	10/31/80		Revised per Latest Program Revision to 1/81
2.4G	Complete Production Readiness for Unicouple Assembly

Figure 3.2-1. Modified Coil Winding Machine for the Yarn Processing Facility

3.3 TECHNOLOGY VERIFICATION

3.3.1 PROCESS IDENTIFICATION

All processes have been approved for production readiness, and two processes have been approved for prime production, vacuum casting and hot pressing. As each process is evaluated for production readiness status or for production of prime hardware status, items are identified which require correction to the specifications. Most items are of an administrative nature. The following specifications were effected during this reporting period:

<u>Identification No.</u>	<u>Title</u>
M8C1	Molybdenum Sheet
RA11A3-2	Procedure for Fabricating the Wrapped Unicouple
47A303858	Hot Shoe
47E303951-1	Thermopile Foil Insulation
47A303940-1	Fibrous Spacer Panel
47A305309-1	Heater and Susceptor Support Disc

47E303917-2	18-Couple Module
47B303945-1	18-Couple Module Heater Assembly
47D303850-2	Foil Insulation End Cap Assembly
47D303849-3	Foil Insulation End Cap Assembly
47C303942-3	Thermopile Assembly
RQ16E2-1	Parts Inspection Detail - Hot Shoe
CP4A1	Silicon Nitride Coating for Alumina Hot Shoe Spacers

3.3.2 PRIMARY AND SECONDARY MATERIAL

All primary materials and secondary materials have been received and all have been accepted. Actions that took place during this report period were as follows:

- Molybdenum Foil - 0.003" thickness - Material for both 12" wide and 9" wide was bought off. One (1) roll was rejected for surface contamination.
- Molybdenum Sheet - 0.005" thickness - Material was bought off.

There were no MRB actions for material acceptance during this report period.

3.3.3 TOOLING/FIXTURING

No work during the reporting period.

3.3.4 PROCESS REESTABLISHMENT

Process experience is reported in Paragraph 3.4.3.

3.3.5 TECHNOLOGY VERIFICATION MODULE FABRICATION

This task is complete.

3.4 PRODUCTION READINESS

3.4.1 PRODUCTION AND QUALITY CONTROL DOCUMENTATION

All documentation forms required for prime fabrication have been prepared.

3.4.2 TRAINING OF PERSONNEL

Two operators were certified for slicing and grinding of parts during this report period. The table below summarizes operator training status:

<u>Process</u>	<u>Total Number of Certified Operators</u>
Vacuum Casting	3
Powder Blending	1
Vacuum Hot Pressing	2
Seebeck Measurement	3
Density Measurement	3
Slicing and Grinding of T/E Parts	2

3.4.3 PRE-PRODUCTION UNICOUPLE FABRICATION

Vacuum Cast P-Type materials, Lots No. PR-70 through PR-82, were made with a minor air leak in the argon gas feed lines, as reported previously. The material met all criteria for Seebeck and density as a vacuum casting and for resistivity as a hot pressed product. Analysis of the oxygen content of this product has been completed, and the results are given in Table 3.4-1. As can be observed, the results are variable. This is believed to be related to the sample preparation technique for the oxygen activation analysis. All materials had to be reduced to a powder state, which itself could increase the oxygen content. Even where the analyses showed a difference in oxygen level between product made during the air leak and during normal runs, such as in vacuum casting, the differences are not clearly apparent in the next processing sequence - hot pressing. Because no difference in oxygen level was definitely established throughout all processing, it was concluded that the minor air leak had a negligible effect if at all. The similarity of thermoelectric properties for product from both groups supports that contention. No detrimental effects have been observed from this product.

A test plan has been delineated to qualify the new Hot Press, HP-3, for production of prime product. The various materials will be pressed into compacts, as shown in Table 3.4-2, and will be fabricated into unicouples, Table 3.4-3. The materials for this evaluation will be two successive compacts of each type of material, preferably from the same powder blend, which meet the acceptance criteria in Specification M28A1. The SiMo N and P type compacts will then be used to fabricate a N-P SiMo bond which meets the criteria in Specification RM2F2. All of the product made in Hot Press No. 3 will be compared with current product made in HP-2 and critiqued against all applicable specifications.

Table 3.4-4 contains a summary of operations performed during production readiness phase of program.

Table 3.4-1. Oxygen Content (ppm) Silicon Germanium, Silicon-Molybdenum P-Type Alloys

Samples	P-Material		No.	Blend No.	Status	Oxygen ppm
	Form	P-Type				
1	Vacuum Casting *	SiMo	--	102	"AirLeak"	2921
2	Vacuum Casting	78 at % Si	--	99	"AirLeak"	1597
3	N-P Bond (PR224)	SiMo	PR216	98	"AirLeak"	6555
4	N-P Bond (PR201)	SiMo	PR192	85	"AirLeak"	4168
5	N-P Bond (PR188)	SiMo	PR173	85	"AirLeak"	4816
6	Vacuum Casting	100% W + Si	--	94	"AirLeak"	3734
7	HP Compact	78 at. % Si	PR210	99	"AirLeak"	4225
8	HP Compact	78 at% Si	PR211	99	"AirLeak"	4739
9	Vacuum Casting*	SiMo	--	112	--	1488
10	Vacuum Casting	78 at% Si	--	114	--	1149
11	HP Compact	SiMo	MHW	HP-2	--	4326
12	Pellets	78 at% Si	MHW	L1515	--	4665

* Molybdenum metal added to vacuum cast 100% W+Si in preparation for Hot Pressing SiMo alloy

Table 3.4-2. Matrix for Hot Pressing SiGe and SiMo Alloys

Material	Prepared	No. of Compacts	Criteria
SiMo N	RM2E2	2	M28A1
SiMo P	RM2E2	2	M28A1
78 At. % Si N	RM2E2	2	M28A1
78 At. % Si P	RM2E2	2	M28A1
63.5 At. % Si N	RM2E2	2	M28A1
63.5 At. % Si P	RM2E2	2	M28A1
SiMo N-P Bond	RM2F2	2	RM2F2

The following process readiness reviews have been held and the status for each is as follows:

- Cold Stack Assembly

Initial meeting held	May 12, 1980
Start of production readiness	Awaiting parts

- Unicouple Assembly

Initial meeting held	May 30, 1980
Start of production readiness	Awaiting parts

- Wrapped Unicouple Assembly

Initial meeting held	July 3, 1980
Start of production readiness	Awaiting parts

Table 3.4-3. Matrix for the Evaluation of SiGe and SiMo Alloys

	First Bond			Second Bond			Unicouples					
Sample Group	No. of Couples	Elec. Res.	Visual Bond Eval.	No. of Couples	Elec. Res. R_T R_J	Visual Bond Eval.	No. of Couples	Visual & Elec. R_T R_J	3K Test	Hrs. Str.	Beam Def.	Met Lab
Hot Shoe P-1 N-1												
78 At. % Si P-1 N-1	10	10	10	8	8	8	8	8	8	2	2	2
63.5 At. % Si P-1 N-1												
Hot Shoe P-2 N-2												
78 At. % Si P-2 N-2	10	10	10	8	8	8	8	8	8	2	2	2
63.5 At. Si P-2 N-2												

Table 3.4-4. Production Readiness Operations

Operation	August 1980	Total Program
<u>Vacuum Casting</u>		
Number of Casting Runs		99
Number of Casting Runs Accepted	Completed	95
Percent Yield	Work	95.9 %
<u>Hot Pressing</u>		
Number of Hot Press Runs	Completed	270
Number of Hot Press Runs Accepted	Work	245
Percent Yield		90.7 %
<u>First Bond Assembly</u>		
Number of First Bond Couples Bonded	174	1093
Number of First Bond Couples Bonded/Accepted	128	846
Percent Yield	73.5 %	77.4 %
<u>Silicon Nitride Coating</u>		
Number of Coating Runs	5	46
Number of Couples Coated	80	736
Number of Couples Coated/Accepted	68	659
Percent Yield	85.0 %	89.5 %
<u>Second Bond Assembly</u>		
Number of Couples Bonded	170	603
Number of Couples Bonded/Accepted	116	514
Percent Yield	68.2 %	85.2 %
<u>Couple Pre-Assembly</u>		
Number of Couples Brazed	105	440
Number of Couples Brazed/Accepted	91	394
Percent Yield	86.6 %	89.5 %

The silicon nitride CVD coating systems had been out of operation the latter part of this month due to erratic furnace temperatures and to low coating deposition rates. A thorough audit of the complete system has been initiated, including consultation by the CVD system manufacturer. A number of minor discrepancies were uncovered and repairs initiated. System No. 2 is now operational and coating of 1st bonds will be resumed in the next reporting period. The over-haul of System No. 1 will be undertaken in the next reporting period.

The resistivity of the 63.5 and 78 At % Si N-Type materials has been at the low end of the acceptance range throughout the PR phase. An unusual number of compacts made during the PR phase were below the minimum level of $0.80 \text{ m}\Omega\text{-cm}$. An extensive investigation of both vacuum casting and hot pressing has been undertaken to identify potential processing "variations" that may result in this low level. In vacuum casting, the variables considered are: (1) size of the phosphorus dopant granules added, large vs small, (2) temperature at which the phosphorus is added to melt, (3) time from addition of phosphorus to the melt until pour, and (4) water cooling efficiency of casting molds. The review of the hot pressing variables include: (1) cooling or quench rate, (2) dwell temperature, and (3) pressure and temperature combinations.

The braze void problem in cold stack fabrication has been satisfactorily resolved by proper closing of the heat shunt gap, performed during radiator attachment fabrication. Specifications are being revised to incorporate this technique.

3.4.4 PRE-PRODUCTION UNICOUPLE CHARACTERIZATION

Characterization of PR product is continuing by routine inspection in accordance with MHW criteria. Statistical analyses are performed to determine comparability of PR unicouples to the MHW product.

3.4.5 PRODUCTION READINESS MODULE FABRICATION

There was no activity during the reporting period.

3.5 SiGe TECHNOLOGY MAINTENANCE

Three N-type and three P-type SiGe compacts were hot pressed representing variations in particle size and dwell time. The objective of shortening the dwell time is to inhibit recrystallization of the SiGe which should tend to lower the thermal conductivity. Dwell times of 20 minutes and 5 minutes (instead of the standard 40 minutes) were used with -80 mesh (< 177 microns) and -400 mesh (< 37 microns) material. These compacts will be machined into parts suitable for electrical resistivity, Seebeck and thermal conductivity measurements as a function of temperature. Room temperature density and Seebeck measurements were completed on these compacts.

Three compacts each of N and P-type $(\text{Si}_{0.8}\text{Ge}_{0.2})_{0.95} - (\text{GaP})_{0.05}$ were received from Syn-cal Corporation. The compacts were checked for Seebeck and density and are now being machined into pellets. This material possesses lower thermal conductivity than unmodified

SiGe which results in an improved figure-of-merit. The SiGe-GaP will be incorporated into MHW uncouple structures for evaluation of single-couple air test stations and in an 18-couple module. The GaP in the modified SiGe material has been known to dissociate at temperatures above approximately 1150°C and the P-type material converts to N-type. To prevent this happening during the high temperature first and second bond cycles (1310° and 1230°C) a low temperature bonding technique developed by GE is being pursued. The bonding temperature for this method is less than 1100°C . A low-resistance and mechanically strong bonds have been achieved. When SiGe-GaP pellets are available, they will also be subjected to first bond tests at 1310°C to determine if the short cycle has an effect on the polarity of the P-leg.

The 18-2 test module fabrication was initiated this month and all hardware assemblies were completed, except the thermopile operation. Thermopile assembly operation is awaiting the availability of the new SiGe GaP uncouples.

3.6 PERFORMANCE EVALUATION

Five single couple air test stations were set up, the purpose of which is to provide means to readily assess differences in the performance of developmental couples. The test setup with control panels can be seen in Figure 3.6-1 and details of an air test station are shown in Figure 3.6-2.

Figure 3.6-1. Air Test Station Facility

Figure 3.6-2. Individual Water Cooled Air Test Station

The 18-couple module, 18-1, continued testing during the month. Heater power was incrementally increased until, at an average hot shoe temperature of 524°C all parameters were satisfactory except the cold shoe temperature. The trend indicated that the final cold shoe operating temperature would be in the 340°C to 350°C range instead of the required 300°C . Therefore, the module was returned to ambient conditions, and an emissivity coating was applied to portions of the radiator fins to achieve the desired operating cold side conditions. This procedure was also found necessary for several of the modules during the MHW Program.

The 18-1 module was placed back under vacuum and the processing cycle continued. Gas samples of the module's internal cavity were obtained for Engineering evaluation. During one weekend period, a test equipment malfunction provided an erroneous overtemperature signal, which reduced the power input to the module by 30%. Full power was reapplied, and normal operation resumed. The equipment has been corrected.

Module 18-1, the first module built during the SiGe reestablishment program, reached full temperature on August 14, 1980. As of August 29, 1980, 355 hours of operation were achieved. Initial conditions were established by setting the heat input to the value required to establish an average hot shoe temperature at 1035°C (hot junction = 1000°C) with the external load voltage at 3.5 volts.

The heat input, 174.4 watts and the load voltage will be kept constant during the life test.

The module consists of two groups of 9 couples which are electrically connected by a link containing a relay. When the relay is opened, it allows separate measurements of the resistance from circuit to foil and outer shell. Link resistance is 55 milliohms and forms part of the total load resistance. The power dissipated in the link is added to the measured load power which is then regarded as the total power.

Table 3.6-1 summarizes the initial performance and the performance at 355 hours. Figures 3.6-3 through 3.6-7 show graphically the performance during the test period. Also shown for comparison is the performance of the last two modules tested at the same temperature level under the MHW Voyager Program, SN-3 and SN-6.

The module performance to date is considered a confirmation of the reestablishment of the SiGe technology with regard to the ability to produce couples with initial power characteristics very similar to past couples. Approximately 1000 hours of test time will be required before a judgment with any degree of confidence can be made on long term performance from the thermoelectric performance standpoint.

The initial power output when normalized for temperature differences and adjusted for lead voltage is 1.1% below the average initial power for 7 previously tested 18-couple modules. Scaled to a full size GPHS RTG operating at 997°C/293°C hot and cold junction, respectively, and 28 volts, the beginning of life (BOC) thermopile power would be 293 watts. A 1% power loss in internal wiring and connector pins would result in 290 watts available at the RTG connector. The RTG product specification requires 285 watts minimum BOM power which these couples would meet based on performance to date.

There are differences in the initial characteristics when compared to previous couples. Most notable is the internal resistance and Seebeck coefficient comparison shown in Figure 3.6-3. It is seen that the new couples have lower values than previous couples. This is indicative of higher dopant levels in solution in the SiGe alloy. These observations are consistent with the fact that the room temperature resistances were 10% lower than previous couples. The slopes of the resistance and Seebeck coefficient are also steeper, again pointing to higher dopant levels.

Figure 3.6-4 shows the power factor, $\frac{\alpha^2}{R_I}$.

The slope is slightly steeper than SN-3 and SN-6, which is consistent with higher dopant levels.

Figure 3.6-5 shows the measured total power and the normalized power. The normalized power is the measured power adjusted to a 700°C hot junction to cold junction temperature difference, by the ΔT^2 approximation. The hot junction, cold junction and ΔT 's are shown in Figure 3.6-6. The slope of the normalized power is less steep than in the past. This is due

Table 3.6-1. 18-1 Initial and 355 Hour Performance

	3 Hrs.	355 Hrs	Change
T_{HS} , Hot Shoe, °C	1034.8	1036.7	+ 1.9°
T_{HJ} , Hot Junction, °C	999.8	1801.7	+ 1.9°
T_{CJ} , Cold Junction, °C	300.6	298.1	- 2.5°
ΔT , °C	699.2	703.6	+ 4.4°
P_L , Load Power, Watts	8.66	8.74	+ 0.9%
P_T , Load + Link Power, Watts	9.0	9.08	+ 0.9%
P_N , Normalized Power, Watts	9.016	8.99	- 0.3%
R_I , Internal Resistance, ohms	1.0102	1.0885	+ 7.8%
R_C , Couple Internal Resistance (milliohms)	56.12	60.47	+ 7.8%
E_{oc} , Open Circuit Voltage, Volts	6.1373	6.355	+ 3.5%
$\bar{\alpha} = (E_{oc}/\Delta T \times 18)$	4.876×10^{-4}	5.018×10^{-4}	+ 2.9%
$P_{max} = E_{oc}^2 / 4 R_I$	9.322	9.275	- 0.5%
P_{max} (normalized)	9.343	9.180	- 1.8%
$\frac{(\bar{\alpha})^2}{R_C}$, Power Factor	4.236×10^{-6}	4.164×10^{-6}	- 1.8%
V_L , Load Voltage, Volts	3.507	3.504	- 0.1%
V_T , Load + Link Voltage, Volts	3.643	3.640	- 0.1%
I , Current, Amps	2.469	2.494	+ 1.0%
Resistances			
Circuit to Foil, ohms	8,000	12,000	+ 50%
Circuit to Shell, ohms	100.10^6	100.10^6	0
Circuit to Heater	100,000	300,000	+ 300%
Heat Input, Watts	174.4	174.6	+ 0.1%

Figure 3.6-3. Module 18-1 Internal Resistance and Seebeck Coefficient

Figure 3.6-4. Module 18-1 Power Factor

Figure 3.6-5. Module 18-1 Measured Total Power and Normalized Power

Figure 3.6-6. Module 18-1 Temperatures

Figure 3.6-7. Instantaneous Current-Voltage-Power Normalized to $\Delta T = 700^{\circ}\text{C}$

to the fact that the 3.65 volt operating point is further from the peak power point for the more highly doped couples. This is illustrated in Figure 3.6-7 which shows the calculated instantaneous current-voltage-power characteristics for SN-3 and 18-1. Shown are the initial characteristics for both modules and the characteristics for 18-1 at 355 hours. The closest test data available for SN-3 was 400 hours. It is seen that the peak power point decrease for 18-1 is greater, but the power decrease at 3.64 volts is less for 18-1 because of the proximity to the peak power point. (It is seen that operation at ~ 3.8 volts would show no change in power for constant ΔT operation.)

The raw measured power in Figure 3.6-5 is seen to have risen by $\sim 1\%$. Figure 3.6-6 shows an increase in ΔT of $\sim 3^{\circ}\text{C}$. There may be some improvement in foil insulation effectiveness taking place or more likely the thermal conductivity of the SiGe is decreasing slightly. This phenomena is known to occur as the legs age and the SiGe becomes more homogeneous. The higher initial dopant level may also be contributing a higher electronic component of thermal conductivity initially.

In summary, the analysis of the test data to date shows the initial power to be $\sim 1\%$ lower than 7 previous modules for the same voltage and temperature conditions. This is in part due to the higher dopant levels which initially cause operation further from the peak of the power curve. (Peak power is 0.4% low.) It is expected that long term performance will not be affected as dopant levels approach their equilibrium values at the end of mission.

4.0 GENERAL PURPOSE HEAT SOURCE RTG

This portion of the SiGe RTG Program is directed toward the development, qualification and fabrication of RTG's to support the Galileo Orbiter Mission scheduled for launch in March 1984 and the International Solar Polar Mission scheduled for launch in March 1985.

4.1 PROGRAM MANAGEMENT AND CONTROL

GE supported the Galileo Quarterly Mission Review at JPL on August 13.

A program status review was held with DOE on August 14 at GE.

The monthly ATF meeting to coordinate fueling and testing of the GPHS-RTG was held at Mound Facility on August 21. The revised GPHS-RTG schedules were reviewed relative to the fueling and testing operations and progress on the ATF was reviewed.

The schedule for the GPHS-RTG for the GLL and ISP Missions is shown in Figure 4.1-1. No revisions have been made during this reporting period.

4.2 HEAT SOURCE LIAISON AND INTERFACE

GE attended the GPHS Status Review Meeting held at DOE on August 5 and a meeting held at MRC on August 7 to review GPHS detail design drawings. LASL and the GE/DOE monitor also supported the meeting. GE agreed to revise the drawings to facilitate fabrication and inspection of MRC. The LMRF module vibration test was completed at GE on August 7. ORNL visited GE to witness the disassembly of the module after the test. The CBCF sleeves were hand carried to ORNL for post test examination.

LASL delivered all graphitic components needed for CET testing (except CBCF sleeves) to GE on August 5. Radiographic inspection of the CBCF sleeves at ORNL indicated unacceptable porosity. GE will machine the CET sleeves using the two spare CBCF billets provided by ORNL.

4.2.1 HEAT SOURCE DEVELOPMENT

LMRF Module Vibration Test

The LMRF module vibration test was initiated on August 4 and completed on August 5. The module test configuration is summarized as follows:

- The GIS and aeroshell, previously used for the LMRE retest, were reworked for the test; new hardware was not available.
- The fuel simulants represented the nominal clearances between fuel pellet, clad and GIS.

Figure 4.1-1. GPHS-RTG Program Schedule for GLL and ISP Missions

- The GIS chamfers were machined to 0.050 inch x 45°. This is the same configuration used in the "B" cavity for the LMRE retest. The GIS torque was increased to 38 in-lb to preclude loosening of the GIS cap.
- The CBCF components were machined to a thickness of 0.070 inch. All CBCF parts were radiographed at ORNL prior to final assembly. Two lots of CBCF were used - C-6 and C-15. Radiographs showed the C-6 parts had greater porosity, but both were judged to be acceptable for the tests. The gaps between CBCF components and other module parts are shown in Table 4.2-1. The CBCF end disks were bonded to the aeroshell. The bonding process used was not representative of the method used to bond flight hardware because the "prime" process still lacked full scale verification.
- Both aeroshell caps were torqued to 2.5 in-lb. This is the same torque used for the "B" cavity in the LMRE retest. Because of the rework performed on the aeroshell and GIS, the lock screw approach could not be used to secure the aeroshell cap. Instead a spot of epoxy was placed on the aeroshell cap threads.

Table 4.2-1. CBCF Sleeve Clearances Before Test

	A Cavity	B Cavity
GIS OD - CBCF ID	0.0135" Radial Gap	0.0135" Radial Gap
A/S ID - CBCF OD	0.0027" Radial Gap	0.0007" Radial Gap
A/S - CBCF Lgth	0.016" Axial Gap	0.011" Axial Gap

The test levels, test sequence, test fixtures, etc., were identical to those used for the LMRE vibration retest. The axial gap between GIS and aeroshell was measured after each test level via the inspection holes built into the module. No gap in either cavity developed throughout the entire test. Disassembly of the module showed essentially little or no wear of the CBCF (see Table 4.2-2). The GIS chamfers showed no evidence of wear - only slight burnishing was evident. The CBCF sleeves were delivered to ORNL for post examination. The results indicated that the design successfully withstood the test environment.

Table 4.2-2. CBCF Sleeve Wear

	Δ OD	%	Δ L	%	Δ W	%
"A" Cavity (C-6-5)	-0.0007"	-0.04	-0.003"	-0.11	-1.5 mg	-0.04
"B" Cavity (C-15)	+0.0001"	0	-0.0007"	-0.02	-3.5 mg	-0.09

GPHS Static Load Test

During reentry the differential temperature of the aeroshell and GIS causes the GIS length to increase ~ 0.002 inch with respect to the aeroshell. If the GIS is initially snug in the aeroshell cavity, the 0.002 inch represents a physical interference. A test was performed to determine the shearing load on the threads of the aeroshell cap caused by a 0.002 inch deflection.

An aeroshell and GIS previously used to evaluate the LMRD configuration, were used for the test. The test set up is shown in Figure 4.2-1. Loading was applied through an aluminum plate which contained a hole to clear the boss on the end of the GIS. The aeroshell was supported on three steel blocks to allow unrestricted deflection of the aeroshell cap. Prior to loading, the aeroshell cap was loosened to relieve any preload. The specimen was initially loaded to 25 pounds. With this preload, the first set of readings were taken at the four measurement points shown in Figure 4.2-1. Figure 4.2-2 shows the plot of the average deflection versus load. The test results indicated the following:

- The threads in the aeroshell end cap can sustain the expected 0.002 inch elongation of the GIS without apparent damage.
- The load induced in the threads due to elongation of the GIS is dependent on the preload (torque) applied to the end cap. For example (see Figure 4.2-2), with a 25 pound preload, the 0.002 inch motion of the GIS will cause an additional load of 35 pounds

* DEFLECTION MEASURED BETWEEN TOP OF GIS AND AEROSHELL (4 PLACES). LOCATION NOTED ①, ②, ③

Figure 4.2-1. Test Specimen

Figure 4.2-2. Load Versus Deflection Aeroshell End Cap

to be resisted by the threads. Should the initial preload be increased to 300 pounds, then the 0.002 inch motion will cause an additional load of 190 pounds to be resisted by the threads.

- The aeroshell cap threads can sustain a load of 700 pounds without apparent damage. After loading the specimen did show a permanent set of approximately 0.007 inch.

4.2.2 HEAT SOURCE ANALYSIS

Reentry and steady state analyses were conducted for the LMRF design. These analyses required several changes to the reentry code. For the reentry cases the contact conductance between GIS and aeroshell was specified as a variable function of time instead of the constant value that had been previously programmed. For steady state calculations, capability to include a specified angle of contact was added, similar to the reentry case.

Table 4.2-3 summarizes the results of several sensitivity analyses performed for the LMRF design. The first two cases assume a constant value of vacuum conductance at the GIS/aeroshell interface for the entire trajectory. The third case shows the effect of a variable vacuum conductance. The variable conductance is due to a variable force at the GIS/aeroshell interface because of expansion differences caused by varying GIS and aeroshell temperatures. The force versus time curve is shown in Figure 4.2-3. The curve is based on applying a 2.5 in-lb torque on the aeroshell cap and assembly. The new steady state operating temperature was

obtained using a vacuum conductance of 2.37 Btu/hr °F. This is equivalent to a 25 pound force in the equation:

$$K = 0.67^{\circ}\text{F} (\text{lb})^{0.393} \text{ Btu/hr } ^{\circ}\text{F}$$

Table 4.2-3. LMRF 3-D Reentry Sensitivity Analyses

Trajectory	Vacuum Conductance Btu/Hr F	Hypersonic Velocity Gradient Parameter	Corner/Corner Tumbling 120% Supersonic Heating					
			Local Clad Temperature C			Recession		
			Oper.	Peak	Impact	Stag. Pt.	Corner	Edge
Orbit Decay (Original)	3.7	0.565	1256	1406	844	0.023	0.022	0.022
Orbit Decay (Revised)	0.72	0.565	1280	1403	897	0.023	0.022	0.022
Orbit Decay (Revised)	Variable (Force Table)	0.565	1260	1383	833	0.023	0.022	0.022
Orbit Decay (Revised)	Variable (Force Table)	0.506	1260	1368	827	0.020	0.020	0.020
Min. Gamma No Skip	Variable (Force Table)	0.506	1260	1558	862	0.036	0.036	0.036

Figure 4.2-3. Contact Force Between Aeroshell (A/S) and GIS for LMRF Tumbling Orbit Decay - Assumes Zero Gap and 2.5 in lb Torque at Assembly

The lower impact temperature is the result of the gap that opens during the heating portion of the trajectory which reduces the heat flow into the clad and the relatively high conductance during the cooling portion of the trajectory.

Table 4.2-3 also shows the sensitivity of the hypersonic velocity gradient parameter. This parameter, which is the square root of the stagnation point velocity gradient on a sphere to that on a flat faced cylinder, had been fixed at 0.565 based on previous SNAP work. To be consistent with the Applied Physics Lab recommendation, this value was changed to 0.506 in the hypersonic regime. The APL recommended variation of this parameter in the supersonic and subsonic regimes had previously been implemented into the code. The effects of the change is only 6°C on the impact temperature although there is some decrease in the peak temperature and recession. The minimum gamma, no skip, case was analyzed to obtain the maximum temperature to which the clad might be subjected. A modified force versus time table was generated for this trajectory.

The LMRF reentry thermal analyses will be updated during the next reporting period when the contact conductances for the LMRF geometry are measured at BCL.

The steady state temperature profile at the time of launch was determined and is shown in Figure 4.2-4. This analysis assumed a contact conductance equivalent to a 17.4 pound force between GIS and aeroshell. This is the force expected at launch due to a 2.5 in-lb assembly torque. A 60° contact was assumed at all other interfaces. A 250 Btu/Hr°F conductance was assumed for these interfaces. The analysis assumed a xenon-helium gas mixture in the critical gaps.

Figure 4.2-4. Launch Temperature Profile Along GIS CL. LMRF

4.3 JPL LIAISON AND INTERFACE

Working sessions were held with JPL representatives to resolve interface details for the ACS system's disconnect and the PRD actuation. The interface control drawing was marked up with the agreed upon revisions. Three open items remain on the ICD which involve electrical connector callout and interfaces associated with the midspan support truss.

GE's evaluation on the RTG test configuration for dynamic testing were provided to Mound for review and comment.

4.4 GENERATOR DESIGN AND ANALYSIS

4.4.1 CONVERTER DESIGN

The ETG assembly drawing (47J305149) was issued. This is the top assembly drawing defining the configuration of the Engineering Unit. Because of the lateness in defining the PRD interface, the Engineering Unit will not have a PRD and none is shown on the assembly drawing. In addition, the cooling tube interface shown on this drawing does not depict the arrangement subsequently negotiated with JPL for the flight converters.

In a working meeting with JPL, agreement was reached on the interface details of the cooling tube disconnect and the PRD actuation. These details supercede the definition previously shown on TRW Interface Control Drawing L320453 and now properly recognize the means of activation - a double lanyard that is wound on a reel. With these interfaces defined, design of the PRD and the cooling tube disconnect fitting can be completed. The agreed interfaces were marked on a print of JPL ICD 10093047 and signed off with three items still open:

- location and size of cut-outs in the fins required to clear the midspan support truss for the Galileo mission.
- appropriate military standard for the electrical connector.
- tolerances and tooling requirements for mounting holes in the midspan stiffening rings.

The converter outer shell for CET-1 has been received and has been instrumented with strain gauges in preparation for conducting a static test prior to dynamic testing.

Spring washers used in both the Inboard Heat Support and Midspan Support Assemblies were checked for dimensional changes under load. It was found that the outside diameters had increased over the blank size as a result of forming to a conical shape, but that the diameter decreased slightly under load. As a result, it was necessary to machine the inside diameter of the inboard guide 20 mils larger to allow the washers to be assembled without binding.

4.4.2 WEIGHT STATUS

The current weight status of the RTG assembly is summarized in Table 4.4-1. This summary does not reflect the result of design changes for the cooling tube disconnect and the midspan mounting for the Galileo mission.

Table 4.4-1. Weight Summary

	Quantity	Current Weight
<u>Housing:</u>		
Outer Shell	1	12.32
Fins	8	2.90
Emissive Coating	X	1.00
Auxiliary Cooling Tube Manifold	1	2.00
Nuts	8	0.22
<u>Converter:</u>		
T/E Unicouples	576	11.98
T/E Sealing Screws	576	1.54
T/E C-Seals	576	0.13
Rivets and Washers	608	0.59
T/E Spacers (Al ₂ O ₃)	576	0.64
Nut Plates	288	0.80
Foil Insulation - T/P	1	13.00
Foil Insulation - Ends	2	1.33
Insulation Support Frame	1	1.65
Power Connector	1	0.35
Gas Management Assembly	1	0.29
Electrical Straps	X	1.08
PRD	1	0.90
C-Seal - Domes	2	0.08
Other Insulation	X	0.20
Pressure Dome	2	1.25
Screws - Pressure Dome	44	0.23
RTG Assembly	1	1.00
<u>Heat Source Support System</u>		
Graphite End Plate	2	1.05
ZrO ₂ Disk	8	0.42
Preload Stud	8	0.48
Shear Plate	1	0.27
Pressure Plate	2	1.11
Bellevilles	3	2.00
Sleeve	1	0.32
Latches	8	0.22
Center Support Assembly	4	0.94
Converter		62.34
Mid Span Plate	1	0.60
Heat Source	18	57.44
RTG		120.38

Preliminary configuration studies have been completed and the results have been provided to MRC for evaluation of the effects on handling and facilities.

Figures 4.4-1, -2 and -3 show candidate fixture configurations for use during lateral vibration. The requirement of a spool piece during qualification testing makes support of the inboard end difficult. An alternate inboard support fixture applicable, if the lateral vibration testing is limited to one axis is shown in Figure 4.4-1. These preliminary fixture configurations do not account for the stiffness characteristics of the boom. Accounting for this stiffness would add significantly to the complexity of the fixture.

4.4.3 STRUCTURAL ANALYSIS

Low Cycle Fatigue Tests on 2219 Aluminum

The combined effects of relative thermal expansions, vibratory loading, internal preload, welding and stress concentration results in the maximum stress at one location near the inboard end of the RTG case exceeding the predicted yield stress for the material. To evaluate this condition, a series of low cycle fatigue tests are being performed using 2219 T6 plate specimen. The specimen incorporates the weld and notch geometry and is being tested at the launch temperature for the case. Combined mean plus alternating loads are being applied to simulate the loading condition. The number of cycles of alternating load prior to failure of the specimen will be compared to the number of equivalent cycles predicted for the qualification test. This series of tests will also be used to finalize the weld technique for joining the cooling fins to the case.

Figure 4.4-1. Lateral Vibration Fixture

Figure 4.4-2. Lateral Vibration Fixture - Midspan Support

Figure 4.4-3. Lateral Vibration Fixture - Alternate Midspan Support

Figure 4.4-4. Lateral Vibration Fixture - Alternate Inboard Support

RTG Case Structural Stability

Structural stability analyses for the RTG aluminum case has been completed using the NASTRAN finite element models. The analyses were performed for both the CET-1 configuration which does not include cooling fins and for the RTG configuration including fins.

Dynamic Test Fixture for Galileo GPHS RTG

In the launch configuration, lateral support of the RTG will be provided at the inboard end by the attachment to the boom and at the midspan ring by the attachment to a "W" frame. All longitudinal support will be provided by the attachment to the boom at the inboard end. JPL has requested that an investigation of the feasibility of simulating these support conditions during dynamic testing of the RTG.

4.4.4 OUTER SHELL EMISSIVITY COATING

Testing was initiated to determine whether emissivity of the PD 224 coating is stable with time at temperature in vacuum. A stainless steel substrated sample was tested to 500°F (260°C) at a pressure of 1.2×10^{-6} Torr. The specimen geometry and test setup are as described in the January 1980 monthly report. The emissivity as a function of time is shown in Figure 4.4-5. There is no evidence of change in the emissive characteristics of the coating during the test period.

The specimen being tested is one of the original two samples that were used for the initial determination of the emissivity of the PD 224 coating. It was reinstrumented with two voltage taps and a new thermocouple for the life test. The original emissivity of this sample was measured at 0.916. The reason for the higher emissivity measured now is not known. After completion of the life test the voltage tap locations will be remeasured and the thermocouple calibrated. It is planned that this specimen will be subjected to 72,000 hours of vacuum testing.

Figure 4.4-5. PD 224 Coating Emissivity as a Function of Time

4.4.5 FORCED COOLING MODEL

The 400 node THT computer model was run to obtain surface temperature distributions and heat pickup by the cooling water. The model is 1/4 of the RTG circumference and extends the entire length as shown in Figure 4.4-6. The present model consists only of the outer shell and fins; end domes are not included. The heat input to the model is reduced to account for end dome losses. The input heat balance is shown in Table 4.4-2.

Three cases were run with the input parameters and results shown in Table 4.4-3.

Figure 4.4-6. GPHS RTG Cooling Model Computer Nodes

Table 4.4-2. Input Heat Balance

Fuel Load	4,410 watts
Electric Power Out	223
End Dome Radiation	<u>75</u>
Heat Into Outershell	4,112
Heat Into Model	1,028

Table 4.4-3. THT Computer Model Results

	Inlet Temperature	Surface Sink Temperature Heat Into			Heat Radiated to Surroundings		
		Emissivity	°C	Fluid	Sides	Ends	Total
Case 1	21°C	0.85	25	3532	580	75	655
Case 2	30°C	0.85	25	3432	680	75	755
Case 3	30°C	0.90	25	3404	708	75	783

Temperature profiles for Case 3 are shown in Figure 4.4-7.

Tests on the PD 224 emissive coating show an emissivity of 0.9; therefore, with the maximum water inlet temperature of 30°C the heat pickup is 3404 watts. The heat into the cooling water is lower and the heat radiated to the surroundings is higher than previously shown in the November 1979 monthly report. Therefore, with a 21°C inlet ($\epsilon = 0.85$) and a 25°C sink, the heat into the fluid was 3760 watts with 430 watts radiated to the environment.

4.5 SYSTEM TESTING AND FUELING

The monthly Mound Facility Assembly and Test Facility (ATF) Meeting was held at GE on 8/21/80. MF was requested to prepare certain portions of the qual and flight RTG test plans. MF was updated on RTG and GSE designs as well as recent changes.

GE recommended that MF formulate detailed plans to identify peripheral equipment required for RTG fueling and testing operations.

4.6 MODULE TESTING

Module 18-1, the first module built during the SiGe Reestablishment Program, reached full temperature on 14 August. As of 29 August, 355 hours of operation were received. Initial conditions were established by setting the heat input to the value required to establish an

Figure 4.4-7. Cooling Model Temperatures, Case 3

average hot shoe temperature of 1035°C (hot junction = 1000°C) with the external load voltage at 3.5 volts. The heat input, 174.4 watts and the load voltage will be kept constant during the life test.

The module consists of two groups of 9 couples which are electrically connected by a link containing a relay. When the relay is opened it allows separate measurements of the resistance from circuit to foil and outershell. Link resistance is 55 milliohms and forms part of the total load resistance. The power dissipated in the link is added to the measured load power and is referred to as the total power.

Table 4.6-1 summarizes the initial performance and the performance at 355 hours. Figures 4.6-1 through 4.6-5 show graphically the performance during the test period. Also shown for comparison is the performance of the last two modules tested at the same temperature level under the MHW Voyager Program, SN-3 and SN-6.

Table 4.6-1. Module 18-1 Initial and 355 Hour Performance

	3 Hrs.	355 Hrs	Change
T_{HS} , Hot Shoe, °C	1034.8	1036.7	+ 1.9°
T_{HJ} , Hot Junction, °C	999.8	1801.7	+ 1.9°
T_{CJ} , Cold Junction, °C	300.6	298.1	- 2.5°
ΔT , °C	699.2	703.6	+ 4.4°
P_L , Load Power, Watts	8.66	8.74	+ 0.9%
P_T , Load + Link Power, Watts	9.0	9.08	+ 0.9%
P_N , Normalized Power, Watts	9.016	8.99	- 0.3%
R_I , Internal Resistance, ohms	1.0102	1.0885	+ 7.8%
R_C , Couple Internal Resistance (milliohms)	56.12	60.47	+ 7.8%
E_{OC} , Open Circuit Voltage, Volts	6.1373	6.355	+ 3.5%
$\bar{\alpha} = (E_{OC} / \Delta T \times 18)$	4.876×10^{-4}	5.018×10^{-4}	+ 2.9%
$P_{max} = E_{OC}^2 / 4 R_I$	9.322	9.275	- 0.5%
P_{max} (normalized)	9.343	9.180	- 1.8%
$\frac{(\bar{\alpha})^2}{R_C}$, Power Factor	4.236×10^{-6}	4.164×10^{-6}	- 1.8%
V_L , Load Voltage, Volts	3.507	3.504	- 0.1%
V_T , Load + Link Voltage, Volts	3.643	3.640	- 0.1%
I , Current, Amps	2.469	2.494	+ 1.0%
Resistances			
Circuit to Foil, ohms	8,000	12,000	+ 50%
Circuit to Shell, ohms	100.10^6	100.10^6	0
Circuit to Heater	100,000	300,000	+ 300%
Heat Input, Watts	174.4	174.6	+ 0.1%

Figure 4.6-1. Module 18-1 Internal Resistance and Seebeck Coefficient

Figure 4.6-2. Module 18-1 Power Factor

Figure 4.6-3. Module 18-1 Measured Total Power and Normalized Power

Figure 4.6-4. Module 18-1 Temperatures

Figure 4.6-5. Module 18-1 and SN-3 Current-Voltage-Power Characteristics
Calculated Instantaneous Values $\Delta T = 700^{\circ}\text{C}$

The module performance to date is considered a confirmation of the reestablishment of the SiGe technology with regard to the ability to produce couples with initial power characteristics very similar to past couples. Approximately 1000 hours of test time will be required before a judgment can be made on long term performances from the thermoelectric performance standpoint.

The initial power output when normalized for temperature differences and adjusted for load voltage is 1.1% below the average initial power of seven previously tested 18-couple modules. Scaled to a full size GPHS RTG operating at $997^{\circ}\text{C}/293^{\circ}\text{C}$ hot and cold junction respectively at 28 volts, the beginning of life (BOL) thermopile power would be 293 watts. A 1% power loss in internal wiring and connector pins would result in 290 watts available at the RTG connector. The RTG product specification requires 285 watts minimum BOM power which these couples would meet based on performance to date.

There are differences in the initial characteristics when compared to previous couples. Most notable is the internal resistance and Seebeck coefficient comparisons shown in Figure 4.6-1. It is seen that the new couples have lower values than previous couples. This is indicative of higher dopant levels in solution in the SiGe alloy. These observations are consistent with the fact that the room temperature resistances are 10% lower than previous couples. The slopes of the resistance and Seebeck coefficient are also steeper, again pointing to higher dopant levels.

Figure 4.6-2 shows the power factor, $\frac{\alpha^2}{R_E}$.

The slope is slightly steeper than SN-3 and SN-6, which is consistent with higher dopant levels.

Figure 4.6-3 shows the measured total power and the normalized power. The normalized power is the measured power adjusted to a 700°C hot junction to cold junction temperature differences by the ΔT^2 approximation. The hot junction, cold junction and ΔT^2 's are shown in Figure 4.6-4. The slope of the normalized power is less steep than in the past. This is due to the fact that the 3.64 volt operating point is further from the peak power point for the more highly doped couples. This is illustrated in Figure 4.6-5 which shows the calculated instantaneous current-voltage-power characteristics for SN-3 and 18-1. Shown are the initial characteristics for both modules and the characteristics for 18-1 at 355 hours. The closest test data available for SN-3 was 400 hours. It is seen that the peak power point decrease for 18-1 is greater for 18-1, but the power decrease at 3.64 volts is less for 18-1 because of the proximity of the peak power point. (It is seen that at operation at ~ 3.8 volts would show no change in power for constant at operation.)

The raw measured power in Figure 4.6-3 is seen to have risen by $\sim 1\%$. Figure 4.6-4 shows an increase in ΔT of $\sim 3^\circ\text{C}$. There may be some improvement in foil insulation effectiveness taking place or more likely the thermal conductivity of the SiGe is decreasing slightly. This phenomena is known to occur as the legs age and the SiGe becomes more homogeneous. The higher initial dopant level may also be contributing a higher electronic component of thermal conductivity initially.

In summary, the analysis of the test data to date shows the initial power to be 1% lower than 7 previous modules for the same voltage and temperature conditions. This is in part due to the higher dopant levels which initially cause operation further from the peak of the power curve. (Peak power is 0.4% low.) It is expected that long term performance will not be effected as dopant levels approach their equilibrium values at the end of mission.

4.7 GROUND SUPPORT EQUIPMENT

4.7.1 ELECTRIC HEAT SOURCE

Modification of the graphite end caps has been completed and all parts are now available to permit completion of the first EHS Assembly. The vacuum chamber in which the EHS performance testing is to be conducted is being prepared for testing. A blank chamber penetration plate is being machined to accept three bulkhead type connectors.

4.7.2 VIBRATION TEST FIXTURE

A simple mass model of the converter has been designed and is being fabricated. The model consists of a round steel bar welded to a plate that duplicates the converter mounting flange. It has approximately the same mass and first bending mode frequency as an RTG. The model will be used to check out the vibration fixture and shaker prior to CET-1 dynamic testing.

4.8 MANUFACTURING

The following is a listing of the major manufacturing activities during the reporting period:

- Titanium details for the inboard and outboard supports were received and inspected.
- Parts were shipped to the vendor for high temperature strain gage installation.
- Insulators for the CET unit were inspected and placed in stock.
- Spool pieces were completed, inspected and placed in stock.
- The CET converter shell was received and submitted for inspection.

4.9 QUALITY ENGINEERING AND CONTROL

Material and parts for the CET-1 and Engineering Unit and the EHS are being received and inspected.

Machining of the aluminum housing for the CET-1 has been completed at Speedring and the housing has been delivered to GE. There were several minor discrepancies, but the unit was accepted.

Material Review Board Activity is summarized in Table 4.9-1.

4.10 RELIABILITY

Changes are being made to the FMECA to amplify steps to be taken in inspection and test to discover and correct defects and failure mechanism. This is in response to request by JPL.

4.11 SAFETY ASSESSMENT

The draft of the proposed GPHS Safety Test Program Plan, GESP-7160, was discussed in a conference call between DOE, LASL, and GE. A number of minor points were resolved, but two major areas of the test plan are still pending resolution by DOE. The first of these involves the explosion test provisions. The plan specifies that the GPHS test modules contain iridium clads with thoria fuel simulant in the configuration of the flight fueled clads. Also, a condition of the test is that the test modules will be preheated so that the temperature of the iridium clads will duplicate that for the launch conditions. LASL cannot preheat the modules because their test apparatus has disposable wooden shock tubes. In order for the preheat to be effected, the testing would have to be performed at a permanent shock tube facility such as exists at Sandia Laboratories, Albuquerque. LASL has been given the responsibility for conducting the safety test program for the GPHS, but their funding is based on the test scheme originally proposed by LASL (CMB-5-C-79-1067, "General Purpose Heat Source Program Plan. Final Design Verification," June 15, 1979). This scheme calls for disposable shock tubes with unheated test specimens. Additional funding would have to be provided to have the explosion test performed at an outside facility.

Table 4.9-1. Material Review Board Summary

ISPM			
NONCONFORMANCE REPORT	ITEM	DISCREPANCY	DISPOSITION
48559	Cap	Dimensions & Workmanship	1) Inspection Error 2) Accept Tool Chatter Marks
48581	Studs	Dimensions	Accept 8 Parts; Return Other Parts to Vendor
48624	Boron Raw Matl.	Iron Content is High	Accept; Change Specifications
48657	Support Tube	Dimensions	Rework to Dwg.
48671	Bracket	Lack Actual Chem. & Physical Property Data for Material	Accept; margin of Safety is High
48680	VOID - WRITTEN IN ERROR		
48684	Molybdenum Sheet	Surface is Scratched & Dirty	Accept Blemishes & Scratches will be "cut around".
48687	Pellets	Resistivity is Low	Scrap
48689	Hot Shoe Space	Foreign Matl.	Accept for Product Readiness Use Only
48692	Insulator, Midspan Support	Four parts are cracked	Scrap
48694	Nut, Spring Washer	Workmanship	Return to Vendor
48697	Ingots	Density is High	Scrap
48698	"N" - Pellets	Resistivity is slightly Low	Accept
48699	Outer Shell	1) Rib Not Cut Correctly 2) Part Not To Latest Revision	1) Accept for CET-1 2) Only deletion is Reqmt. for cleaning - which was not applicable to CET

Table 4.9-1. Material Review Board Summary (Cont)

NONCONFORMANCE REPORT	ITEM	DISCREPANCY	DISPOSITION
48700	Machined Radiator Attachmt.	Not Made to Latest Revision	Parts are acceptable as is.
48702	Plate, Midspan Support	Workmanship	Accept for CET-1
48703	Outer Shell	Dimensions	Accept for CET
48704	Latch, Outboard	Dimensions	Accept for CET-1
48706	Outer Shell	Various Dimensions & Workmanship	Accept for CET-1
48707	Billet, Preform	Autoclave Failed During Impregnation Cycle	Resume cycle after density checks
48710	C-Seals	Failed Plating Adhesion Tests	Return to Vendor
48716	C-Seals	Failed Lot Compression Test	Accept; Spec. will be changed.

Figure 2.12-1. ACS Engineering Performance Test

The other major area involved the projectile tests. The test proposed in GESP-7160 are considerably more extensive than those proposed by LASL (CMB-5-C-79-1067). Additional testing proposed in GESP-7160 includes skin-fragment (representative of propellant tank walls or other Shuttle structure) projectiles and electronic module (box) projectiles. For these types of tests to be performed would require a rocket sled test facility such as that at Sandia or at Holoman Air Force Base. The question of funding also arises for these types of tests since they were not included in the LASL safety test budget.

While DOE has not yet reached a decision on these areas of the test plan, the plan will be distributed officially in the GESP-7160 version. If it is found to be necessary at a later date, the plan will be modified according to the methods chosen for the explosion and projectile tests.

4.12 FIELD AND LAUNCH SUPPORT

No effort planned or undertaken.