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FSEC-ESD-217/81/186

CID #8357
CALC #30-04
MITG TEST PLAN

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August 4, 1981

MITG TEST ASSEMBLY

I. INTRODUCTION AND SUMMARY

The plan presented in the following paragraphs is for the testing of a prototypical slice of the Modular Isotopic Thermoelectric Generator (MITG). This slice is shown in detail in Fairchild Industries' (FI) drawing SK-8104-07, and is subsequently referred to as the test assembly. The test assembly will be heated electrically, but the electrical heater will be enclosed in a graphite box having the same outer dimensions as the General-Purpose Heat Source (GPHS) module. The test assembly contains eight MITG thermoelectric (T/E) modules and prototypic sections of the generator housing and of the proposed foil insulation. The top and bottom of the heater box are particularly well insulated, to minimize non-prototypic heat losses to the housing covers; and the covers are mounted to the housing side wall so as to minimize heat conduction between them. As in the MITG, heat from the prototypic housing side wall flows to the corner fins. From these, it is removed by circulating water through tubes brazed to clamped-on copper saddles. The details of this arrangement are shown in FI drawing SK8106-11. Heat is removed from the top and bottom covers by separate instrumented circulating water circuits.

Four test assemblies are to be fabricated. Two of these will contain the standard SiGe material, and two will contain the GaP-doped material. All will be tested at the reference hot-junction temperature of 1000°C. Accelerated tests may be conducted after observation of performance trends. It is planned to test each assembly in its own vacuum bell jar. It would be possible to run two test assemblies in a single bell jar, but this would necessitate test shutdown of both test assemblies in the event of a failure of a single test assembly. The use of a single bell jar for two test assemblies is therefore not recommended.

Extreme care has been taken in the design of the test assembly to maximize the accuracy of the efficiency determination and of the test assembly heat balance. It is essential that good calorimetry be performed, since establishing T/E module efficiency and the differences in performance between the standard SiGe and the GaP-doped SiGe T/E material are the primary objectives of this test.

There are four major objectives of the proposed test plan. These objectives are:

1. To establish T/E module performance in a systems context. The test must be conducted with sufficient accuracy to discriminate output power and efficiency differences between standard SiGe and GaP-SiGe in identical systems, and to determine the absolute values of the T/E module efficiency and of the shunt loss degradation to a reasonable degree of accuracy.
2. To establish the performance of the module's thermal insulation.
3. To estimate potential T/E module lifetime by careful degradation measurement of each of the individual T/E module's power output. In this manner, it will be possible to determine whether a single T/E module is the cause of test assembly degradation, or whether the individual T/E modules are degrading approximately equally. It will also allow segregation of 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 $\pm 100^{\circ}$ around the design value of 300°C , while holding the hot junction temperature constant at its specified value (1000°C or 1100°C).

The rationale for establishing these test objectives is as follows:

1. In the past, there have been too many surprises when T/E elements have been assembled into T/E modules and generators. A number of materials have looked promising when tested in a controlled laboratory environment. We need to establish T/E module performance in a realistic generator environment. The proposed methods of testing the externally variable electrical circuit and the strong emphasis on calorimetry of the test assembly will generate sufficient test data so that problems which develop can be identified and interpreted properly. The inability to determine where the heat was going and what was going on within the test setup has been a major shortcoming of previous tests conducted in this area.
2. The insulation performance must be established in a generator context. Most thermal losses in foil-insulated systems are caused by penetrations. The test assembly must duplicate the generator geometry, including the thermal stress patterns, and it must be instrumented so that the heat flow patterns may be determined accurately.
3. Too many previous tests of couples and elements have missed synergistic problems which occurred at the generator level

and caused premature performance degradation. The tests must be on a system environment mock-up. The test assembly has been designed as a faithful reproduction of a central slice of the MITG. Since the test assembly contains only a single generator slice, some non-prototypical end effects are unavoidable. But these have been minimized, and the test assembly is several levels of complexity more faithful to the generator design than has ever been attempted at this development stage in previous test programs.

4. It is important to establish performance changes over a range of cold-junction temperature. This information will be useful in optimizing weight and performance tradeoffs. Each thermoelectric module will have its own hot-shoe and cold-stud thermocouples. In addition, it is necessary to assess the temperature losses between the cold studs and the housing wall, and the temperature drops along the wall to the corner fins, as well as the parametric losses through the insulation penetrations, so that this information may be applied to the generator design.
5. Shunt degradation as a result of silicon sublimation is an important life-limiting mechanism in present SiGe RTGs. In the present multi-couple design for the MITG, the role of the sublimation suppression coating is played by a 3-mil silica glass layer instead of the thin silicon nitride coating used in present RTGs. The efficacy and long-term stability of that glass coating must be determined. This is one of the reasons for going to accelerated (high temperature) tests.

The proper methodology for measuring shunt impedance characteristics and for using those measurements to determine the resultant power loss in a full generator has only recently been established. This methodology will be applied in the proposed test plan, not only for the whole test assembly, but separately for each T/E module, to determine variability and permit statistically meaningful predictions.

II. TEST PLAN

The following test plan is presented as a means of achieving the necessary objectives stated in the Introduction and Summary. This plan establishes the MITG module test methodology. It must be augmented by a detailed test procedure when the exact equipment which is to be used to obtain the required test conditions and data is defined.

The details of the test assembly are shown in FI drawing SK8104-7. How and why the data are to be taken are discussed in the following sections.

A. Test Assembly Description

This test assembly has been conceived and designed to allow the performance of careful calorimetry. The level of detail employed to allow good calorimetry is necessary to confirm the potential advantages of the GaP-doped SiGe material. It will also be needed to establish the efficacy of the proposed foil insulation system. To separate the heat losses of the prototypic MITG slice from the non-prototypic end losses, considerable care has been taken to minimize heat transfer between the housing side walls and end covers. Separate heat rejection loops are used on these covers, so that only the heat passed through the simulated generator section will show up in the module calorimetry. Thermocouples and RTD's are located at the critical areas within the module, to provide information on the various heat transfer paths. The details of these locations are presented in subsequent paragraphs. The instrumentation has been selected to allow the careful investigator to determine not just that a performance problem has been encountered but to provide the information to help identify and understand that problem.

A detailed description of the various components which make up the test assembly is presented in the following paragraphs.

1. Module

The thermoelectric (T/E) module is of the type developed by SyncaI and discussed in detail in Reference [1]. Details of the T/E module are shown in FI drawing SK8103-35. Two test assemblies will be fabricated from T/E modules containing the standard SiGe material (eight T/E modules per test assembly), and two test assemblies will be fabricated from the GaP-doped SiGe.

Each T/E module is fitted with its own hot-and cold-junction thermocouple. The T/E module power leads and the cold-junction thermocouple leads are taken through the generator housing via the T/E modules' mounting studs, while the hot-junction thermocouple leads go through the housing in ceramic sheaths.

Determining the performance of the T/E module under a variety of test conditions and durations is the ultimate goal of the test. To assist in attaining this goal, output voltage leads from each T/E module are separately taken through the bell jar base plate. By reading this voltage and measuring circuit current, one may make individual measurements of the output power and current-voltage characteristic of each T/E module. A 32-wire feed-through capable of carrying instrument current at 30 volts is required for this purpose.

2. Heater

The MITG heater element is fabricated from 0.020 inch diameter HT-molybdenum wire. The coil is approximately 0.2 inch in diameter, and is wound approximately 10 turns per inch. The details of the heater element

[1] A. Schock, "Modular Isotopic Thermoelectric Generator", 1981 IECEC, August 1981.

are shown in FI drawing SK8104-28. The wire coil is supported on grooved alumina plates, which are folded to form a rectangle within a POCO graphite box. The heater assembly is shown in FI drawing SK8104-27. The heater is designed to operate at approximately 120 volts. The heater power-lead bell jar feed-through should be capable of carrying five amperes at 250 volts.

Care must be taken to make sure that the pressure within the POCO graphite box is not excessive for proper heater operation. The avoidance of corona discharge within the heater enclosure must be addressed in the detailed test procedure. It is recognized that the design of the heater is crucial to obtaining 10,000 hours' operation on the T/E module test. Careful preconditioning of the heater wire and maintenance of an acceptable atmosphere at the heater surface will be key factors in obtaining the desired heater life. It will be necessary to limit the heat-up rate during the initial start-up period, to minimize component outgassing rates and the adverse effects that these could produce.

The heater is adequately designed to provide 500 watts at an element temperature of 1200°C. Calculations have shown that this heater will give acceptable lifetime if operated in a reasonably good (less than 10^{-3} torr) atmosphere.

3. Insulation

The details of the test assembly insulation package are given in FI drawing SK8104-10. Previous foil insulated RTG systems have used quartz cloth spacers to separate the foil layers. The MITG insulation is the type pioneered by TECO and extensively tested on the BIPS program.

The foil packet on the simulated generator case side has 60 layers

of 0.0003 inch thick molybdenum. The top and bottom cover packets have 120 foils of 0.0003 inch thick molybdenum each. The additional insulation was used to minimize the axial heat loss from the heater and to improve the accuracy of the efficiency determination and of the heat balance. There are no penetrations through the upper foil package, and only four 0.125"-diameter alumina tubes through the bottom. These tubes support the heater block and insulate the heater leads and T/C leads.

Experience has shown that losses at penetrations and joints can be major contributors to heat losses through multifoil insulation. The package has been designed to interleave the foils in such a way as to minimize all losses at edge joints.

Each thermoelectric module is wrapped with a quartz yarn to separate the foil hole edges from the glass coating on the T/E legs, and to fill the gap between the module and the foils. This is done to minimize the module penetration loss. The entire test assembly is covered with an H-blanket type insulation to minimize radiation heat losses and assure that all heat leaving the housing shows up in the cooling water circuit. Care must be taken to assure that all test assemblies have the same external insulation.

The efficiency of the foil insulation is a major issue in establishing the feasibility of the MITG design. Careful calorimetry is required to resolve this issue. The test assembly has been designed with this in mind.

4. Housing

The details of the simulated generator housing are shown in FI drawing SK8104-08. The fins shown in this drawing are not prototypical

of the generator. However, the body of the housing is an exact replica of what has been proposed for the midsection of the MITG. The purpose of the fins, their geometry, and their heat sink are discussed in a subsequent section.

The housing slice shown represents the basic building block for the MITG. The housing and its fin stubs are machined from 6061-T651 stress relieved aluminum plate. Its geometry provides for the eight T/E modules and the insulation for a single 250-watt GPHS module. Modifications to the case are limited to those necessary to accommodate the test instrumentation.

The top and bottom covers for the test assembly housing are shown in FI drawings SK8104-12 and SK8106-10, respectively. These covers carry a water-cooled loop which is used to remove the axial heat losses from the heater block, so that the end losses can be separated from the prototypic side losses, and a precise heat balance may be made. Considerable care has been taken to minimize heat flow in the attachment of the end covers to the housing. The upper and lower covers are mounted to the housing using ceramic standoff insulators. The general arrangement of the cover attachment is shown on FI drawing SK8104-07.

5. Fins, Saddles and Coolant Tubes

Good calorimetry cannot be performed in the absence of the ability to measure the heat passing through the simulated generator housing. Attempts to determine system performance by measuring heat input only would not be sufficiently accurate for the purposes of this test. Therefore, a water cooling loop has been added to the housing fins. Water from a constant temperature bath is circulated through this loop. The flow rate and temperature rise are carefully measured, and the amount of

heat arriving at the fins is determined. The sum of the electrical output and the heat removed from the fin water loop and the cover water loop should equal the heat input. The details of the water cooling loop are shown in FI drawing SK8106-11.

The fin cooling water loop is fabricated from 5/16 inch refrigeration-grade copper tube. Each tube is brazed to a copper block, which is in turn bolted to a copper compression plate through the slotted holes in the housing stub fins. Slots are used to permit shifting the location of the cooling blocks on the fins after assembly. This makes it possible to equalize and adjust the fin root temperatures. Shifting the cooling blocks will change the length of the connecting tubes. These length changes, as well as thermal expansion differences, are accommodated by the flexible (corrugated) bronze tubes which connect the individual coolant pipes.

Each of the housing stub fins is trapped between two copper blocks. These blocks contain thermocouples and can be moved along the fin slot to the location which will produce the proper cold-junction temperature at each fin root.

The coolant flow rate was selected to give a 20°C rise from inlet to outlet. Variations in the block position on the fins can compensate for changes in the coolant water temperature from fin to fin and for any differences in contact conductance between the fins and the copper blocks.

The stub fins act as heat dams. They were sized to produce a temperature drop from the housing to the coolant tube wall which will keep the coolant water temperature well below its boiling point at atmospheric pressure. The details of this analysis are presented in Appendix A.

6. Instrumentation

The four test assemblies will be tested at one or two test sites. Each test organization will have at least one SiGe and one SiGe/GaP assembly, to be tested at the same temperature. This will optimize comparison of the two materials.

The test assembly will require considerable support instrumentation. The details of this support instrumentation are presented in Chapter III. Each test assembly will be turned over to the test operator with forty two installed thermocouples. There will be two W/Nb thermocouples in the POCO graphite heater block, and eight W/Nb hot-junction thermocouples. Other W/Nb thermocouples include eight cold-junction thermocouples, eight at the module mounting points on the housing wall, four additional housing thermocouples, four at the fin roots, four on the copper saddles, two on the top cover and two on the bottom cover.

Provisions have been made to isolate the refractory metals from the carbon heater block so that there will be no chemical reaction. Although temperatures in the range of the T/E cold-junction and housing are usually covered by chromel/alumel, the use of this material in vacuum at the proposed test temperatures is potentially bad practice. The output at this temperature is 3 mV. Thermocouple longevity is a serious issue in the performance of a life test. All thermocouples should be refractory metal to obtain the desired longevity. As can be seen, however, this choice results in serious sensitivity problems. The use of good thermocouple readout instrumentation (16 bit) is essential to the use of refractory metal thermocouples for this application.

It is not likely that refractory metal feed-throughs for the vacuum bell jar will be available. As a result, it is recommended that the cold-junction reference be established inside the vacuum bell jar and that all

wires leaving the bell jar be copper. This requires that an artificial cold-junction reference be provided inside the vacuum bell jar.

The critical nature of the rise in the coolant temperature across the fin loop requires the use of an RTD or a differential thermocouple. The same is true for measuring the temperature rise in the coolant in the top and bottom cover loops. These temperature sensors will be mounted in wells in the coolant stream, close to their inlets and outlets. Differential thermocouples will also be used to measure critical temperature drops, e.g., that between the T/E module stud and the generator housing due to contact resistance.

Approximately 50 thermocouples per test assembly have been identified at this time. Good test practice would dictate that provisions be made for accommodating approximately 120 thermocouple lead penetrations per test assembly.

B. Test Set-Up

The MITG test assembly will require the use of some special equipment. It is assumed that most of the incidental test equipment will be available at the testing laboratory. The principal equipment necessary to conduct the proposed test consists of:

- Four 18-inch diameter vacuum bell jars
- One constant-temperature water bath
- Data logging equipment capable of digitizing 100 analog signals per test assembly, and interfacing either with a data processing system or with a data acquisition and storage system. In the latter case, the stored data would subsequently be transmitted to a computer for post-processing, including statistical analysis and graphic output preparation.

The data logger requirements are discussed in Chapter III. The requirements of the vacuum station and the constant-temperature bath are discussed in the following paragraphs.

1. Vacuum Bell Jar

The vacuum station must be capable of producing a pressure of 10^{-6} torr with the outgassing load of the test assembly. This should be within the capability of any of a number of commercially available vacuum stations.

Electrical feed-throughs will be a problem. It is unlikely that W/Nb thermocouple vacuum feed-throughs can be obtained on a reasonable

schedule. As a result, it is recommended that an electronic cold-junction be installed inside the bell jar and the corrected thermocouple signals be carried through the bell jar wall by copper wires and standard vacuum feed-throughs. Provision for accommodating 60 thermocouple feed-throughs (120 wires) per test assembly will be required. Four standard 32-wire connectors would accommodate the necessary thermocouple instrumentation.

For reasons which will be discussed later, it is necessary to bring the individual test assembly output voltage measurement taps through the bell jar wall. This will require a 32-wire connector capable of handling instrument currents at 30 VDC.

A low-voltage power supply is required for the shunt resistance measurement. Since this is a very low power requirement, spare thermocouple connector pins will provide the necessary current-carrying capacity.

The heater will require two power leads. The feed-through for these leads must be capable of carrying 5 amperes at 250 VDC. The series-connected module output leads carry 2 amperes at 50 VDC.

The water cooling loops may be carried through the bell jar wall on a single flange plate fitted with four 5/16 inch O.D. copper tube stubs.

In summary, the following bell jar feed-throughs will be required:

- 4 connectors - 120 thermocouple (copper) wires
- 1 connector - 32 pins, 20 used for output voltage and shunt resistance measurement. The remainder are spares
- 1 connector - 2 copper wires, 250 VDC, at 5 amperes (+ spares)
2 copper wires, 50 VDC, at 2 amperes
- 1 connector - spare

The above requirements are typical of a standard vacuum bell jar station which has eight blank Conflat flanged penetrations. The connectors can be obtained from stock and fitted to these flanges, or they may be purchased from a vendor from his stock.

2. Constant Temperature Bath

The constant temperature bath must have a 2 kw heat rejection capacity at a cooling water temperature of $40^{\circ}\text{C} \pm 2^{\circ}\text{C}$. The minimum flow rate must be 200 lbs/hr.

There are a number of commercially available units which meet these specifications. It is recommended that a bath which recirculates demineralized water be chosen. The use of tap water as the cooling medium is not recommended because of potential scaling problems at the high wall temperatures encountered in the copper tubes brazed to the copper block heat sinks.

Provisions must be made for flow control on the side fins and top- and bottom-covers of the individual test assemblies. NUPRO micrometer valves are recommended. Individual turbine type digital (pulse counter) flow meters are recommended. The flow sensing devices deliver readings to the data acquisition system, and are used to signal heater power cut-off on loss of coolant flow. The details of this and other safety interlocks are presented in Chapter III.

C. Thermoelectric (T/E) Module Performance

The absolute level of the T/E module performance is a critical issue in the MITG design. The relative performance of the standard SiGe and the GaP-doped material is an issue in the future development plans for high temperature T/E materials. The T/E module performance must be established to a high degree of accuracy in order to determine if continued research in this area is worthwhile.

The principal issues involved in determining the T/E module performance are related to test assembly calorimetry, T/E module output power, and internal losses due to shunt degradation. Each of these issues will be discussed in the following paragraphs.

1. Calorimetry

The design of the test assembly was complicated by the desire to provide accurate calorimetry. Test instrumentation is required to measure input power, heat output through the simulated generator housing, heat output through the top and bottom covers, and electrical power output. Input power can be determined by measuring heater voltage and current. It is recommended that separate heater voltage taps be used within the test assembly rather than measuring the voltage at the heater power supply. Uncertainties which arise in calculating the various wire and connector voltage losses can be eliminated by using this technique.

Heat rejection is significantly more difficult to determine. Each test assembly must be supplied with cooling water flow to the stub fins and cooling water flow to the top and bottom covers. This water flow must be measured carefully during the test assembly calorimetry. It is recommended that performance tests be conducted over a relatively long period of time

(10's of minutes) and that the coolant flow over that period be collected and weighed. This technique is also used to calibrate the turbine flow meters. Serial measurements of hot-junction, cold-junction, and housing temperatures should also be made during the period of the performance tests. The details of the data acquisition are presented in Section III.B.1.

The inlet and outlet temperatures of the coolant flow must be determined very accurately. RTD's or differential thermocouples should be used to measure the temperature rise across each test assembly cooling water loop. These sensors are mounted in wells at the fin coolant and cover coolant inlets and outlets. Indirect measurement of the coolant temperature by the use of external thermocouples at the relevant fin locations will be useful as a guide to the water temperature distribution along its flow path, but will not be sufficient to provide the required measurement accuracy.

The coolant inlet temperature should be controlled in the constant-temperature bath reservoir. It should also be measured there by an immersion type temperature indicator. The return temperature should be measured in the same manner. The coolant bath reservoir should be large enough to allow diversion of the demineralized water flow over the test period without adversely affecting the coolant flow to the remaining test assemblies.

Once the cooling water mass flow rate is determined and the temperature rise is known, one can calculate 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 electrical power input to the heaters. Error in the comparison of these values will be an indication of 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.

2. Power Output

The output voltage of each individual T/E module is measured. The output voltage of the eight T/E modules connected in series and the current flowing in the T/E module electrical circuit are also measured. The product of voltage and current is used to determine the T/E module and test assembly output power. The individual T/E module output power measurements are useful in determining the scatter among the T/E modules, after correcting for small variations in hot- and cold-junction temperatures. This scatter, by inference, is a measure of the T/E module production quality control.

Each module is fitted with a hot-and cold-junction thermocouple. Differences in these temperatures among the modules may be indicative of variations in stud contact resistance, bond thickness, T/E material thermal conductivity, hot shoe emissivity and variations in the parasitic heat losses through the T/E module quartz yarn wrap. The strategic location of the thermocouples on the housing may be used to determine the probable cause of T/E module power output variations.

Part of the T/E module performance will involve generation of I-V curves for each individual T/E module. These curves will be useful in determining the maximum efficiency and maximum output power operating conditions for T/E modules deployed in a generator context. The primary design points for measurement of output power are a hot-junction temperature of 1000°C and a cold-junction temperature of 300°C . Parametric tests around the 300°C cold-junction temperature are planned and are discussed in a subsequent section. Accelerated tests at hot-junction temperatures higher than 1000°C are planned for two of the four modules, one of each T/E material.

Measurement of the relative power output of the standard SiGe and GaP/SiGe will give a fair evaluation of the potential improvement which

can be obtained using GaP/SiGe in a generator context. The test articles have been configured to minimize parasitic losses so that the relative merit of the GaP additive can be determined by power output comparisons, even if the heat balance cannot be completely closed. The results of this relative comparison may then be used to determine the emphasis of further SiGe development efforts.

3. Shunt Degradation

In thermoelectric generators with SiGe legs, operating at hot-junction temperatures of 1000°C or more, silicon tends to sublime from the hot ends of the legs, and to travel through the interstices of the quartz yarn wrap, until it condenses in a lower-temperature zone. The resultant deposits act as conductive shunts between the thermoelectric legs and the multifoil insulation. The consequent shunt currents cause unacceptable power output degradation in the generator, unless silicon sublimation can be eliminated or significantly retarded. Present SiGe RTGs use legs coated with a thin (~ 12000 Angstrom) layer of Si_3N_4 as a sublimation retardant. Even with that coating, the gradual coating loss and the consequent silicon sublimation and shunt degradation is the principal life-limiting mechanism in the RTG.

In the T/E module design used in the MITG, the role of sublimation suppressant is played by a relatively thick (0.003 inch) coating of SiO_2 glass. Preliminary sublimation tests of glass-coated SiGe have shown very encouraging results, but the long-term stability of those coatings is far from demonstrated. Nor have they as yet been tested in the context of a prototypical generator slice which duplicates the geometric and chemical environment of the MITG. The proposed test is designed to answer both of those questions.

Great care is warranted in properly performing the required shunt characterization experiments, since the shunt effects may well limit the ultimate lifetime and/or hot-junction temperature of the MITG. Recent studies have shown that the shunts formed by the silicon condensate are non-ohmic in nature, with highly non-linear current-voltage characteristics which do not even pass through the origin. Therefore, these shunts cannot be characterized by a single resistance measurement, since their resistance is a strong function of the voltage between the T/E leg and the foil package. In a typical generator, that voltage will vary over a range of 30 volts. Therefore, the current-voltage characteristic of each shunt must be measured over that range of voltage, typically from -30 volts to +30 volts. This can be done by using an adjustable external power supply, varying the module to foil voltage over the desired range, and measuring the resultant shunt currents.

To be able to interpret the above measurements, it is essential that all the couples in the test assembly operate at the same voltage relative to the foils. Clearly, this would not be the case under open-circuit or on-load conditions, since the 144 couples in series would operate at very different voltages under those conditions. The only way to ensure that all 144 shunts are subjected to the same voltage differential is to short-circuit the thermoelectric circuit.

One way of shorting the circuit would be to short out the external load. In this way, the combined or average IV characteristic of all the shunts could indeed be determined, by applying an adjustable voltage between the foils and the shorted circuit, and by measuring the resultant combined shunt current. But this type of measurement would tell one nothing about the variability or scatter of the shunt characteristics. For example, a seemingly severe shunt degradation might be due to the

anomalous shunt behavior in a single T/E module, while the other seven continued to operate in a low-degradation mode. Such a condition could only be identified if the shunt characteristics of the eight T/E modules in a test assembly were measured individually.

Individual shunt characteristics within a test assembly can be easily determined if the series circuit between modules is broken during shunt current measurements. As will be shown in a subsequent section, this can be readily accomplished by using a ganged 8-pole double-throw relay. The relay simultaneously breaks the series connections between the eight T/E modules and shorts each one. The eight shorted T/E modules are connected to a common terminal of an external power supply through individual current-measuring resistors. The other terminal of the power supply is connected to the foil package. By this arrangement, the individual shunt characteristics for the eight T/E modules can be measured simultaneously. The individual measurement variation observed is potentially of great value for subsequent statistical reliability studies and confidence limit computations.

Once the individual shunt characteristics have been determined at a given point in time, they can be used to compute the resultant state of power degradation in a full generator. This can be done by means of an iterative computer program which has been developed at FI.

D. Insulation Performance

The MITG is insulated with 60 foils of 0.0003 thickness. These foils consist of molybdenum in the hottest region, titanium in a central zone, and aluminum in the coldest region. The test assembly insulation uses all-molybdenum foils. The delivery time for the titanium foils was too long to be useful in the test assembly program.

Foil insulation of the type employed was developed by TECO and was extensively tested on the BIPS program. This insulation uses a fine ZrO_2 powder to hold the thin metal foils apart. A separate dynamic test is planned to examine the behavior of the insulation and the thermoelectric modules. The stability of the ZrO_2 particle bonding during vibration was demonstrated during the BIPS program tests. This stability will be checked again during the planned test assembly dynamic tests.

1. Apparent Heat Loss

The general heat loss through the foils can be determined by careful calorimetry of the top and bottom covers. There are no penetrations in the insulation of these covers so that this will be a relatively good test of the planar foil section losses. The heat transferred to the covers by way of the supports will somewhat affect the insulation efficiency prediction; however, these losses will be predicted analytically and a good approximation of the insulation performance should be attainable.

2. Penetration Effects

Most losses which occur in foil-insulated systems occur at penetration locations. The test assembly has thermocouples on the housing at strategic locations so that the penetration losses can be approximated.

The penetration losses will be predicted analytically by post-processing the data obtained during the test. The empirical housing temperature profiles will be compared to the analytically-predicted profiles and an assessment of the penetration losses will be prepared.

E. Thermoelectric (T/E) Module Life

The construction methods used in the MITG T/E module employ essentially unproven technology. The ability of the bonds and the foil insulation to perform their required functions over a reasonable period of time is unproven. It is essential that the lifetime potential of the MITG T/E module technology be established. This is clearly a MITG feasibility issue. The intent of the lifetime test is to demonstrate that the proposed construction methods are promising. The proposed test will not prove 100,000 hour life. Successful completion of this test will provide a positive basis for a recommendation to continue the development of T/E modules of this type.

The life test shall be conducted holding the hot-junction temperature constant at its prescribed value, and the cold-junction at 300°C. It is assumed that there will be small variations around these values due to instrumentation and control drift. The power will be adjusted to account for changes in the thermal conductance path between the hot shoe and the cold stud. Power input, power output and module efficiency are plotted as a function of test time. The details of the data reduction are presented in III.B.2.

The power output during the life test will be measured at a constant output voltage of 28 volts. The output load impedance (adjustable power supply) will be set to maintain this voltage constant.

Periodic measurements of T/E module open-circuit voltage will be conducted. Individual T/E module I-V curves will be generated periodically.

The performance of the various tests, as well as controller and instrumentation drift, will cause data to be obtained at slightly different

absolute values of hot- and cold-junction temperatures. Provisions are made in the data logging equipment to normalize the measured output to the nominal 1000°C - 300°C T/E module temperature interval. The normalizing algorithms will be standardized among all parties involved in the data reduction.

The shunt resistance characteristics and the output power of the T/E modules are measured independently for each module, to provide an insight into any degradation mechanisms which may develop. These measurements will be used to determine the scatter in the initial T/E module outputs, and to follow the changes in that scatter with time. It is important to see how the individual modules vary within the average. This information can be used to infer if system degradation is caused by a single T/E module failure or if it is a general lowering of the aggregate power output. The scatter data is important for statistical reliability predictions and for establishing confidence limits on generator degradation.

The change in shunt resistance with time is a key degradation mechanism. It is not clear that the shunt resistance mechanism intrinsic to the MHW T/E elements is applicable to the MITG T/E module. The details of how this test is to be conducted were presented in II.C.3. It is recommended that the shunt resistance measurements be made relatively frequently in the beginning of the test (perhaps once a day). Guidance on the frequency with which this test should be conducted should be taken from the results of the initial measurements.

It must be remembered that the thermal cycles engendered by some of the tests being performed do not occur over the course of an operational generator's lifetime. Discretion must be used in determining the intervals over which data are taken. It is necessary to trade off the need for information against the thermal cycling inherent in obtaining those data. At this point in the MITG program, it is probably wise to sample at as high a rate as is practical. This observation should be tempered by experience gained as the test program progresses.

F. Parametric Tests

Parametric variations in the test cold-junction temperature are conducted. Analyses which predict weight and power output variations as a function of cold-junction temperature are invariably compromised by lack of knowledge of the behavior of second-order variables. Things like changes in contact resistance, parasitic heat losses, insulation performance, and temperature variation in the housing are difficult to predict accurately by analysis. This test is intended to give an empirical basis from which the predictive analyses may be calibrated.

The parametric tests should be conducted at cold-junction temperatures of 400°C and 200°C. Individual T/E module and system I-V curves should be obtained, and the scatter in these results should be analyzed. Calorimetry should be performed at each temperature, and a system efficiency should be calculated.

The change in cold-junction temperature should be accomplished while holding the hot-junction temperature constant at 1000°C. This will require adjustment of heater power and cooling water flow. Calculations have been made which show that the parametric temperature range may be accommodated by varying the cooling water flow rate from 10 to 40 lbs/hr for cold-junction temperature of 400 and 200°C, respectively. The details of these calculations are presented in Appendix A.

III. INSTRUMENTATION, DATA ACQUISITION AND REDUCTION PLAN

The basic objectives of the MITG T/E module test program and a description of the manner in which those objectives are to be accomplished were presented in the previous chapters. The manner in which the tests are to be instrumented were previously discussed in general terms. The details of the instrumentation required to perform the proposed tests are discussed in this chapter.

One hundred data channels per test assembly are required to conduct the proposed tests. The reduction of these data by standard techniques would present an unreasonable manpower burden. It is therefore necessary that, after initial manual check-outs, automated data collection and data reduction techniques be employed. Data sampling rates and sampling sequences are established in the data logger software. The data acquisition program is then exercised, using a programmed test sequencer, conventional analog-to-digital converters, and data logger-to-floppy disc computer interfacing equipment.

The usefulness of the diagnostic output of the proposed instrumentation is almost totally dependent upon sophisticated data reduction techniques. Methods of data sampling, preprocessing, and post-processing of the collected data by statistical techniques are discussed in a subsequent section.

A. Instrumentation

The instrumentation required to obtain the data necessary to establish MITG T/E module performance and lifetime may be divided into four basic categories. These are:

1. Temperature measurements.
2. Cooling water conditioning and flow measurements.
3. Electrical measurements.
4. Control and annunciator functions.

The items listed above will be discussed as they relate to the performance tests, the shunt resistance measurements, the life tests, and the parametric tests.

The location and type of thermocouples necessary to provide the required temperature measurements are shown in Figure 1. An electrical wiring diagram for the test assembly is shown in Figure 2. An electrical wiring diagram for the heater control and safety interlocks is shown in Figure 3. A sketch showing the cooling water flow path, conditioning and flow control and measurement is shown in Figure 4.

1. Performance Test

Conducting the performance test requires that the individual thermoelectric modules be connected in series, that their individual voltages be monitored, and that the load impedance be varied to produce individual thermoelectric module and aggregate thermoelectric module I-V curves. Analytically generated curves of the type expected are shown in Figures 5 and 6. Curves showing the expected output power as a function of load voltage for a single thermoelectric module and the series-connected test assembly are shown in Figures 7 and 8.

The experimental I-V curves are generated by connecting the output of the test assembly to a stiff adjustable power supply. Relays are provided to allow measurement of individual thermoelectric module open-circuit voltage, series-connected thermoelectric module open-circuit

Figure 1. General Arrangement of MITG Test Assembly Thermocouples

Figure 2. MITG Test Assembly Wiring Diagram

Figure 3. MITG Test Assembly Control and Annunciator Functions

Figure 4. MITG Test Assembly Cooling Water Flow Chart

Figure 5. MITG Thermoelectric Module I/V Characteristics, Si/Ge-GaP

Figure 6. MITG Test Assembly I/V Characteristics, Si/Ge-GaP

Figure 7. MITG Thermoelectric Module Power/Voltage Characteristics, Si/Ge-GaP

Figure 8. MITG Test Assembly Power/Voltage Characteristics, Si/Ge-GaP

voltage, and load and short-circuit current. The adjustable power supply also provides a means of producing variations in current (I) around the 30 VDC design point.

The output voltage from each thermoelectric module is fed into an analog-to-digital converter, which is interfaced to the floppy disc data storage computer. The details of this data processing equipment are discussed in a subsequent section.

a. Temperature Measurement. The operating temperatures of the simulated heat source and thermoelectric hot junction are too high for conventional thermocouple materials. These measurements must be taken with refractory metal thermocouples. The use of W/Nb is recommended for this application. The lower temperatures, such as thermoelectric module cold-junction, housing, etc., are in a range which would normally be covered by chromel/alumel thermocouples. Chromel/alumel thermocouples are, however, not reliable at these temperatures in vacuum. The use of refractory-metal thermocouples at the low temperatures results in a decrease in sensitivity. The output of a refractory metal thermocouple at 300°C is only 3 mV, compared to 12 mV for chromel/alumel thermocouples. The need for long-life thermocouples outweighs the sensitivity disadvantage. However, extreme care should be used to minimize a possibility of noise and other spurious signals at these projected low output voltages. Cooling water temperature measurements may be performed with chromel/alumel or copper/Constantan thermocouples, since these temperatures are very low. A listing of temperature instrumentation which must be provided to obtain the required test information follows. The values shown in parentheses are the number of places the temperature is monitored in each test assembly, and the expected range of variation in that temperature.

1. Thermoelectric module hot-junction temperature (8 places, $900-1150^{\circ}\text{C}$).
2. Thermoelectric module cold-junction temperature (8 places, $200-400^{\circ}\text{C}$).
3. Thermoelectric module cold stud-housing interface temperature (8 places, $200-400^{\circ}\text{C}$, requires high resolution).
4. MITG housing segment face temperature (4 places, $200-400^{\circ}\text{C}$).
5. MITG housing segment fin root temperature (4 places, $200-400^{\circ}\text{C}$).
6. Cooling water saddle temperature (4 places, $200-400^{\circ}\text{C}$).
7. Simulated GPHS module temperature (2 places, $1200-1400^{\circ}\text{C}$).
8. Cooling water inlet temperature (1 place, 40°C).
9. Cooling water outlet temperature (1 place, 60°C).
10. Top and bottom cover cooling water inlet temperature (1 place, 40°C).
11. Top and bottom cover cooling water outlet temperature (1 place, 45°C).

b. Cooling Water Conditioning. Heat is removed from the test assembly by the circulation of cooling water. A constant-temperature bath is used as a reservoir for the cooling water supply. A schematic of the flow and control functions was shown in Figure 4. It is assumed that a suitable constant-temperature bath is available commercially. This bath must have a reservoir sufficiently large to allow the diversion of coolant from the return line to a collecting vessel without affecting the test of the other assembly, so that the mass flow rate may be measured accurately.

NUPRO micrometer globe valves are used to set the cooling water flow

for the test assembly fins and covers. The cooling water return lines are fitted with Tygon tubing sections so that flow can be diverted from the common constant temperature bath into a vessel which can be weighed. This will reduce the accuracy requirement on the inline flow meter and will provide a convenient and ongoing method for flow meter calibration. Turbine type digital pulse generating flow meters are used.

Two coolant flows must be measured in each test assembly. The fin cooling water flow instrumentation has a range of 0-50 lb/hr. The top and bottom cover cooling water flow has a range of 0-5 lb/hr.

c. Electrical Measurements. The electrical wiring diagram for the test assembly was presented in Figure 2. Electrical measurements are made to determine the performance of the MITG thermoelectric module. The following data channels are required to conduct the electrical measurements on one test assembly:

1. Individual module voltage (8 places, 0-10 VDC).
2. Series-circuit voltage (1 place, 0-50 VDC).
3. Series-circuit current (1 place, 0-30 Amp.).
4. Heater voltage (1 place, 0-200 VDC).
5. Heater current (1 place, 0-5 Amp.).

d. Control and Annunciator Functions. The primary control function required during the conduct of the performance test is maintenance of constant hot-junction temperature. Each thermoelectric module is fitted with a hot-junction thermocouple. The output of this thermocouple is fed into the data logger as part of the normal data acquisition system. These signals are sampled by the heater power controller and auctioneered to determine if there is an open or erratic thermocouple circuit. After discarding erratic or implausible measurements, the remainder are averaged

and used as the sensor signal for the heater power supply controller. This controller functions separately from the data acquisition system. It has rate, reset, and proportional-band functions, so that it can be tuned to accommodate the step changes in thermoelectric module thermal conductivity which occurs during open- and short-circuit testing. The controller is also provided with a number of safety interlocks, which are used to shut down the heater power if prescribed limits on the following variables are exceeded:

1. Low cooling water flow.
2. High hot-junction temperature.
3. High cold-junction temperature.
4. High heater power
5. High vacuum bell jar pressure.

In the event any of the above alarms occur, the data acquisition system logs the time of occurrence and sounds an audible and visual alarm. Automatic restart capability is not provided. The cool-down rate of the module is monitored after heater shutdown and, if it is too high, the cooling water flow to the stub fins is secured. If high thermoelectric module hot-junction/or cold-junction temperatures are sensed, the cooling water flow is restarted.

2. Shunt Resistance

The determination of the shunt characteristic requires that an external voltage be applied between the foil insulation and the thermoelectric module power output leads, with the leads shorted. Figure 2 shows the circuit for the shunt resistance test in phantom line. Shorting relay (K1) contacts are provided within the vacuum chamber for each of the eight thermoelectric modules.

a. Temperature Measurements. The temperature measurement requirements for the shunt resistance test are identical to those described in III.A.1.a. above.

b. Cooling Water Conditioning and Flow Measurement. The cooling water conditioning and flow measurement requirements for the shunt resistance test are identical to those described in III.A.1.b. above.

c. Electrical Measurement. The following data channels are required in order to perform the shunt resistance measurements on a single test assembly:

1. A module-to-foil applied shunt voltage (1 place, -30 to +30 VDC).
2. Module-to-foil shunt current (8 places, microamps to milliamps, depending on state of degradation).

d. Control and Annunciator Functions. The shunt resistance tests are conducted within the performance and lifetime tests. As such, they require input power to be controlled to hold the hot-junction temperature constant at 1000°C , and the cold-junction temperature constant at 300°C . The method of control is the same as described in III.A.1.b. and III.A.1.d. Small variations in these temperatures are expected and will be accommodated by normalization in the data reduction program.

Special control functions are required to modify the electrical circuit of the performance test so that accurate shunt resistance measurements may be obtained. The circuit requirements for the shunt resistance tests are shown in phantom line in Figure 2.

Relays (K1 and K2) are actuated to disconnect the adjustable power

supply and to short-circuit the output of each thermoelectric module. Relay K4 is actuated to place a ± 30 VDC adjustable power supply in series with the shunt resistance measuring circuit.

The shunt material has been shown to be a non-linear resistance akin to a semi-conductor. After allowing the thermoelectric module to recover from the temperature change brought about by shorting its electrical output, the ± 30 VDC power supply is swept in one VDC increments through a voltage range of -30 to +30 VDC by the test sequencer. The individual module-to-foil shunt currents are measured and recorded for each value of applied voltage. Sampling rates and the methods of acquiring and reducing the resultant data are discussed in Section III.B.

No special annunciator is required for the shunt resistance tests. If there is a failure of the shunt resistance test power supply, the relays, or any of the current recording channels, the data logger software should set a flag that the failure has occurred. The test, of which the shunt resistance measurement is a subtest, should not be automatically terminated for failure in instrumentation specific to the shunt resistance test.

3. Life Test

The life test is conducted by serial repetition of the basic performance test over a period of 10,000 hours. The instrumentation required to conduct this test is that which was discussed in Section III.A.1. above. A heat balance should be conducted on a daily basis to identify any change in the system thermal efficiency. Such a change would first present itself as a change in the heater power required to maintain the thermoelectric modules at the specified hot-junction temperature.

It is planned that the life test be conducted at constant hot- and cold-junction temperatures. This will require variations in heater input power and cooling water flow rate to compensate for any changes which occur in the test assembly performance during the course of the life test.

a. Temperature Measurement. Temperature measurements needed to evaluate the test assembly life are the same as those required to evaluate its performance. These measurements were discussed in detail in Section III.A.1.a.

b. Cooling Water Flow. The cooling water flow measurements needed to evaluate the life of the test assembly were discussed in detail in Section III.A.1.b.

c. Electrical Measurement. The electrical measurements needed to evaluate the life of the test assembly were discussed in detail in Section III.A.1.c.

d. Control and Annunciator Functions. The control and annunciator functions needed to evaluate the life of the test assembly are identical to those discussed in Section III.A.1.d.

4. Parametric Tests

Two cold-junction temperatures besides the 300°C reference value are to be investigated. The hot-junction will be held at 1000°C while cold-junction temperature is varied. Heater power will automatically change to respond to the 1000°C controller set point. Cold-junction temperature will be varied by changing the cooling water flow rate.

a. Temperature Measurement. Temperature measurements needed to evaluate the test assembly parametric behavior are the same as those required to evaluate its performance. These measurements were discussed in detail in Section III.A.1.a.

b. Cooling Water Flow. Variations in the cold-junction temperature are produced by changing the cooling water flow rate over the range 10 lb/hr to 40 lb/hr. The flow is varied by manually changing the setting of the NUPRO micrometer flow control valve. Measurements are made in the manner discussed in III.A.1.6.

c. Electrical Measurement. The electrical measurements needed to evaluate the parametric variations of the test assembly were discussed in detail in Section III.A.1.c.

d. Control and Annunciator Functions. The control and annunciator functions needed to evaluate the parametric variations of the test assembly are identical to those discussed in Section III.A.1.d.

B. Data Acquisition and Reduction

The plan for data acquisition and reduction is based on the use of a test event programmer (sequencer), sequence programmable analog-to-digital converters, a floppy-disc data storage system at the test site, and a main frame post-processor computer, either on or off the test site. The data acquisition system is separate from the control and annunciator system. Its functions are to position relays used to produce the required electrical test configurations, to sweep the necessary applied voltages through their required ranges, to select the desired instrumentation signals, to digitize those signals and to store them in numerical arrays on a floppy disc.

Data reduction is accomplished in a main frame computer. The arrays stored on the floppy disc are transferred to the main frame on a daily basis for post-processing. Sampling rates are selected such that both short-term and long-term trends may be detected. The details of the Data Acquisition and Reduction Plan are presented in the following paragraphs.

1. Data Acquisition

The desired data will be acquired using the general techniques described above for the performance tests, the shunt resistance determination, the life tests, and the parametric tests. The details of the data acquisition will be described in the context of those tests in the following paragraphs.

a. Performance Test. The performance test results will be obtained by establishing the electrical circuit shown in bold line in Figure 2. The test event sequencer positions relay K1 to connect the eight thermoelectric modules in series with the 28-volt load. This position is the

no-voltage or fail position of this relay. The test sequencer establishes the set-point voltage in the adjustable power supply. The data logger is automatically stepped to read and record the eight individual thermoelectric module output voltages and the load current. The test sequencer then activates relay K2, which removes the adjustable power supply from the test assembly output bus. The data logger sequencer records the individual thermoelectric module open-circuit voltages (V1-V8). The aggregate open-circuit voltage (V10) is also measured. The sequencer closes the shorting relay (K3), the short-circuit current is measured and recorded, and the data logger steps through the individual thermoelectric module voltages and again records them. Shorting relay K3 is opened and the adjustable power supply load voltage is reconnected by de-energizing relay K2.

The above sequence establishes one cycle within the performance test. Throughout this cycle, the cooling water flow and temperature rise has been sampled and recorded. The heater power has also been sampled and recorded. Care must be taken to sequence the heat balance information in such a way that equilibrium values are recorded. The short-circuit and open-circuit voltage measurements will cause variations in the heater input power, which will not allow heat balance calculation to be performed.

The duration of the performance test must be such that the various thermal transients are allowed to subside before the test cycle is repeated. The exact duration of this time and the number of times that the open-circuit and short-circuit tests are conducted must be determined after the test assembly thermal response time is experimentally determined. The basic performance test sampling rate should be such that a scan of the eight module temperatures, the cooling water flow, the cooling water inlet and outlet temperature and the heater power input is performed every 10 minutes. Burst tests are conducted at the data logger maximum scanning

rate for continuous periods of 10 minutes several times a day. These tests are needed to observe any very-short-term performance fluctuations.

Sampling at the above rates leads to the generation of 160,000 bytes of data per test assembly per 24 hours. This sampling rate and data generation rate is consistent with the use of a Tektronix 4907 floppy disc system. This type disc has the capacity to store 640,000 bytes. The floppy discs are reused after they are unloaded onto the main frame post-processing computer. Archiving of all of the data channel information at these data sampling rates would require the use of two 1600 BPI nine-track magnetic tapes per test assembly, partitioned to have one file per day.

b. Shunt-Characteristic Measurement. The shunt resistance measurement requires the repositioning of circuit relays to disconnect each thermoelectric module from the bold-line circuit shown in Figure 2, and to short the individual thermoelectric module outputs. The test sequencer energizes relays K1, K2, K3 and K4 to establish the electrical circuit required to conduct the shunt resistance test. The sequencer steps through the ± 30 VDC power supply through a voltage range of -30 to +30 VDC in 1 VDC increments. The shunt current is measured on each of the individual thermoelectric modules, digitized and stored on the floppy disc. The time during which this test is conducted is established experimentally, since the shunt material has a non-linear resistance and a somewhat delayed response. The shunt resistance test is performed once daily.

c. Life Test. The life test is a serial repetition of the performance test and shunt characteristic test over a period of 10,000 hours. The basic procedures described in the performance test are repeated throughout the life test, at sampling rates approximately equal to those used in the initial performance test.

The data burst tests are conducted throughout the life test so that short-term trends, such as the ratcheting which occurred in the selenide program, may be detected. This sampling rate will produce sufficient information to perform statistical data analyses and degradation predictions, and allow a basis for determining if observed trends are intrinsic or instrumentation-related.

d. Parametric Tests. The parametric tests require variations in the test assembly cooling water flow rate. These variations will be used to produce thermoelectric module cold-junction temperatures of 200°C and 400°C. The NUPRO micrometer valves will be manually adjusted to produce the cooling water flow rate required for the cold-junction temperature selected. The heater controller set point will remain at 1000°C. The test sequencer will step through the performance test, and the data logger will perform in the same manner as described in Section III.B.1.a. above. The flowmeter will be checked by cooling water collection and weighing at each of the selected parametric cold-junction temperatures.

2. Data Reduction

The data obtained by the data acquisition system and stored on floppy discs must be processed to extract the maximum possible information and understanding, and to display the results in a convenient and informative format. Performance test information will be correlated by regression analysis for each individual T/E module. Variations in the initial thermoelectric module outputs will be determined, and a mean and standard deviation will be established for design point, open-circuit, and short-circuit conditions.

I-V curves of the type shown in Figures 5 and 6 will be prepared, as will power and efficiency curves of the type shown in Figures 7, 8, 9

and 10. The efficiency calculations will be performed automatically, using main frame data reduction algorithms.

Shunt resistance calculations will be performed, using the current and voltage measurements obtained by the data acquisition system and stored on the floppy disc. These data will be plotted as a function of time for each thermoelectric module. The shunt characteristic (IV) curves for the individual modules will be curve-fitted, and the results used to predict the consequent performance degradation of a full-sized generator. These predictions will be plotted as a function of time, for the individual modules and for the complete test assembly. Both short-term and long-term plots will be prepared by the computer, and updated at frequent intervals. The measured trends will be extrapolated and used to prepare frequently updated EOM power degradation predictions. A suitable regression analysis will be performed, and the shunt resistance population mean and standard deviation, as a function of time, will be calculated and graphically represented. The statistical scatter of the test data will be used to compute confidence limits for the predicted EOM performance degradation.

The life test data obtained in the 10,000 hour serially conducted performance tests will be corrected for any fluctuations in hot- or cold-junction temperatures. The corrected data will be analyzed by regression analysis and graphically presented as a function of time. Mean thermoelectric module power output and standard deviation will be calculated and presented graphically as a function of time. Open-circuit voltage and short-circuit current will be graphically presented for each module as a function of time. The mean and standard deviation of the open-circuit voltage and short-circuit current population will be calculated and presented graphically as a function of time, and used to compute confidence limits on the EOM power output of the generator.

Figure 9. MITG T/E Module Efficiency/Voltage Characteristics, Si/Ge-GaP

Figure 10. MITG Test Assembly T/E Efficiency/Voltage Characteristics, Si/Ge-Gap

3. Rationale

The proposed methodology for real-time data acquisition and storage for subsequent processing by a main-frame computer is not only very convenient but also of great potential value, since it offers maximum flexibility for future data analysis and reduction. This comes about because all the data are stored on magnetic tape. There may well be data analyses and studies or graphic outputs which cannot be defined at the beginning of the tests, and whose usefulness becomes apparent only in the light of subsequent results and interpretations. With all past data stored on magnetic tapes, such desirable analytic studies can be performed retroactively. This explains the rationale for the rather voluminous data acquisition and storage proposed in this test plan.

APPENDIX A

Cooling System Design

Cooling System Design

The cooling system must be designed to maintain a thermoelectric [T/E] module cold junction temperature of approximately 300 degrees Centigrade. It should also be capable of maintaining the cold junction temperatures 300 $\pm$ 100 degrees Centigrade for the parametric tests.

In designing the cooling system, it is important to select the coolant mass flow rate and the input parameters such that the tube wall temperature stays below the boiling point of the coolant (water).

The input parameters for the cooling system design are the total amount of heat dissipation, the inlet water temperature, the total temperature rise (or the coolant mass flow rate), tube inner diameter, and, the tube length.

The total amount of heat absorbed by the coolant is calculated from the following equation,

$$\dot{q} = \dot{m} \cdot c \cdot \Delta T, \quad (1)$$

where:

$\dot{q}$ = Total amount of absorbed heat rate,
 c = Specific heat of the coolant,
 $\dot{m}$ = The coolant mass flow rate, and
 ΔT = Temperature rise of the coolant.

The isothermal tube wall temperature is obtained from the following equation,

$$T(\text{tube wall}) = \frac{T(\text{outlet}) - T(\text{inlet}) \cdot e^{-(hPL/\dot{m}c)}}{1 - e^{-(hPL/\dot{m}c)}}, \quad (2)$$

where,

$T(\text{outlet}) = T(\text{inlet}) + T(\text{Temperature Rise}),$
 $h = \text{Convective Heat Transfer Coefficient},$
 $P = \text{Tube Inner Perimeter, and},$
 $L = \text{Tube Axial Length};$
 note that the FLUID/TUBE heat transfer area is : $A = PL.$

The preceding equation may be derived from an energy balance on a fluid element inside the tube (integrated over the entire tube axial length) for an isothermal tube wall .

Figure 1 shows a quadrant of the test configuration of the MITG housing and the thermal barrier (fin). The cooling tube (not shown) is brazed to a copper block which in turn is clamped to the fin at point C, in Figure 1.

The following assumptions were made for this cooling system design:

- . Water Temperature Rise Per [Housing] Corner = 5 °C
- . Inlet Water Temperature = 40 °C
- . Tube Inner Diameter = 0.25 inch
- . Temperature Drop (Cold Junction to Housing) = 30 °C

For a known heat load, the coolant mass flow rate is calculated from equation (1). Figure 2 depicts the variation of the heat removed per [MITG Housing] corner - the heat load - with the coolant mass flow rate for different values of the fluid temperature rise. A design point is also shown in the same figure for a 300 degree Centigrade T/E cold junction temperature. The convective heat transfer coefficient

is then obtained from the known relations depending on the fluid flow condition (laminar or turbulent) inside the tube and the tube wall temperature is calculated from equation (2). Figure 3 shows the results of a parametric study for the variation of the tube wall temperature with the coolant mass flow rate again for different fluid temperature rises. The design point is also shown in the same figure. As shown the tube wall temperature is obtained from the previously calculated coolant mass flow rate. Once the tube wall temperature is calculated the fin (or thermal barrier) dimensions may be obtained for a known temperature gradient from the tube wall, point C, to the penetration point of the T/E module on the housing, point A. The temperature drop from point A to point B, in Figure 1, is known (from the housing dimensions and the heat flow), therefore, the temperature drop from the root of the fin to its tip, Point C (tube wall) is known. The fin length-to-thickness ratio can now be calculated from the known heat flow rate and the temperature gradient. The variation of the fin length-to-thickness ratio with the fluid mass flow rate for different values of the coolant temperature rise is shown in Figure 4. The design point is also shown in the same figure. Finally, Figure 5 depicts the fin root-to-tip length as a function of both the fluid mass flow rate and its temperature rise.

Table 1 lists the summary of a cooling system calculations performed for a T/E cold junction temperature of 300°C .

Table 1. Summary of results for T (T/E cold junction) = 300 C

T/E Cold Junction Temperature	= 300	°C
Temperature Drop [Cold Junction-to-Housing]	= 30	°C
Water Inlet Temperature	= 40	°C
Water Temperature Rise	= 5	°C
Heat Load Per Corner	= 51	Watt
Tube Inner Diameter	= 0.25	Inch
Tube Length	= 8.50	Inch
Water Mass Flow Rate	= 19.4	Pound/Hour
Reynold Number [Laminar].	<2000	
Tube Wall Temperature	= 75	°C
Fin Length-to-Thickness Ratio	= 28	
Fin Thickness (assumed)	= 0.071	Inch
Fin Root-to-Tip Length	(=28 * 0.071)	= 2 Inch

Figure 1. MITG HOUSING SLICE SCHEMATIC

Figure 2. Variation of the heat load with the coolant mass flow rate

Figure 3. Variation of tube wall temperature with the coolant mass flow rate

Figure 4. Variation of length-to-thickness ratio with the coolant mass flow rate

Figure 5. Variation of fin root-to-tip length with the coolant mass flow rate

Thermoelectric Characteristics curves

The characteristic curves of the MITG test segment and the thermoelectric module ,i.e., current/voltage, power/voltage, and efficiency/voltage, were generated using the "modified" silicon-germanium material properties. The cold- and hot- junction temperatures were 300 and 1000 degree centigrade, respectively.

The temperature-dependent values of the Seebeck coefficient α , conductivity k , and, resistivity ρ were used to compute temperature-averaged values $\bar{\alpha}$, $\bar{k}$, $\bar{\rho}$, using the averaging techniques recommended in Reference [1]. Table 2 illustrates the averaged values for the aforementioned properties for both "standard" and "modified" silicon-germanium materials.

Refence [1] : R.R. Heikes; R.W. Ure, "Thermoelectricity : Science and Engineering", Interscience Publishers, N.Y., 1961, Section 15.6.4.

Table 2. TEMPERATURE-AVERAGED PROPERTIES

TEMPERATURE-AVERAGED PROPERTIES (300 °C TO 1000 °C)		"STANDARD" Si/Ge	"IMPROVED" Si/Ge-GaP
$\bar{a} = \int_{300}^{1000} (a_N + a_P) dT / 700$	SEEBECK COEF. ; VOLT/°C	0.533×10^{-3}	0.497×10^{-3}
$\bar{\kappa}_N = \int_{300}^{1000} \kappa_N dT / 700$ $\bar{\kappa}_P = \int_{300}^{1000} \kappa_P dT / 700$	THERMAL CONDUCTIVITY WATT/CM °C	0.0421 0.0480	0.0278 0.0316
$\bar{\rho}_N = \int_{300}^{1000} \kappa_N \rho_N dT / 700 \bar{\kappa}_N$ $\bar{\rho}_P = \int_{300}^{1000} \kappa_P \rho_P dT / 700 \bar{\kappa}_P$	ELECTRICAL RESISTIVITY OHM-CM	0.260×10^{-2} 0.243×10^{-2}	0.179×10^{-2} 0.318×10^{-2}
$(A_N/A_P)_{opt} = [(\bar{\kappa}_P/\bar{\kappa}_N) / (\bar{\rho}_P/\bar{\rho}_N)]^{1/2}$ $(KR)_{min} = [(\bar{\kappa}_N \bar{\rho}_N)^{1/2} + (\bar{\kappa}_P \bar{\rho}_P)^{1/2}]^2$	OPTIMUM LEG AREA RATIO WATT-OHM/°C	1.1 4.522×10^{-4}	0.8 2.918×10^{-4}
$\bar{Z} = \{\bar{a} / [(\bar{\kappa}_N \bar{\rho}_N)^{1/2} + (\bar{\kappa}_P \bar{\rho}_P)^{1/2}]\}^2$ $V_{opt} = \bar{a} \Delta T / [1 + (1 + \bar{Z})^{-1/2}]$	FIGURE OF MERIT ; K ⁻¹ OPTIMUM LOAD VOLTAGE ; VOLT	0.628×10^{-3} 0.208	0.846×10^{-3} 0.199
$\eta^* = [(1 + \bar{Z})^{1/2} - 1](T_H - T_C) / [(1 + \bar{Z})^{1/2} T_H + T_C]$	OPTIMUM MATERIAL EFFICIENCY	8.3%	10.5%