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MITG TEST PROCEDURE AND RESULTS

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Abstract

Elements and modules for Radioisotope Thermoelectric Generator have been performance tested since the inception of the RTG program. These test articles seldom resembled flight hardware and often lacked adequate diagnostic instrumentation. Because of this, performance problems were not identified in the early stage of program development. The lack of test data in an unexpected area often hampered the development of a problem solution.

A procedure for conducting the MITG Test was developed in an effort to obtain data in a systematic, unambiguous manner. This procedure required the development of extensive data acquisition software and test automotion. The development of a facility to implement the test procedure, the facility hardware and software requirements, and the results of the MITG testing are the subject of this paper.

I. INTRODUCTION AND SUMMARY

Fairchild Industries, under contract* to the U.S. Department of Energy (DOE), conducted performance tests on a total of 20 multicouples for the Modular Isotope Thermoelectric Generator (MITG) described in Reference 1 . These multicouples, described in Reference 2 , were fabricated by Syncal Corp., also under DOE contract. The multicouples measured 0.340 inches square x 0.300 inches long. Each multicouple was fitted with a heat collector and a cold mounting stud. They were fabricated from a 6 X 6 array of n and p silicon germanium (SiGe) or gallium phosphide (GaP) modified SiGe thermoelectric (T/E) legs. Eight multicouples were mounted in a prototypical MITG housing slice and tested as a unit. The rationale for testing at this level of assembly and a detailed description of the test article was presented in a companion paper (Ref. 2). A cutaway drawing of the MITG prototypical module tested is shown in Figure 1.

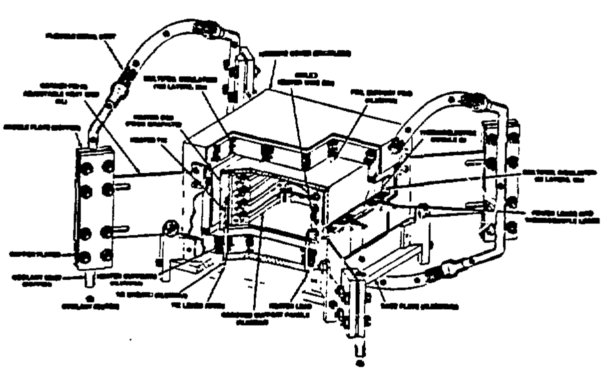

Figure 1. MITG Test Arrangement

The test assembly was heated electrically but the electrical heater was enclosed in a graphite box having the same outer dimensions as the General Purpose Heat Source (GPHS) re-entry module. The test assembly contained eight MITG multicouples and prototypic sections of the generator housing, and the proposed foil insulation. The top and bottom of the heater box were particularly well insulated to minimize non-prototypic heat losses in the housing covers. The housing covers were

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mounted on insulators to the housing side wall. This minimized heat conduction between the prototypical and non-prototypical portions of the test assembly. As in the MITG, heat from the prototypic housing wall flows to the corner fins. Heat was removed from the fins by circulating water through tubes which were brazed to clamp-on copper saddles. Heat was removed from top and bottom housing covers by separate instrumented circulating water circuits.

Four test assemblies (modules) were fabricated. Two were used in the subject test program and two were reserved for future testing. One module contained the standard SiGe material and one contained the GaP modified material. Each was tested at the reference hot junction temperature of 1000°C. Cold junction design temperature was 300°C. However, in practice, there was a large variation in the cold junction test temperature.

Extreme care was taken in the design of the test assembly and the test facility to maximize the accuracy of data taken for efficiency and heat balance determinations. It was essential that good calorimetry be performed, since the establishment of multicouple efficiency and a determination of the differences in performance between the standard SiGe and the GaP modified SiGe T/E material were the primary objectives of this test.

The four major test objectives were:

1. To establish multicouple performance in a systems context. The testing was conducted with sufficient accuracy to discriminate output power and efficiency differences between standard SiGe and GaP modified SiGe in identical systems. The absolute values of the multicouple efficiency and of the degradation due to shunt loss were also to be determined.

2. To establish the performance of the module's thermal insulation.

3. To estimate potential module lifetime by careful measurement of the degradation of the individual multicouple's power output. In this manner, it was possible to determine whether a single multicouple was the cause of test assembly degradation or whether the individual multicouples were degrading approximately equally. This also allowed segregation of the degradation effects due to shunt resistance and to degradation mechanisms essentially associated with the T/E materials.

4. To make parametric variations in the T/E module voltage and cold junction temperature of +100°C around the design value of 300°C while holding the hot junction constant at its design value of 1000°C.

Meeting these ambitious test objectives required the design and development of a highly reliable test facility. This established the need to acquire reliable and very clean vacuum bell jars, and to design a highly adaptive control and data acquisition system. The design and operation of this test facility is the principal subject of this paper.

The general arrangement of the MITG test facility is shown in Figure 2. The facility consisted of four turbomolecular/Vac-Iron pumped bell jars and two CVC diffusion pumped bell jars. Only two turbomolecular/Vac-Iron stations were used for the subject tests.

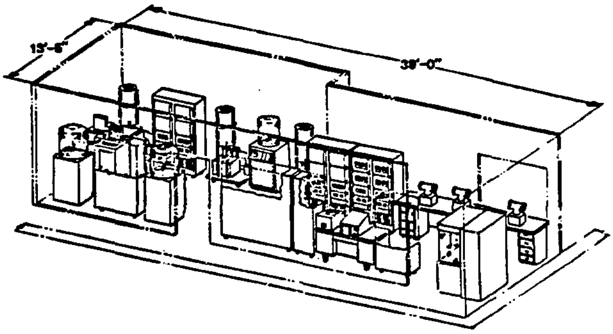

Figure 2. Perspective Drawing of [illegible] Test Facility

The tests were conducted automatically using diagnostic, control, and data acquisition software specifically written for this purpose. The heart of the control system was a Hewlett Packard (HP) 21 MXE computer with 576K bytes of fast core and 2.3 megabyte hard disc. The computer listened to the system through an HP 3965 scanner and addressed the system through an HP6940 multiprogrammer. HP 3455 and HP3456 DVMS were used to digitize the analogue input. Separate control data acquisition and safety functions were provided to minimize potential equipment failure problems. Battery backup for the computer and diesel backup for the test facility were provided. Software was written to provide an automatic restart capability. Post-processing software was written to provide automatic data reduction and plotting.

Figure 3 and 4 are typical of the data reduction performed during the test program. The predicted Seebeck coefficient (alpha) of the single multicouple is seen to track the theoretical value rather closely until a catastrophic event occurred. The theoretical and measured alpha curves were obtained by post-processing, using the measured multicouple hot and cold junction temperatures and the open circuit voltage. The internal resistance was obtained using a stiff power supply as a load, varying its voltage, measuring current flow, and calculating the multicouple resistance. All these functions were performed automatically by the control and data acquisition computer software.

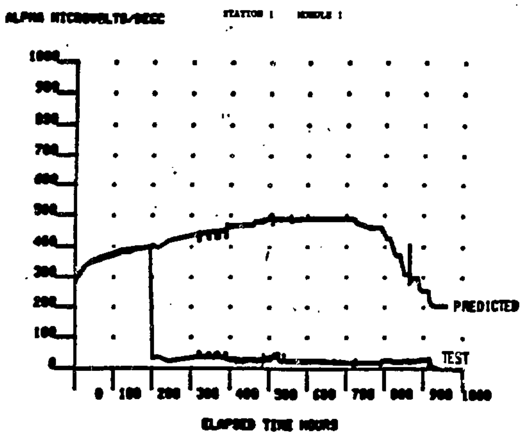

Figure 3. Seebeck Coefficient

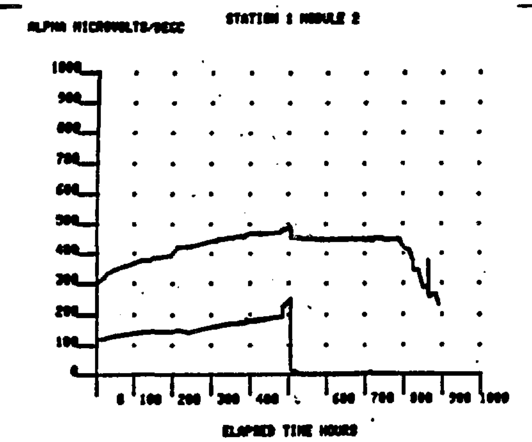

Figure 4. Seebeck Coefficient

A detailed description of the test facility, the computer and the software which established the test procedure are presented in the following chapters. Selected test results are also shown. A description of the steps taken to overcome the multicouple mechanical problems uncovered by the subject testing is presented in the next two papers these proceedings (Refs. 3, 4).

II. Discussion

A brief description of the test assembly was presented in the Summary. Figure 5 shows this article partially assembled and mounted in one of the turbomolecular/VAC-Ion pumped vacuum stations. A detailed description of the test assembly and the rationale for its design is presented in reference 1. The paper at hand is focused on the test operations of the MITG program.

Figure 5. Top View of Partially Assembled Module

The MITG test facility was designed and built in less than six months. Although Fairchild personnel were authorized to begin planning the facility in December 1981, authorization to begin construction was not received until February 1982. Multicouple testing was begun in May 1982. The use of a substantial amount of Government Furnished Equipment (GFE) greatly reduced procurement lead time. The computer, data acquisition system, vacuum stations and a number of accessories were obtained as surplus from various DOE facilities. This equipment was received at the Sherman Fairchild Technology Center in Germantown, Maryland, in January 1982. Substantial modifications to most of the GFE were accomplished after their receipt.

The MITG area was selected partitioned and provided with utilities in the period 15 February through 15 April, 1982. This effort was complicated by the need to install a separate 150 amp 220 VAC electric service from the diesel backed emergency bus. The test equipment installation was completed in late May 1982 just prior to the receipt of the test assembly components from SynCal. Figure 6 is a photograph of the MITG test area and the test equipment arrangement.

Figure 6.
Photograph of General MITG Test Area

A. Vacuum Stations.

Six vacuum stations are available in the MITG test facility. Two turbomolecular/Vac-Ion pumped 18 inch diameter by 30 inch high stainless steel bell jars were selcted for testing the MITG modules. A Welch mechanical pump was used to rough the bell jars and as a foreline pump for the turbomolecular pumps.

Each chamber was fitted with five 26 pin electrical feedthrough to accommodate the need for electrical and instrumentation penetrations. Heater power and module output power were carried by a single 7 pin connector. Separate voltage taps from the heater were also carried through the 7 pin connector. These taps were necessary to remove the uncertainty of power wiring voltage drop from the calculation of input power. A photograph of a typical turbomolecular/Vac-Ion pumped vacuum station is shown in Figure 7.

Figure 7.
Photograph of Typical Turbomolecular/Vac-Ion Pumped Vacuum Station

Testing in vacuum at temperatures of 1000°C and at pressures less than 10^{-6} Torr requires high pumping capacity. None of the components assembled into the test article were planned to be outgassed at their design temperatures before being installed in the test vacuum station. Because of this, a decision was made to modify the GFE chambers to add pumping capacity and to increase conductance for the existing pumps.

The chambers as received were mounted on the inlet flange of an ULTEK (now Perkin-Elmer) 550 l/s Vac-Ion pump. The chambers were roughed by a 450 l/s Leibold-Hereus turbo-molecular pump using a Welch pump to establish a suitable foreline pressure. As received, the roughing port was only 2-1/2 inches in diameter. This port was blanked and a six inch port, tee, and elbow were added to accommodate an additional 220 l/s Perkin-Elmer Vac-Ion pump and to provide adequate conductance to the turbomolecular pump. A six inch gate valve was used to isolate the turbomolecular pump from the chamber. This arrangement allowed unattended operation with very little chance of test article damage due to air in leakage in the event of loss of facility electric power.

The vacuum stations performed very well. Clean, dry and empty, they blanked off at 5 X 10^{-8} Torr. After 1000 hours of testing at heater temperatures as high as 1100°C, the chamber pressure was steady at 8 X 10^{-7} Torr with the turbomolecular pump secured and both Vac-Ion pumps operating. The turbomolecular pump was very useful in outgassing the test assembly. The Vac-Ion pumps would not start above 5 X 10^{-6} Torr. As a result, signficiant system processing was performed using just the turbomolecular pumps. Once the pressure fell below 2 X 10^{-6} Torr, Vac-Ion pump operation was very stable and they provided adequate pumping capacity.

B. Computer.

All MITG testing, as dicsussed earlier, was under computer control. The hardware used for this function was manufactured by Hewlett-Packard, and except for a few new purchases, it was obtained as Government Furnished Equipment (GFE). A brief description of the computing hardware is given below.

1. Main Frame (HP) 21 MXE with 576K bytes of fast core and a 2.3 megabyte hard disc.
2. Multiprogrammer Model HP6940B.
3. Magnetic Tape Unit Model HP 7970E.
4. Line Printer Model HP 2631B.

The functional design of the MITG test assembly is shown in Figure 8.

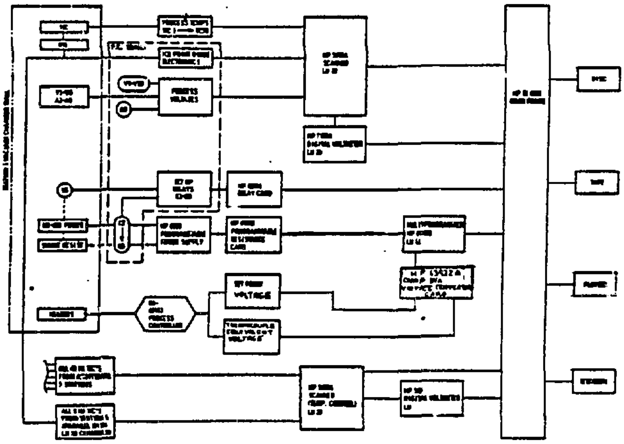

Figure 8. MITG Test Assembly Functional Design

C. Software

1. Functional Design.

The primary function of the control program during the conduct of MITG testing was the maintenance of a constant hot junction temperature. The functional description of the software providing dynamic control of the hot junction temperature is discussed in the following paragraphs.

a) Scanner Function. Each test assembly had 50 thermocouples installed, the general arrangement of which is shown in Figure 9. The millivolt output of these thermocouples was input to an HP Model 3495A scanner. The software control of the scanner was performed over the Hewlett Packard Interface Bus. The scanner was first commanded to "listen" to a selected channel address and then the signal was output to a Model HP3456 digital voltmeter. The DVM converted the analogue input to a digital output which is read by the program (SCAN). Tho functional design of the scanner program is given in Figure 10.

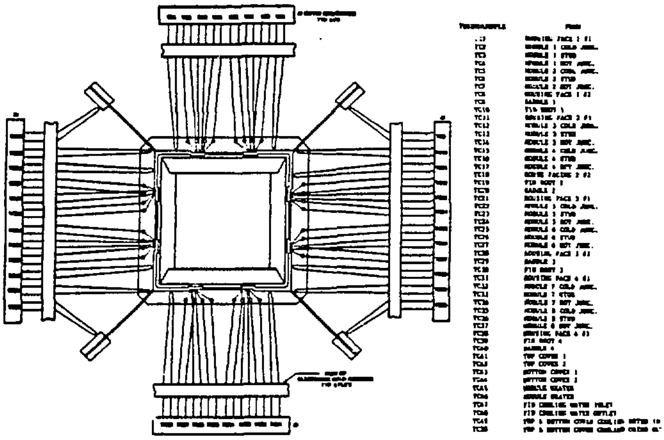

Figure 9. General Arrangement of MITG Test Assembly Thermocouples

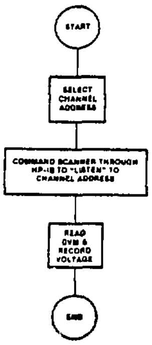

Figure 10. Scanner Functions

b) Averaging Function. The control scanner receives millivolt signals from the eight hot junction thermocouples. A program (MEAN) was written to compute an average hot junction temperature from these signals through an autioneering procedure. This is an important precautionary step which enabled the program to detect and discard any spurious signals due to multicouple damage etc.

An arithmetic mean voltage was computed from the signals received from the eight hot junction thermocouples. Each individual signal was compared to the mean. Any signals which deviated more than 20 % from the mean was discarded and a new average hot junction voltage was computed using the remaining signals. An appropriate error message indicating the time and the multicouple number thrown out of the auctioneering process was recorded.

The average millivolts, thus obtained, was converted to give an average hot junction temperature after correcting for the cold junction reference provided by the ice point diode sensors.

c) Flow Measurement Function. Heat was removed from the test assembly by the circulation of cooling water in the housing fins. Water from a constant temperature bath was circulated through the loop. In order to determine the heat rejected by the system, it is important to measure the temperatures of the inlet and outlet water very carefully. The critical nature of the rise in coolant temperature across the fin loop required the use of copper/constant differential thermocouples. The same was true for measuring the temperature rise in the coolant in the top and bottom covers. A program (FLOW) was written to convert the millivolt signals, obtained from the differential thermocouples, to the rise in coolant temperature across the fin loop.

The flow rate was determined by a signal (volts) delivered to the scanner from the flowmeter. A program was written to convert the volts into flow rate (lbs/hr). Once the cooling water mass flow rate was determined and the temperature rise was known, the program computed the heat rejection in each of the coolant loops.

The sum of these heat rejection rates and the module electric power output should equal the electric power intput to the heaters. Error in the comparison of those values indicates the accuracy of the heat balance, and by inference, may be used to determine the uncertainty in the observed system efficiency of the MITG slice.

d) Multiprogrammer Function. The power supply to the heater was controlled by RI 633911 process controller which in turn received its input analogue signals from the HP6940B Multiprogrammer.

A quad D/A voltage converter card was installed in the multiprogrammer. The quad card contains 4 individually programmable 10-bit D/A voltage converter circuits that produce high speed bipolar output voltage proportional to the programmed digital data.

A program (QUADV) was written to drive the multiprogrammer. It addressed the quad voltage card in the multiprogrammer, selected the appropriate circuit which was loaded with digital data. This immediately activated the card to produce an output proportional to the programmed digital data. A functional design of the multiprogrammer program is shown in Figure 11.

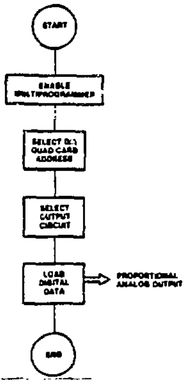

Figure 11. Multiprogrammer Function

2. Detailed Design

The control program was activated every 30 seconds and was designed to perform the following functions.

a) Heatup/cooldown of hot junction.

b) Steady state operation.

c) Safety interlocks.

Each of these functions will be discussed in the following paragraphs.

a) Heatup/cooldown

The heatup or cooldown of the hot junction temperature should be executed at a carefully controlled rate. Large up or down transients in the temperature lead to unacceptably high thermal stresses which would very likely damage the multicouple. Programs were written which enabled the operator to heatup (HEATP) or cooldown (SHTDN) the hot junction at a specified controlled rate.

The programs allowed the operator to enter

1) the rate (in degrees/hour) at which the heatup/cooldown should be executed, and

2) the final steady state temperature at which the hot junction should be maintained.

A time versus temperature ramp was set up to reflect the rate entered by the operator and the control program (CNTRL) is scheduled every 30 seconds.

During every execution of the control program, the following two signals were sent to the process controller through the quad D/A card:

1) A proportional voltage corresponding to the set point temperature along the time/temperature ramp and

2) A proportional voltage corresponding to the current hot junction temperature.

The process controller then sampled the two analogue signals. It increased/decreased the power to the heaters so that the hot junction temperature was set equal to the set point temperature.

b) Steady State

The heat up/cooldown proceeded automatically at the specified rate until the set point temperature was equal to the final temperature input by the operator. At this point in time, the control loop became a steady state operation with the temperature of the hot junction being maintained at the final temperature. It should be noted that the heatup/cooldown or the steady state operations procedure could be interrupted at any time by the operator who could enter a new rate and final temperature. The control program then proceeded to increase/decrease the temperature of the hot junction at the new rate till steady state conditions were achieved.

The functional design of the control program is given in Figure 12.

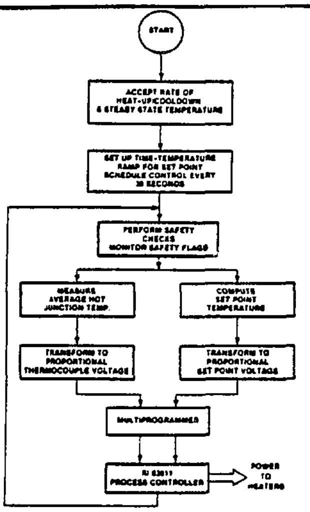

Figure 12. Control Function

c) Safety Interlocks

During the execution of the control loop, a number of safety interlocks have been incorporated to shut down the heater power if prescribed limits on the following variables are exceeded. (Figure 13)

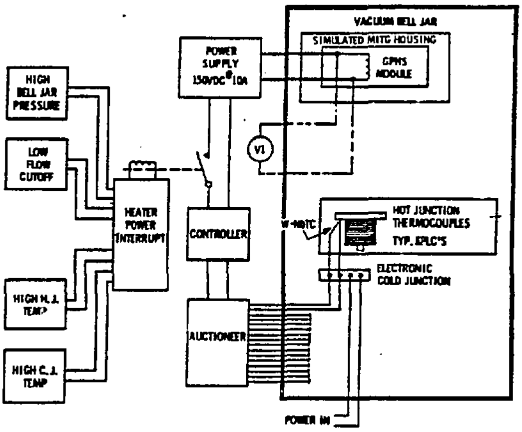

Figure 13. MITG Test Assembly Control and Safety Functions

- High hot junction temperature (>1100°C)
- High cold junction temperature (>325°C)
- Low flow rate of cooling water (<10 lbs/hr).
- High bell jar pressure (>10^{-4} torr)

A safety relay was provided to control the power to the heaters. Normally, this relay was closed, but in the event of any one of the safety flags being set, the following actions were performed by the safety program.

- The safety relay was opened so that the power to the heater was turned off.

- The set point voltage was gradually set to zero volts along a cooldown ramp.
- The time of occurrence and appropriate safety alarm message was recorded.

The control loop halted stepping the set point voltage up or down the set point ramp. The program entered a safety mode of operation wherein the safety flags were continuously monitored. As soon as all the safety alarms were cleared, the control loop measured the current hot junction temperature and proceeded to step it up the set point ramp at the specified rate.

This mode of recovery from a safety alarm ensures that large up/down transients of the hot junction temperature are avoided minimizing damage to the multicouple.

Since the occurrence of any of the above safety alarms caused the heater to be turned off, it was important to monitor the rate of cooling of the hot junction. If the rate was too high (>100°C/hour) and temperature of the cold junction was less than 325°C, the safety function caused the cooling water flow to be stopped. If high hot junction or cold junction temperatures were sensed, the cooling water flow was restarted immediately.

3. Data Acquisition

A program was written to acquire temperature and electrical data from each test assembly. This program was scheduled to be activated every 10 minutes. The raw data (mV), the converted data (degrees C), and the open circuit module voltages were stored in a time sequenced format on magnetic tape.

a) Temperature Measurements - Each test assembly had 50 thermocouples installed, the general arrangement of which was shown in Figure 9.

A listing of temperature instrumentation which must be provided to obtain the required test information is as given below.

The values shown in parenthesis are the number of places the temperature is monitored in each test assembly and the expected range of variation in that temperature.

- Multicouple hot junction temperature. (8 places, 900-1150°C)
- Multicouple cold junction temperature. (8 places, 200-400°C)
- Multicouple cold stud housing interface temperature. (8 places 200-400°C)
- MITG housing segment face temperature. (8 places, 200-400° C)
- MITG housing segment fin root temperature. (4 places, 200-400° C)
- Cooling water saddle temperature (4 places, 200-400°C)
- Simulated GPHS module temperature (2 places, 1200-1400°C)

- Top cover temperature (2 places, 40°C)
- Bottom cover temperature (2 places, 40°C)
- Fin cooling water inlet temperature (1 place, 20°C)
- Fin cooling water outlet temperature (1 place, 20°C)
- Top and bottom cover cooling water inlet temperature (1 place, 20°C)
- Top and bottom cover cooling water outlet temperature (1 place, 20°C)

The signals were corrected for the cold junction reference temperature obtained from the ice point diode electronics and converted to temperature using mV-temperature calibration for W/Nb thermocouples.

The cooling water temperature measurements were made with copper/constant differential thermocouples. These signals are converted to temperatures using the appropriate algorithm for a TYPE T thermocouple.

b) Electrical Measurements - The program measured the following electrical outputs.

- The eight individual multicouple output voltages.
- The series connected module voltage.
- The shunt power supply voltage.
- The voltages across the high precision current measuring resistors in series with the multicouples. These voltages were used to compute the individual multicouple shunt currents.

c) Shunt Degradation Measurements. Shunt degradation as a result of silicon sublimation at the hot end is an important life limiting mechanism in present SiGe RTGs. The silicon condenses in a low temperature zone and the resultant deposit acts as a conductive shunt between the thermoelectric legs and the multifoil insulation. The consequent shunt currents cause unacceptable power output degradation in the generator, unless the silicon sublimation can be eliminated or significantly retarded. In the thermoelectric module design used in the MITG, the role of sublimation supressant is played by a relatively thick (.003 inch) coat of mulite. The following test which was performed once a day is designed to evaluate the efficacy and the long term stability of the coating.

Individual shunt characteristics for each module are measured by using a ganged 8-pole double throw relay which simultaneously breaks the series connections between the eight multicouples and shorts each one. The eight shorted multicouples were connected to a common terminal of an external supply through individual high precision current measuring resistors R1-R9 (Figure 14). The other terminal of the power supply was connected to the foil package. By this arrangement, the individual shunt characteristics for the eight multicouples could be measured simultaneously. The functional design of the shunt program is discussed below.

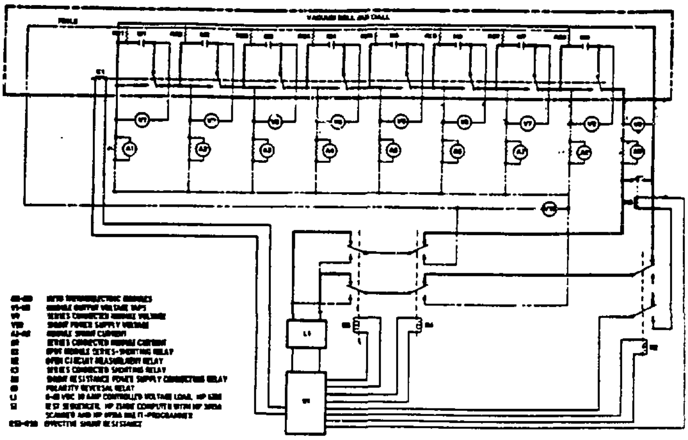

Figure 14. MITG Test Assembly Wiring Diagram

1) Relay Function. The open circuit, short circuit and shunt resistance measurements necessitate the energizing of relays on the HP12551 relay card.

A program was written to enable the individual relays to be energized. It set up an appropriate bit pattern depending on the relay to be energized.

2) Resistance Function. The current-voltage characteristic of each shunt must be measured over a range of load voltage. Typically, the multicouple foil voltage must be varied from +30 to -30 volts. The programmable resistance card. HP69501A, installed in the multiprogrammer, was used in conjunction with the programmable power supply to produce output voltages (of the powersupply) proportional to the programmed digital data. The program selected the address of the resistance card in the multiprogrammer and loaded it with data which generates the required output voltage on the power supply.

The polarity reversal relay (K5) was energized to generate negative module-to-foil voltages.

The voltages across the individual high precision resistances were measured. For each value of the load voltage, the individual multicouple shunt currents and shunt resistances are computed.

All the data from the open circuit, short circuit and shunt resistance measurements were stored on magnetic tape in a time sequenced format for post processing. The shunt characteristics (IV) curves for each multicouple can be plotted as a function of time. This will verify the non-ohmic nature of the shunts formed by the silicon condensate and the resultant highly non-linear current-voltage characteristics.

A detailed design of the shunt resistance function is shown in Figure 15.

4. Check-out Software

A program DOCTR was written to perform system diagnostics. This program was used as a tool to check out the installation of the test assemblies.

DOCTR assisted the user in verifying the wiring for the control and instrumentation in a systematic manner.

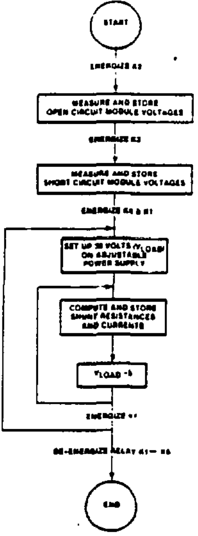

Figure 15. Shunt Resistance Function

The program presented the user with the following options for verification:

a) Scanner function

b) Power Supply function

c) Relay function

d) Safety function

e) Shunt Calibration

A brief description of each of these options is given below.

The scanner option allowed the user to scan and measure the voltage across each of the 80 channels, and an appropriate message indicating the channel number and the voltage across it appears on the screen. The millivolts from the 50 thermocouples are also converted into temperatures.

The power supply option allowed the user to generate a user defined voltage on the adjustable power supply.

The control option allowed the user to enter set point and thermocouple temperatures and determine the voltage generated at the RI63911 process controller.

The relay option allowed the user to open or close individual relays or a combination of relays on the HP12551 relay card.

The safety option allowed the user to determine whether a safety alarm caused the safety relay to be opened.

The safety features which could be tested were:

- High hot junction temperature.
- High cold junction temperature.
- Low flow rate of coolant.
- High rate of cooling of hot junction.

The shunt calibration option allowed the user to calibrate selected shunt resistances with respect to the actual measured shunt resistances for different values of the load voltage.

5. Post-Processing Software

All the data acquired during the test was stored on magnetic tape in a time sequenced format. Post-processing programs were written to read the tape and extract the following data values as a function of elapsed time for each multicouple.

a) Multicouple open circuit voltage.

b) Hot junction temperature.

c) Cold junction temperature.

The Seebeck coefficient was extracted using the measured multicouple hot and cold junction temperatures and the open circuit voltage. Each of these variables was plotted as a function of elapsed time. Typical plots are shown in Figure 3 and 4.

D. Test Operations

Test operations were conducted continuously as planned. Some control and data acquisition system bugs were detected and corrected; however, the software took much of the drudgery out of running the tests and obtaining and reducing data. In addition, the system diagnostic program, DOCTR, was very useful in checking out the installation of the test assemblies.

1. Installation

The multicouples were inspected when received from Syncal. A resistance check was made and compared to the Syncal measurements. Syncal personnel installed the multicouples in the prototypical insulated housing and Fairchild personnel installed and instrumented the test assembly in the vacuum chamber. The control and instrumentation wiring had already been installed and rung out (using (DOCTR) up to custom built terminal strips inside the vacuum chamber. Specially built teflon terminal strips were used because of outgassing problems encountered with standard "low outgassing" terminal strips.

After installing the test assembly in the chamber, all internal instrumentation and power wiring was completed, the cooling water lines were connected and leak checked, the module internal pressure monitoring ionization gauge tubulation was installed and the chamber was closed. The system was then roughed with the turbo-molecular pump and leak checked. The chamber, if leak tight, would reach the 10 Torr scale in 25 minutes. Pump down time and the pitch of the turbomolecular pump were very good indicators of system leak tightness.

2. Heat-Up

The electric heaters (and foil insulation packages) were manufactured by Thermo Electron Corporation (TECO). These heaters were fabricated from HT molybdenum wire. This material is very oxidation sensitive and TECO provided an out-gassing-temperature schedule which severely constrained the system heat-up rate. Although Syncal allowed a 100°C/hour heat-up rate, the TECO limitations on temperature and pressure stretched the heat-up period to approximately 600 hours. The chamber pressure rarely rose above 2×10^{-6} Torr while the test assembly was outgassing. The module internal pressure varied from 1×10^{-4} to 5×10^{-6} Torr during the outgassing period. The extreme limitations on heat-up rate caused by the heater pressure limitation was the basis for a system redesign. Future system test assemblies will be fitted with a removeable plug in the top foil insulation pack. During outgassing operations, this plug will be lifted to improve the conductance between the module internals and the vacuum chamber. This, and the removal of the internal pressure monitoring ionization gauge, should greatly increase the rate at which the test assembly can be processed.

The fact that there were problems with the multicouples first became evident during the assembly heatup testing phase. The wealth of instrumentation and the ease with which the data could be reduced was very helpful in determining the system test program direction.

3. Steady State

Steady state operations were conducted with only the Vac-Ion pumps operating and all system isolation valves closed. These operations were routine and were completely under computer control. Post-processing of these data produced easily interpreted figures which were very useful in assessing the condition of the individual multicouples. A pattern emerged which gave credence to the theory that a common mode failure had occurred and that nothing would be gained by continuing the test. If the individual multicouples could not have been isolated and their performance measured, the existence of this common mode failure could not have been inferred.

4. Cool-Down

The multicouples were cooled down using the cool-down program SHTDN. The down ramps were interrupted at specific temperatures to make open circuit, internal resistance and shunt resistance measurements. These data were also post-processed using the software developed for the test program. No problems were encountered during this period until the failure of the HP 3456 DVM. This failure locked the HP-IB bus and prevented the heater controllers from receiving updated temperature information from the computer. At the time of failure, one controller was supplying power above the set point and one was below. As a result, one system continued to heat and the other continued to cool.

A system redesign has added an independent noncomputer-related override to prevent exceeding a pre-selected temperature. The RI heater controllers have a power limiter which indirectly provide this function. When operating below the design temperature, the power limiter has insufficient range to control the heater power; although it will prevent the design temperature being exceeded, rapid ramps to the design value can be encountered. The independent safety system will preclude these ramps.

III. Results

The test durations for the several MITG builds are summarized in Table 1. The tests were terminated because of the high observed internal resistance measured in all multicouples. A snapshot of the parameters measured in the SiGe module is shown in Figure 16. Table 2 shows a summary of the before and after test module resistances. A plot of internal resistance vs temperature of a standard SiGe multicouple is shown in Figure 17. This multicouple (Station 1, Build 2, Multicouple 8) was the best behaved in terms of output power and internal resistance of all the tested multicouples. A plot of the output voltage vs time for this multicouple

- STATION 1 STANDARD SiGe
- TWO BUILDS
  - 29 JUNE 82 - 2 JULY 82
    MAX H.J. TEMP ~ 420°C
    TIME AT MAX TEMP < 10 HOURS
    TOTAL TEST TIME < 70 HOURS
  - 17 JULY 82 - 31; 9 AUG 82 - 28 SEPT 82
    MAX H.J. TEMP 1000°C
    TIME AT MAX TEMP >200 HOURS
    TOTAL TEST TIME >960 HOURS

- STATION 2 GaP DOPED SiGe
- ONE BUILD
  - 9 AUG 82 - 28 SEPT 82
  - MAX H.J. TEMP 1000°C
  - TIME AT TEMP >200 HOURS
  - TOTAL TEST TIME >1100 HOURS

Table 1. Performance Testing

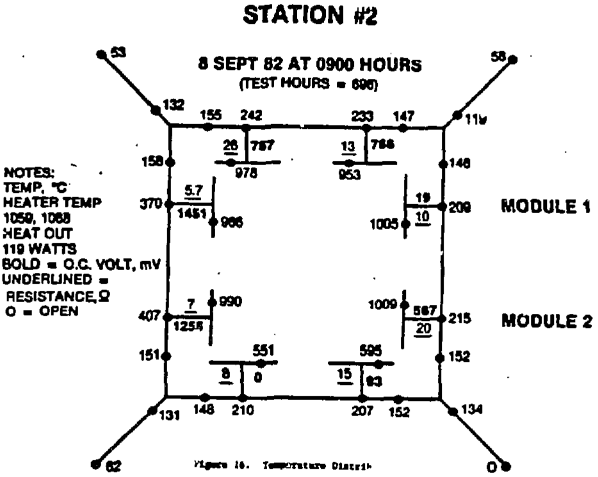

Figure 16. Temperature Distrib

	STATION 1		STATION 2	
Module	Resistance as Installed	Resistance After Test	Resistance as Installed	Resistance After Test
	Ω	Ω	Ω	Ω
1	48	1405	82.0	332.0
2	30	1103	24.0	241.0
3	303	1013	41.0	120.0
4	34	72	10.3	321.0
5	121	33	9.7	[illegible]
6	41	41	9.8	10.4
7	1776	997	41.7	96.0
8	124	36	110.0	.24

Table 2. Module Resistance

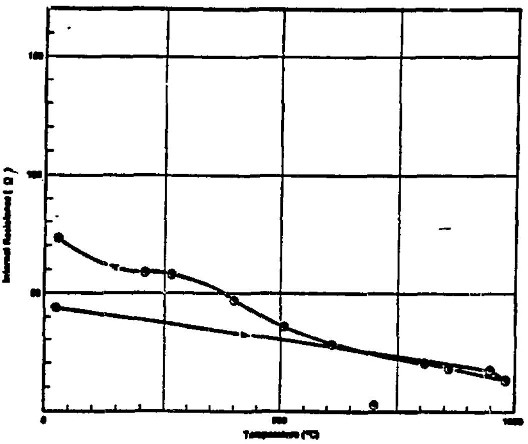

Figure 17. Module 8 Internal Resistance - Temperature History

is shown in Figure 18. The multicouple was at design temperature (1000°C HJ, 300°C CJ) during the period 500 to 720 hours. Controlled heatup and cooldown ramps were used to reach this temperature.

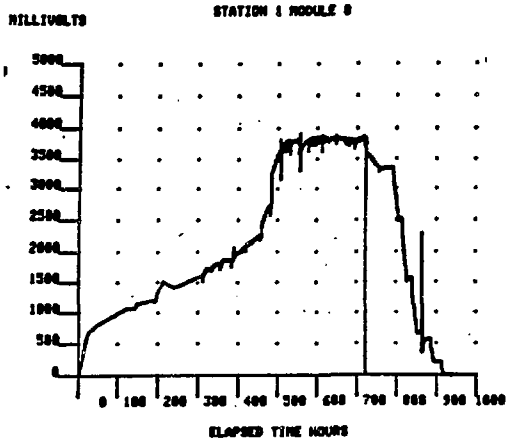

Figure 18. Module Output Voltage

Examination of the multicouples removed from all builds showed cracking at the cold stud-SiGe interface. This cracking was predominantly in the SiGe, not in the glass. Figure 19 shows a typical cracked module.

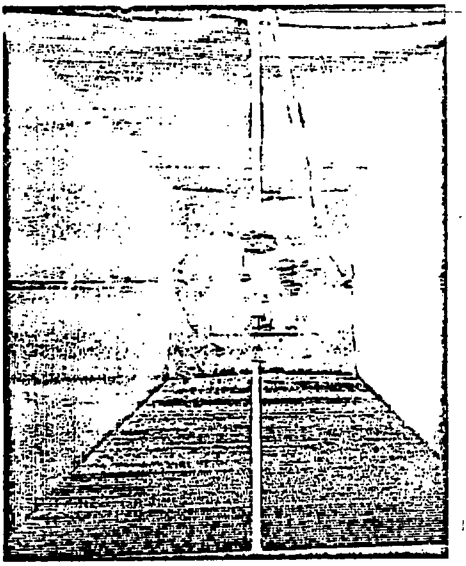

Figure 19. Photograph of a Cracked Module

Detailed metallographic examination of the multicouple hot end showed that there was incomplete glass coverage of the hot shoes. This led to a diffusion of germanium from the shoe bonding sites to the intra-shoe glass. The change in shunt resistance which is shown in Figures 20 and 21 resulted from volatilization and deposition of germanium through porosity in the hot shoe protective glass.

In general, the post mortem showed what was inferred from the test data. Steps are now underway to redesign the multicouple cold end hardware, to modify the heat collector design and to improve the glass coverage at the hot shoes. Additional test results at the component level have been encouraging. New module level tests are planned for September 1983.

A detailed discussion of the analysis of the cold end cracking and of the corrective design modifications is presented in References 3, and 4, the next two papers in these proceedings.

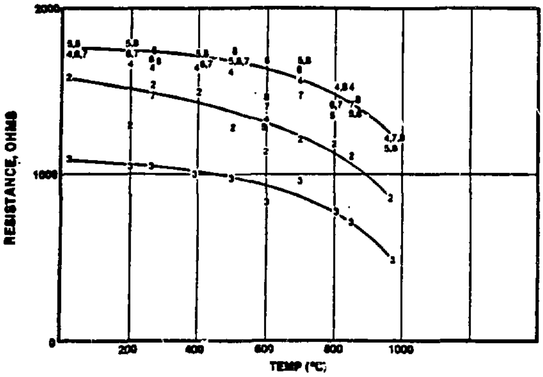

Figure 20. Shunt Resistance Station 1

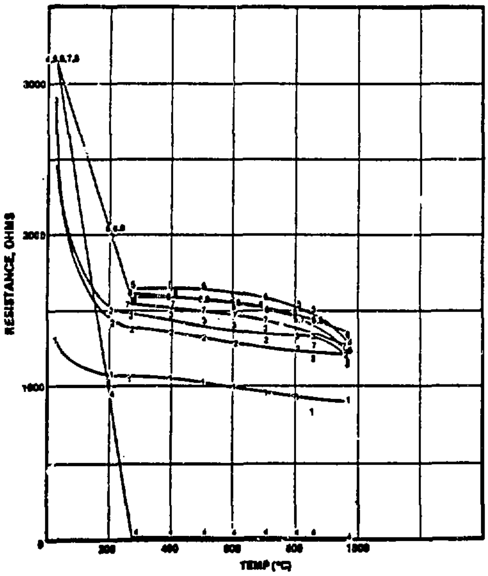

Figure 21. Shunt Resistance Station 2

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[1] A. Schock, "Modular Isotopic Thermoelectric Generator", Proceedings of the 1981 IECEC, Volume 1, Pg. 327.

[2] A. Schock, "MITG Test Assembly Design and Fabrication", Proceedings of the 1983 IECEC, preceding paper.

[3] A. Schock, "MITG Post Test Analysis and Design Improvements", Proceedings of the 1983 IECEC, next paper.

[4] A. Schock, "Revised MITG Design, Fabrication Procedure, and Performance Predictions", Proceedings of the 1983 IECEC, following paper.