DOE/NE/32115--T1

SPECIAL APPLICATIONS RTG TECHNOLOGY PROGRAM

THERMOELECTRIC MODULE DEVELOPMENT SUMMARY REPORT

TES-32115-194

September 1988

100
JUL 17 1988
OSTI

★TELEDYNE ENERGY SYSTEMS

**110 W. Timonium Road
Timonium, Maryland 21093**

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

SPECIAL APPLICATIONS RTG TECHNOLOGY PROGRAM

THERMOELECTRIC MODULE DEVELOPMENT

SUMMARY REPORT

TES-32115-194

September 1988

This report was prepared for the United
States Department of Energy under Contract
DE-AC01-NE32115.

83

Prepared by: Wayne M. Brittain
Wayne M. Brittain
Project Engineer

TELEDYNE ENERGY SYSTEMS

110 W. Timonium Road
Timonium, Maryland 21093

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED 848

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately-owned rights.

CONTENTS

	<u>PAGE</u>
Notice	ii
Contents	iii
I. Summary	I-1
II. Introduction	II-1
III. Cascaded Module Development	III-1
IV. PbTe/TAGS CPA Module Development	IV-1
V. Selected PbTe/TAGS Module Technology	V-1

I. SUMMARY

The primary objective of the Special Applications thermoelectric module development program is to design, develop and demonstrate the performance of a module which provides a significant thermoelectric conversion efficiency improvement over available technology for low power, relatively high voltage RTGs intended for terrestrial applications. "Low power" can be construed as an RTG power output of 10 watts or less, and "high voltage" can be considered as a load voltage of 5 volts or greater. In particular, the effort is to improve the system efficiency characteristic of the state-of-the-art bismuth telluride-based RTG systems (e.g., Five-Watt RTG and Half-Watt RTG), typically 3 to 4%, to the range of 6% or better. This increase in efficiency will also permit reductions in the weight and size of RTGs in the low power range.

In the course of the module development program, numerous options were evaluated including available thermoelectric materials (lead telluride, bismuth telluride, silicon germanium and TAGS*) and module configurations (cascaded multiple-stage thermoelectric modules, conventional single-stage modules, and segmenting thermoelectric couple legs). A single-stage module consisting of a lead telluride N-leg and a segmented TAGS P-leg has been selected as the baseline design module. The thermoelectric conversion efficiency of the selected couple configuration is in the range of 8.0 to 8.5% when operating at temperatures consistent with the thermal environments for anticipated terrestrial applications. These terrestrial applications include both subsea and land installations. The thermoelectric conversion efficiency of the selected couple configuration compares

---

* Acronym for tellurium, antimony, germanium, silver - the components of Teledyne Energy Systems' P-type material for use with N-type PbTe.

with 4.5 to 5.0% for bismuth telluride couples under similar operating conditions.

A total of 18 modules representing the selected module design approach have been fabricated during the development program. The power level of these modules is approximately 3.5W at 5V load voltage. Typical hot/cold junction operating temperatures are 800°F/200°F, respectively. These 18 modules include two configurations. Twelve of the modules are disc-shaped (3 inch O.D. by 0.875 inch thick) and 6 are ring-shaped (3.5 inch O.D. by 1.25 I.D. by 0.875 inch thick). Both modules contain 68 thermoelectric couples with 0.104 inch square by 0.625 long N and P-legs. Additionally, the P-legs of the 6 ring-shaped modules incorporate a bismuth telluride segment at the cold side to enhance performance for terrestrial applications where the RTG will be exposed directly to a cold environment such as a subsea installation. The ring-shaped module is a derivative of the disc-shaped module for applications requiring high dynamic loading. The center hole in the disc permits the use of a central heat source support, independent of the thermoelectric module, to minimize dynamic loading of the module. In RTGs employing the disc-shaped module, the heat source support is directly through the thermoelectric module structure.

A total of 14 of the modules fabricated (11 disc-type and 3 ring-type) either has been or is currently under long-term test in bell jars, module test boxes and electrically-heated generators. The test time on individual disc-shaped modules as of the preparation of this report is approximately 20,000 hours. The test time on individual ring-shaped modules, whose design evolved over the last year of the development program as a result of a potential near-term RTG requirement having a high g shock requirement, is approximately 1300 hours.

Three electrically-heated generators were fabricated using the selected thermoelectric module design approach. Two generators, designated the EDU and GDS #1, respectively, employed the disc-type module. One generator, GDS #2, incorporated the ring-type module. GDS #1 has the longest operating time, approximately 13,000 hours, as of the preparation of this report. The system efficiency of all these units is approximately 6%. The test results and performance characteristics of these electrically-heated units are discussed in detail in separate topical reports and are not included in this report.

In summary, the thermoelectric module development program has accomplished its objective of significantly improving both the thermoelectric conversion efficiency and system efficiency of "low power," relatively "high voltage" generators. Thermoelectric conversion efficiency has been improved approximately 75% and system efficiency 50%. In a scoping comparison of weight and size reduction, the 3.5 watt power level GDS #1 (which incorporates a beryllium copper housing designed for subsea application) weighs approximately 17 pounds and is 4.5 inches in diameter by 10.1 inches long, while the 5-watt, bismuth telluride-based RTG (also constructed with a beryllium copper housing) weighs approximately 80 pounds and requires a 20-inch by 20-inch square plate on an 11-inch high by 6.5-inch diameter housing for heat rejection. Thus, the improvement in efficiency, size and weight are significant at the generator system level.

II. INTRODUCTION

A. Thermoelectric Materials Selection

1. Materials Options Evaluated

In the selection of thermoelectric materials for the Special Applications RTG, current technologies of thermoelectric materials, including lead telluride (PbTe), silicon germanium (SiGe) and bismuth telluride (Bi_2Te_3), were evaluated for applicability. Use of SiGe usually results in a "high temperature" system where hot side temperatures are in the 1800°F range. PbTe and Bi_2Te_3 are generally considered "low temperature" systems with hot side temperatures in the 1000°F and 600°F range, respectively. When operated at the same cold side temperature, PbTe and SiGe systems are generally comparable efficiency-wise. PbTe is more efficient than SiGe at lower temperatures up to its maximum operating limit of approximately 1000°F . However, with its higher operating temperature capability, the increased Carnot efficiency achievable with SiGe compensates for its inherently lower materials efficiency. This high temperature capability, which permits high radiator operating temperatures without serious compromise on conversion efficiency, makes SiGe especially attractive for space applications where power-to-weight maximization is paramount.

The efficiency of a Bi_2Te_3 system is generally significantly lower than that of either a PbTe or SiGe system due to its lower operating temperatures. However, at the lower temperature performance is usually stable and the materials problems characteristic of the PbTe and, more prominently, SiGe systems are avoided.

Experience has shown that for terrestrial applications, although weight and size are important factors, thermal integration generally presents the most problems. Thus, means to maximize system conversion efficiency were evaluated.

One approach examined to accomplish this for a terrestrial application was "cascading" wherein two or more thermoelectric modules employing different thermoelectric materials are used. The modules are configured (staged) thermally in series, and each module is operated over a temperature range that will result in maximum conversion efficiency for the system. Take, for example, a SiGe and PbTe cascaded system. Since PbTe is more efficient over its total operating range, the PbTe stage would be the cold stage and operated on the hot side at its maximum operating temperature capability (approximately 1000°F). The SiGe hot stage would operate at approximately 1000°F on its cold side and at its maximum capability of approximately 1832°F (1000°C) on the hot side. In this manner the best features of both thermoelectric technologies are utilized to maximize efficiency. Bi₂Te₃ can be considered in cascading, but efficiency-wise doesn't offer much improvement in efficiency over PbTe unless the cold side temperature is 100°F or less. Single stage (non-cascaded) and cascaded configurations were examined during the early study phase of the technology program.

Another technique to improve conversion efficiency is by segmenting the individual N and/or P-legs within the thermoelectric module. A segmented leg includes different thermoelectric materials along its length, each operating over its optimum temperature range. This technique accomplishes the objective of cascading without the attendant interface temperature drops between stages experienced with cascaded modules and, in general, is more cost-effective. An example of segmenting is a thermoelectric couple leg employing PbTe or TAGS as the hot side segment and Bi₂Te₃ as the cold side segment. The segment lengths are sized such that the interface between the two segments operates at approximately 450°F, the maximum temperature where the efficiency of Bi₂Te₃ equals or exceeds that of PbTe or TAGS.

B. Thermoelectric Module Technology Background

A thermoelectric module with a 10 watt maximum power output level at 5 volts minimum necessitates a thermoelectric module with many couples of small element cross section arranged in either a close-pack-array (CPA) block-type module or as individual minicouples within a couple array. Prior to the initiation of this technology program only Bi_2Te_3 and SiGe modules had been developed for these small couple sizes. The Bi_2Te_3 CPA module technology developed for the Five-Watt RTG program produces 5 watts(e) at 16 volts, but the system efficiency is relatively low (approximately 4%) due to the low hot junction operating temperature typical for Bi_2Te_3 (approximately 550°F). The SiGe multicouple currently being developed by DOE and pioneered at Thermo Electron Corporation (TECO) for space applications provides an improvement in system efficiency over Bi_2Te_3 but at a significant increase in system complexity and cost due to the nature of the module construction and the requirement for high temperature thermal insulation and heat source technology. Although extensively used for numerous space and terrestrial applications, PbTe technology did not, as yet, include a module configured for the Special Applications RTG requirement. However, with the significant thermoelectric efficiency improvement possible over a Bi_2Te_3 module (approximately a factor of 2), development of a PbTe module as part of this technology program was considered essential if a more efficient, cost-effective alternative to Bi_2Te_3 module technology was to be made available for terrestrial applications.

C. Thermoelectric Module Operating Temperature Considerations

An RTG designed for terrestrial use must consider all reasonable operating environments if the RTG is to have widespread terrestrial applicability. Thermal

considerations have perhaps more influence on the design of the RTG than any other. The philosophy for selecting a "standard" thermoelectric module for terrestrial use is to design for the worst credible terrestrial thermal environment and thereby permit operation in all the other potential terrestrial environments. Fortunately, the penalty involved in a standardized thermoelectric module design is considered acceptable.

There are four commonly encountered terrestrial environments, each having thermal implications. Listed generally in order of increasing thermal severity, they are:

- (a) Direct water exposure
- (b) In-air operation
- (c) Burial (silting) underneath water
- (d) Burial in earth, possible with snow on surface

Teledyne has had experience in all four applications. The HPG MOD 3 RTG is involved with environments (a) and (b). The Five-Watt RTG application includes the (b) and (c) environments. In general, the last three environments are not very different from the standpoint of thermal design of the thermoelectric module, and as a group generally result in RTG cold junction temperatures up to 100°F warmer than the first environment (direct water exposure). An RTG using a module optimized solely for low temperature underwater applications would probably require special handling during in-air operating and installation procedures (i.e., auxiliary cooling) to prevent overtemperature. The selected module design approach will permit safe operation of an RTG designed for underwater installations in air environments during shipping, storage and installation in the system.

The selected cold junction temperature for the Special Applications module design initially was 160°F, and early development modules used this temperature.

The cold junction was later increased to 200°F to further reduce generator size at a small sacrifice in conversion efficiency.

D. Report Structure

This report presents the results of development effort performed on three thermoelectric module design approaches:

- (1) Cascaded module (PbTe/TAGS with SiGe) (Section III)
- (2) PbTe/TAGS CPA module (Section IV)
- (3) PbTe/TAGS minicouple module (Section V)

As stated in the Summary, the selected design approach for the Special Applications thermoelectric module employs the PbTe/TAGS minicouple arranged in either a disc-shaped or ring-shaped module. The topics in this report are generally discussed in their chronological order of occurrence in the development program.

III. CASCADED MODULE DEVELOPMENT

The thermoelectric (T/E) materials evaluated for a cascaded module system can first be compared on a figure-of-merit* basis. This is done in Figures III-1 and III-2 for P and N materials, respectively. This comparison is useful because figure-of-merit is directly related to T/E efficiency and, further, it helps identify the appropriate temperature range to operate each material. Note that several of the materials in Figures III-1 and III-2 include a scaling factor to increase electrical resistivity and thereby account for bond and contact resistance. These scaling factors were determined empirically based on T/E module experience at TECO and Teledyne prior to the Special Applications program.

As is evident from Figures III-1 and III-2, both PbTe/TAGS and SiGe thermoelectric materials offer a substantial increase in thermoelectric efficiency over bismuth telluride because of their higher temperature capability. An even greater improvement in thermoelectric efficiency may be realized if PbTe/TAGS and SiGe are cascaded to take maximum advantage of each material property over its most productive temperature range. Since PbTe/TAGS is more efficient over its entire operating temperature range than SiGe but has a lower hot junction operating temperature limit (approximately 1000°F as compared to approximately 1832°F for SiGe), in a cascaded system the PbTe/TAGS stage (or cold stage) is operated on the hot side up to near its temperature limit. The SiGe stage (or hot stage) cold side temperature is then operated near the PbTe/TAGS hot side temperature.

---

* Defined as Seebeck coefficient squared divided by the product of electrical resistivity and thermal conductivity.

FIGURE III-1. P-TYPE FIGURE-OF-MERIT

FIGURE III-2. N-TYPE FIGURE-OF-MERIT

Both fibrous and vacuum foil thermal insulation systems were evaluated as design options. The vacuum foil insulation system offered the promise of higher thermal efficiency but proved effective only with an all-SiGe system since PbTe/TAGS requires a cover gas. The resulting system efficiency of the SiGe-vacuum foil system operating at an 1832°F hot junction temperature showed no efficiency advantage over a more conventional PbTe/TAGS-fibrous insulation system operating at a 925°F hot junction. With the attendant high temperature problems associated with the more complex SiGe-vacuum foil system (such as the impact on the design of a sealed heat source being developed for the Special Applications RTG), detail design studies were limited to an all-PbTe/TAGS system and a cascaded PbTe/TAGS-SiGe system, both with fibrous insulation. The cascaded system operated at a maximum hot junction temperature of 1472°F. The hot junction temperature was limited to 1472°F to allow the use of fibrous insulations to provide the mechanical support for the heat source. Interim thermal studies had shown that the decrease in system thermal insulation efficiency from the use of various "hard" heat source support design approaches (e.g., ZrO_2) in conjunction with the increased thermal losses resulting from the higher heat source operating temperature, offsets the increase in thermoelectric efficiency of the hot stage operating at 1832°F. Thus, there is no advantage in operating the SiGe hot stage in a cascade system at 1832°F since the resulting increase in heat losses offsets the increase in T/E conversion efficiency.

With these constraints on the thermoelectric system design, performance predictions were performed for three of the most attractive system design approaches including a single stage PbTe/TAGS CPA module system and two cascaded SiGe-PbTe/TAGS module systems. Figure III-3 shows a generalized configuration for the cascaded system. Table III-1 presents the predictions for the three system

FIGURE III-3. CASCADED SYSTEM CONFIGURATION

TABLE III-1

SPECIAL APPLICATIONS RTG OPTIONS SUMMARY

	<u>PbTe/TAGS</u> <u>CPA</u>	<u>SiGe-PbTe/TAGS</u>	
		<u>STD</u>	<u>GaP-N</u> <u>STD-P</u>
POWER INPUT (W(t))	62.5	62.5	62.5
GAS FILL	Xe	Xe	Xe
T/E PROPERTIES	100 hrs.	0 & 1500 hrs. avg. (SiGe) 100 hrs. (PbTe/TAGS)	

SiGe STAGE ($T_H/T_C = 1472^\circ\text{F}/995^\circ\text{F}$)

NO. COUPLES	36	42
BIT LENGTH (in.)	0.85	0.85
BIT WIDTH (in.)	.118	.114
MODULE WIDTH (in.)	1.004	1.038
VOLTAGE (V)	3.08	3.22
POWER OUTPUT (W)	1.30	1.37

TAGS/PbTe STAGE ($T_H/T_C = 925^\circ\text{F}/160^\circ\text{F}$)

NO. COUPLES	126	95	93
BIT LENGTH (in.)	0.5	0.4	0.4
BIT WIDTH (in.)	0.063	0.057	0.057
MODULE WIDTH (in.)	1.268	1.023	1.021
VOLTAGE (V)	12	8.92	8.78
POWER OUTPUT (W)	4.70	3.76	3.75

SYSTEM

VOLTAGE (V)	12.0	12.0	12.0
T/E EFFICIENCY (%)	9.74	12.61	12.78
THERMAL EFFICIENCY (%)	77.15	64.08	64.14
POWER OUTPUT (W)	4.70	5.05	5.13
SYSTEM EFFICIENCY (%)	7.52	8.08	8.20

NOTE: 70°F temperature drop assumed between stages based on interface conductance studies.

design approaches operating at a cold junction temperature of 160°F and a load voltage of 12 volts. Also included in the table are the dimensions of the module thermoelectric elements (bits) for each design. The assumed thermal inventory was 62.5 watts, the thermal power available from a single General Purpose Heat Source (GPHS) fueled clad which was the basis for the sealed heat source design at that point in the Special Applications program. Calculated system efficiency ranged from 7.52% for the single stage PbTe/TAGS CPA system to 8.20% for the optional cascaded system.

Two SiGe hot stages were evaluated, one employing so-called "standard" material and the other using a GaP doped N-leg in conjunction with a standard material P-leg. GaP doped P-material was considered but not used because of its marginally improved efficiency and the question of its performance stability.

A. SiGe Multicouple Module

The design, fabrication and initial test of SiGe thermoelectric modules for use in a cascaded system were performed by Thermo Electron Corporation (Waltham, MA) under subcontract to Teledyne Energy Systems. The basis for the module design was the SiGe multicouple module, pioneered by personnel at Thermo Electron Corporation.

The most efficient SiGe thermoelectric material available is SiGe/GaP, as demonstrated by property characterization and fabrication of multicouples. At the time of the silicon germanium module design only "beginning of life" (BOL) properties had been established for this material in contrast with "standard" SiGe which had been characterized by test for properties up to 12 years after BOL. A decision was made to develop two first stage SiGe module designs concurrently. The first module design, designated as "standard," would use SiGe for the P and N

thermocouple elements, and the second "hybrid" module design would utilize SiGe/GaP for the N-element only. SiGe/GaP P-type material was not used as it provided only a marginal increase in efficiency over the reduced temperature range for the cascaded module design approach.

1. Multicouple Module Design

Multicouple module construction for the Special Applications program consists of a series connection of all thermoelectric N and P-elements using SiMo (N) type shoes on both the hot and cold side of the module. A thin germanium (Ge) deposition is sputter-applied to the shoes which are then diffusion bonded onto the elements in a vacuum furnace with high pressure unit loading applied over the bond areas. Electrical isolation and jacketing is provided through use of aluminosilicate high temperature refractory type glass fired at conditions similar to the shoe bonds. The same glass is also utilized in mounting the silicon carbide coated graphite hot and cold pads to the multicouple providing structural bonding and electrical isolation from the shoes. This module construction and materials are capable of continuous operation at temperatures in excess of 1000°C, and is shown in Figure III-4.

A photograph of the multicouple module fully jacketed prior to pad bonding is seen in Figure III-5. The final dimensions of the two multicouple designs are shown in the table which follows. Thermoelectric elements with a rectangular cross section were utilized in lieu of a square cross section to permit a more optimum module configuration.

FIGURE III-4. MULTICOUPLE MODULE CONSTRUCTION

**FIGURE III-5. COMPLETED MULTICOUPLE MODULE
(LESS HOT AND COLD PADS)**

	<u>Standard</u>	<u>Hybrid</u>
No. of couples	36	42
Element length (in.)	.85	.85
Element width (in.)	.169	.150
Element thickness (in.)	.083	.087
Multicouple area (sq. in.)	1.06	1.16
Multicouple height (in.)	1.16	1.16

Output power is extracted from the multicouple module using .50 mm diameter bifilar platinum lead wires brazed into the cold side of the output P and N-elements. A third smaller voltage tap lead is also brazed into each element for test purposes.

Two SiGe multicouple modules were designed, developed and fabricated by Thermo Electron Corporation in support of the cascaded module system design approach, one using "standard" SiGe and the other SiGe/GaP for the N-element and a "standard" P-element.

2. Multicouple Test Configuration

A program decision was made to test each stage of the cascaded module stages separately in order to verify design predictions before proceeding with an actual prototype cascaded electrically-heated generator (ETG). Using this approach, testing is simplified and problems relating to mismatched thermal conductivity or excessive interface losses are eliminated.

Testing of the two SiGe modules took place in individual, well-insulated, hermetically sealed test fixtures designed with feedthrough electrical connections for temperature measurement, heater power supply, and multicouple output power. Thermal power was provided to the multicouple using a 4 cm diameter resistance heater simulating the GPHS heat source. An identical heater was used on the cold side to permit fine adjustment of the cold junction temperature to 995°F (535°C).

The hot and cold side heaters were in direct contact with the graphite multicouple heat pads as shown in Figure III-6. This assembly was compression loaded against the test fixture housing cold side by a spring loading applied during the housing cover installation. The height of the PbTe/TAGS second stage was simulated by the cold side heater (1.5 cm), and its thermal conductivity simulated by the use of a thin mica disc between the cold side heater and housing. This system was thermally sized to produce a cold junction temperature slightly below 995°F (535°C), with an unpowered cold side heater, when operating under one atmosphere of xenon fill gas.

Heater design criteria were its size (4 cm dia. x 1.5 cm ht.), continuous operation at 900°C, and an input current less than 2.0 amps at 80 watts. This was achieved by using a molybdenum alloy (TZM) as the housing material, with a 1 mm diameter sheathed inconel heater element brazed to the inner and outer housing walls as shown in Figure III-7. A nickel-gold brazing alloy (980°C melting temperature) was used in assembling the heater, including the attachment of the platinum power leads.

3. Test Results

The performance specifications for the two Thermo Electron multicouple module designs are as shown below:

<u>Type Module</u>	<u>Minimum Power Output (watts)</u>
Standard SiGe	1.16 @ 2.86V
Hybrid SiGe	1.27 @ 3.14V
Test Conditions: Hot junction = 1472°F (800°C)	
Cold junction = 995°F (535°C)	

The minimum specifications are 85% and 81%, respectively, of the expected design power for the two module designs based on a nominal performance prediction determined

FIGURE III-6. SiGe MULTICUPLE TEST CONFIGURATION

FIGURE III-7. HIGH TEMPERATURE HEATER CONSTRUCTION

analytically using nominal materials property data and expected extraneous resistance due to bonds, hot shoes and cold shoes.

The two modules were acceptance tested at Thermo Electron with results as shown in Table III-2. Also included for comparison in the table is the performance prediction for each module. The power output of both modules was approximately 75% of the power prediction, and neither module satisfied the performance specification requirements. Both modules failed to satisfy the power requirements primarily because of the higher-than-expected resistance, 17% higher for the standard multicouple module and 33% higher for the hybrid module.

The two multicouple modules, contained within their respective test fixtures, were transported to Fairchild Industries (Germantown) where they were placed on life test. The modules were tested for approximately 14,000 hours before a test facility power failure in July 1986 caused a shutdown of the test. The tests were never restarted due to funding considerations and the fact that a cascaded system design approach was not selected as will be discussed next. At the conclusion of the test at Fairchild, the standard and hybrid modules were producing 90% and 89% of their initial power when placed on test in December 1984.

B. Cascaded Module System Performance

The performance of a cascaded system based on the SiGe multicouple technology discussed above and the PbTe CPA technology to be discussed in Section IV permitted a reassessment of merits of a cascaded module system as opposed to a single stage PbTe/TAGS module. The scaling factors from Table III-2 for the SiGe multicouple and those typical for PbTe/TAGS CPA development modules, shown in Table III-3, were used to modify the performance predictions of Table III-1.

TABLE III-2**SiGe MULTICOUPLE MODULE PERFORMANCE**

	<u>Open Circuit (volts)</u>	<u>Internal Resistance (ohms)</u>	<u>Load Voltage (volts)</u>	<u>Power Output (watts)**</u>
<u>STANDARD MULTICOUPLE @ 1472°F/995°F (800°C/535°C)</u>				
PREDICTION*	5.12	4.71	2.86	1.37
INITIAL TEST (DURING BURN-IN)	4.812	5.45	2.86	1.02
FINAL TEST (AFTER BURN-IN)	4.827	5.50	2.86	1.02
RETEST	4.820	5.55	2.86	1.01
SCALING FACTOR***	0.941	1.168		
<u>HYBRID MULTICOUPLE @ 1472°F/995°F (800°C/535°C)</u>				
PREDICTION*	5.57	4.86	3.14	1.57
INITIAL TEST (DURING BURN-IN)	5.500	6.34	3.14	1.17
FINAL TEST (AFTER BURN-IN)	5.607	6.58	3.14	1.18
SCALING FACTOR***	0.996	1.33		

---

* Based on average of 0 and 1500 hr. property data and 10% extraneous resistance to include shoes and bond resistances.

** Output power normalized to the design load voltage.

*** Used for cascaded system performance prediction to scale open circuit and internal resistance.

TABLE III-3**BASIS FOR PbTe/TAGS MODULE PERFORMANCE PREDICTION
USING PROTOTYPE MODULE HARDWARE TEST RESULTS**

	Scaling Factor*	
	<u>Voltage</u>	<u>Resistance</u>
19-Couple Quadrant #1	.990	1.008
19-Couple Quadrant #2	1.000	1.012
30-Couple Quadrant #3	.998	.985
76-Couple Module	<u>.998</u>	<u>.995</u>
Average Scaling Factor	.997	1.000

---

* Scaling Factors are Relative to Predictions Using Thermoelectric Property Data.

The performance of the Engineering Demonstration Unit (EDU) generator for both a PbTe/TAGS single stage and a Pb/TAGS-SiGe cascaded design was evaluated. The basis for predicting the thermoelectric materials performance was the data from four PbTe/TAGS modules fabricated by TES to be discussed in Section IV and the two SiGe modules fabricated by Thermo Electron. The nominal materials property data were assumed, modified by the scaling factors in Tables III-2 and III-3 for voltage and resistance. Table III-4 shows the results of these analyses. System efficiency for the PbTe/TAGS single stage design is 7.0%, while the cascaded designs shows an increase to the 7.3 to 7.4% range.

In conjunction with DOE, the decision was made that the Special Applications RTG would be a single stage PbTe/TAGS design. The more complex cascaded design with its inherent higher operating temperatures, greater risk and increased cost was not considered justified for the modest system efficiency increase.

TABLE III-4

**SPECIAL APPLICATIONS PERFORMANCE COMPARISON
BASED ON TEST HARDWARE DATA**

	<u>PbTe/TAGS</u>	<u>SiGe-PbTe/TAGS</u>	
	<u>CPA</u>	<u>STD</u>	<u>GaP-N</u> <u>STD-P</u>
POWER INPUT (W(t))	62.5	62.5	62.5
GAS FILL	Xe	Xe	Xe
POWER OUTPUT (W(e))	4.38	4.57	4.65
<u>SiGe STAGE ($T_H/T_C = 1472^{\circ}\text{F}/995^{\circ}\text{F}$)</u>			
NO. COUPLES		36	38
VOLTAGE (V)		2.60	2.73
POWER OUTPUT (W)		1.00	1.07
<u>PbTe/TAGS STAGE ($T_H/T_C = 925^{\circ}\text{F}/160^{\circ}\text{F}$)</u>			
NO. COUPLES	100	105	103
VOLTAGE (V)	9	9.40	9.27
POWER OUTPUT (W)	4.38	3.57	3.58
<u>SYSTEM</u>			
VOLTAGE (V)	9.0	12.0	12.0
T/E EFFICIENCY (%)	9.39	11.60	11.73
THERMAL EFFICIENCY (%)	75.6	63.1	63.4
POWER OUTPUT (W)	4.38	4.57	4.65
SYSTEM EFFICIENCY (%)	7.00	7.32	7.44

IV. PbTe/TAGS CPA MODULE DEVELOPMENT

A. PbTe/TAGS CPA Module Design

Prior to the Special Applications Program, TES experience with close-pack-array (CPA) eggcrate type modules was primarily in using bismuth telluride thermoelectric elements with plasma-sprayed shoes. TES has fabricated thousands of these type modules on their commercial TELAN production line. This module type was also used on the Five-Watt RTG Program. Thus, the first attempt to fabricate a PbTe/TAGS CPA module was to use the same techniques as for a bismuth telluride module. Numerous attempts to plasma spray shoes on PbTe and TAGS were performed with variable success. Figure IV-1 shows a Special Applications CPA module being prepared for application of plasma-sprayed Ni hot and cold shoes. The eggcrate is first assembled into a holding fixture and the individual elements inserted in the eggcrate matrix. The assembly is then plasma-sprayed with Ni. After the plasma-spray operation, both faces are sanded flat and parallel and the module is removed from the tooling. Figure IV-2 shows the completed module with power leads installed.

Table IV-1 shows the performance of the completed module. Module performance agreed well with the predicted performance values for this particular module. However, in general, the process yield was unacceptably low due to the cracking of element legs during the plasma-spray operation, and other techniques for fabricating the Special Applications module were sought.

After exploring other techniques, fabrication of individual couples was selected as the most viable approach. With this method, large couples are bonded using processes employed by TES on prior TES space and terrestrial programs. These

EGG CRATE IN ASSEMBLY HOLDING FIXTURE

PARTIALLY "STUFFED" MODULE

FIGURE IV-1. PLASMA-SPRAYED CPA DEVELOPMENT
THERMOELECTRIC MODULE TOOLING

**FIGURE IV-2. PLASMA-SPRAYED CPA DEVELOPMENT
THERMOELECTRIC MODULE**

TABLE IV-1

PLASMA-SPRAYED 126-COUPLE CPA MODULE PERFORMANCE
(Element Size = .061" sq. x .466" lg.)

	<u>Prediction</u>	<u>Module S/N 5 (10/12/84)</u>
Power Output (Watts(e))	4.51	4.47
Power Input (Watts(t))	59.7 ⁽¹⁾	60.0 ⁽²⁾
Hot Junction (°F)	925	925 ⁽³⁾
Cold Junction (°F)	160	160
Open Circuit Voltage (VDC)	19.27	19.30
Load Voltage (VDC)	9.63	9.72
Internal Resistance (ohms)	20.56 ⁽⁴⁾	20.83

---

(1) Includes: $Q_{T/E}$ (49.4W) + $Q_{Separators}$ (8.2W) + $Q_{Inert\ Couples}$ (2.1W).

(2) Measured Power Input Less Test Fixture Tare Losses.

(3) Inferred Temperature Based on Power Input and Open Circuit Voltage.

(4) Includes $R_{T/E}$ (20.40 ohms) + R_{Straps} (.06 ohms) + R_{Leads} (.10 ohms).

large couples are then sliced to obtain the final small couples used in the assembly of a PbTe/TAGS CPA module.

Figure IV-3 depicts the process flow for the fabrication of individual couples. Cold-pressed-and-sintered (CP&S) N-elements and cast TAGS legs are first cut longitudinally in half. Each half-section of the N and P-element is then bonded to a 0.5 inch diameter hot shoe and half-disc cold shoe in a two step operation. First the N-leg is bonded to its hot shoe and cold shoe at a 1450°F bond temperature. Then the P-leg is bonded to the hot shoe and its cold cap at 1050°F using an 80w/oSn//20w/oTe exothermic wafer. The bonded assembly is then sliced-and-diced into small, individual couples for assembly into an eggcrate grid frame. Figure IV-4 shows the couple design for the PbTe/TAGS CPA module.

The module itself is comprised of a glass fiber-based grid frame material (assembled from interlocking strips) into which the individual couples are inserted (See Figures IV-5 and IV-6). After the individual couples are inserted, 20 gauge copper wire strips are soldered to the cold shoes of the couples to complete the electrical circuit. A ceramic filler material is then used on the hot and cold sides of the module to fill in the grid frame. Both faces are subsequently sanded to assure flatness and parallelism. Figure IV-7 shows the design configuration for a 76-couple development module.

Four development modules were fabricated using the selected module fabrication technique. Two modules contained 19 couples, one module contained 76 couples and one module contained 30 couples. Element sizes for the first three modules above were identical, 0.077 in. square x 0.483 in. long. The last module was assembled to demonstrate module fabrication feasibility with smaller cross section elements (0.067 in. square). Figure IV-8 shows the 30-couple module quadrant employing .067 in. square elements.

FIGURE IV-3. PbTe/TAGS COUPLE FABRICATION FLOW CHART

ES-32115-194

FIGURE IV-4. COUPLE DESIGN FOR PbTe /TAGS CPA MODULE

FIGURE IV-5. PbTe/TAGS THERMOELECTRIC COUPLE AND GRID FRAME ASSEMBLY

**FIGURE IV-6. $PbTe$ /TAGS 30-COUPLE DEVELOPMENT MODULE QUADRANT
(PARTIALLY "STUFFED" WITH COUPLES)**

FIGURE IV-7. SPECIAL APPLICATIONS PROGRAM 76-COUPLE DEVELOPMENT MODULE

**FIGURE IV-8. 30-COUPLE (.067" SQ. ELEMENTS) MODULE QUADRANT
(HOT SIDE VIEW)**

B. Test Results on Development Modules

Tables IV-2, IV-3 and IV-4 show the results of performance testing on the three respective module designs. The performance prediction, based on the TES computer prediction model for PbTe/TAGS materials, is also included for comparison. The measured performance of the four modules agreed very closely with the performance prediction. Table III-3 from Section III summarizes the scaling factors necessary to correlate the performance of the four modules with prediction.

C. PbTe/TAGS Baseline CPA Module

After the successful completion and performance testing of the four development modules discussed above, a baseline module was designed for use in the Engineering Demonstration Unit (EDU) electrically-heated generator and life test fixture. The baseline module design is shown in Figure IV-9. The module contains 98 couples with elements 0.077 in. square by 0.625 in. long. Overall module size is 1.424 in. square by 0.740 in. thick.

Four modules of the baseline configuration were fabricated, one for use in the EDU, two for installation in a life test fixture and one spare. Table IV-5 shows the performance test results for the four modules. The performance of all modules agreed closely with the performance prediction.

1. Life Test Fixture

Baseline modules S/N 001 and S/N 002 were assembled into the life test fixture for long-term testing. Figure IV-10 shows the two modules positioned inside the test fixture.

TABLE IV-2**PbTe/TAGS 19-COUPLE QUADRANT MODULE PERFORMANCE**

	<u>Prediction</u>	<u>Quadrant #1 (10/30/84)</u>	<u>Quadrant #2 (10/26/84)</u>
Power Output (W(e))	1.03	1.00	1.01
Power Input (W(t))	14.3	14.0	14.4
Hot Junction ($^{\circ}\text{F}$)	925	925	925
Cold Junction ($^{\circ}\text{F}$)	160	160	160
Open Circuit Voltage (V)	3.04	3.01	3.04
Load Voltage (V)	1.50	1.49	1.51
Internal Resistance (ohms)	2.25	2.27	2.28
Extraneous Resistance (%)	0	0.8	1.2

TABLE IV-3**PbTe/TAGS 76-COUPLE MODULE PERFORMANCE**

	<u>Prediction</u>	<u>Module S/N 6 (11/3/84)</u>
Power Output (Watts(e))	4.25	4.26
Power Input (Watts(t))	56.1	56.2
Hot Junction ($^{\circ}\text{F}$)	925	925
Cold Junction ($^{\circ}\text{F}$)	160	160
Open Circuit Voltage (V)	12.16	12.14
Load Voltage (V)	6.10	6.10
Internal Resistance (ohms)	8.69	8.65

TABLE IV-4**PbTe/TAGS 30-COUPLE MODULE PERFORMANCE**

	<u>Prediction</u>	<u>Quadrant #3 (11/11/84)</u>
Power Output (Watts(e))	1.27	1.28
Power Input (Watts(t))	16.3	15.8
Hot Junction ($^{\circ}\text{F}$)	925	925
Cold Junction ($^{\circ}\text{F}$)	160	160
Open Circuit Voltage (V)	4.80	4.79
Load Voltage (V)	2.40	2.41
Internal Resistance (ohms)	4.55	4.48

FIGURE IV-9. BASELINE PbTe/TAGS 98-COUPLE CPA MODULE

TABLE IV-5
 BASELINE PbTe/TAGS 98-COUPLE CPA MODULE PERFORMANCE

	<u>Prediction</u>	<u>MOD S/N 001</u> <u>(3/5/85)</u>	<u>MOD S/N 002</u> <u>(3/11/85)</u>	<u>MOD S/N 003</u> <u>(3/21/85)</u>	<u>MOD S/N 004</u> <u>(4/1/85)</u>
Power Output (W(e))	4.37	4.49	4.39	4.31	4.25
Power Input (W(t))	50.4 ⁽¹⁾	50.5 ⁽²⁾	50.5 ⁽²⁾	50.5 ⁽²⁾	50.7 ⁽²⁾
Hot Junction (°F)	925	927 ⁽³⁾	927 ⁽³⁾	927 ⁽³⁾	930 ⁽³⁾
Cold Junction (°F)	160	160	160	160	160
Open Circuit Voltage (V)	15.68	15.63	15.36	15.06	15.17
Load Voltage (V)	9.00	9.12	9.03	9.06	9.01
Internal Resistance (ohms) ⁽⁴⁾	13.75	13.23	13.03	12.60	13.05

(1) Includes: $Q_{T/E}(47.2W) + Q_{Separators}(3.2W)$.

(2) Measured power input less test fixture tare losses.

(3) Inferred temperature based on power input

(4) Includes: $R_{T/E} + R_{Straps} + R_{Leads}$.

NOTE: Element Size = .077" Sq. x .625" Lg.

TES-32115-194

FIGURE IV-10. BASELINE 98-COUPLE CPA MODULES INSTALLED IN LIFE TEST FIXTURE
(MODULES S/N 001 AND S/N 002)

Table IV-6 presents the performance data obtained on modules S/N 001 and S/N 002. The initial acceptance test values from Table IV-5 are included to permit comparison with the module performance after installation in the test fixture. The 100% A and initial 100% Xe power points were taken during the test fixture outgassing operation. The other data is from the life test installed on the life test station. The life test fixture heat-up for long-term testing was completed on 4/10/85 with initial measured powers as shown in Table IV-6. These initial power outputs are almost identical to those measured at the completion of the 24-hour burn-in after outgassing. The testing continued without incident until 4/28/85, at which time short-term (seconds-to-minutes) slight fluctuations in the load voltages of both modules were noted (0.2 to 0.5 volts from the nominal 9.0 volt operating point). These fluctuations continued with the magnitude of the variations remaining in the range noted above. Diagnostic evaluations, including module circuit and thermocouple instrumentation insulation resistance measurements and check of laboratory instrumentation, failed to determine the cause of these voltage fluctuations. It should be noted that this behavior was not observed on any of the four development modules of similar design including the testing of one 76-couple module for approximately one month.

The effect of hot junction temperature and operating voltage on the fluctuations was evaluated. The hot junction temperature of the two modules was reduced from the nominal 925°F to 850°F. The voltage fluctuations on the modules disappeared initially, but were back within a week. The modules were then operated on open circuit to see if the higher voltage might "burn-out" any shorts present. Again, initially the voltage fluctuations disappeared but reappeared within a week.

TABLE IV-6

THERMOELECTRIC MODULE LIFE TEST FIXTURE PERFORMANCE HISTORY

	Prediction @ 100 Hrs.	Initial Acceptance* (3/5/85)	Module S/N 001 Test Fixture				
			100% (4/4/85)	100%Xe** (4/6/85)	100%Xe (4/10/85)	100%Xe (4/19/85)	100%Xe (4/25/85)
Power Output (W(e))	4.37	4.49	4.47	4.48	4.50	4.45	4.40
Hot Junction (°F)	925	927	924	921	927	929	929
Cold Junction (°F)	160	160	159	157	161	157	159
Open Circuit Voltage (V)	15.68	15.63	15.95	16.12	16.31	16.40	16.35
Load Voltage (V)	9.00	9.12	9.05	9.05	9.02	9.03	9.03
Internal Resistance (ohms)	13.75	13.23	13.97	14.27	14.55	14.95	15.03
Module S/N 002							
Power Output (W(e))	4.37	4.39***	4.34	4.36	4.35	4.28	4.24
Hot Junction (°F)	925	927	925	927	928	929	929
Cold Junction (°F)	160	160	160	161	162	160	159
Open Circuit Voltage (V)	15.68	15.36	15.60	15.82	15.86	15.96	16.03
Load Voltage (V)	9.00	9.03	9.07	9.06	9.06	9.06	9.11
Internal Resistance (ohms)	13.75	13.03	13.63	14.05	14.17	14.62	14.88

* Data from Table IV-5.

** Final power check after 24-hour burn-in in Xenon.

*** Initial acceptance occurred on 3/11/85.

An external DC power supply was used to apply 20 volts across the two modules to "burn-out" the intermittent shorts. Again, the intermittent shorting disappeared briefly but reappeared on both modules within a week.

Four independent parallel tests were conducted in addition to the module diagnostic tests discussed above to determine the cause of the shorting phenomenon. These tests were oriented towards evaluating the electrical insulating capability of the Synthane eggcrate separator material at operating temperature, both by itself and in the presence of thermoelectric material. Instrumentation permitted measurement of insulation resistance in situ at temperature. These tests included:

- a. Four samples of Synthane operating at 950°F in air.
- b. Five samples of Synthane operating at 950°F in argon. Four of the samples were against TAGS and SnTe to evaluate the effect of thermoelectric sublimation products.
- c. A module containing all P-legs in three rows, all N-legs in three rows, and alternating N and P-legs in two rows. Instrumentation permitted the measurement of insulation resistance across the Synthane separating each row.
- d. A 12-couple module operating at the nominal 925°F hot junction temperature.

None of the above tests, with the exception of c., showed any evidence of the shorting phenomenon noted in the life test fixture. The test module in c., which was operated at an accelerated temperature of approximately 1000°F, duplicated the shorting phenomenon and was removed from test and diagnostically disassembled. Shorting was traced to buildup of T/E element sublimation products both in the small, 1 to 2 mil openings created by the interlocking fingers of the Synthane eggcrate and around the end of the eggcrate at the hot side. There was no apparent shorting through the Synthane eggcrate material itself.

Since none of the above tests indicated shorting through or breakdown of the Synthane material, it was postulated that electric shorting in the test fixture was caused by bridging of the separators by T/E element sublimation products. Based on these conclusions the life test fixture was removed from test and diagnostically disassembled in June 1985. The disassembly revealed metallic T/E deposits at the hot side of the two modules on the ends of the 10-mil thick Synthane separators which provide the electrical insulation between individual T/E elements. In several areas the sublimation products bridged the Synthane thickness, thus causing the intermittent shorting. The experience from the operation of these two modules led to the conclusion that an increase in element spacing and a reduction in hot junction temperature were warranted to eliminate this problem. These improvements are discussed in Section V for the baseline minicouple module design employing discrete minicouples.

2. EDU Testing

The EDU was assembled and tested in the same time frame that the first life test fixture, discussed above, was on test. Module S/N 003 was used for the EDU assembly. The EDU design is shown in Figure IV-11 and Table IV-7. A Five-Watt RTG configured housing was used for the EDU build to expedite the generator assembly to permit an early assessment of module performance and capability to withstand dynamic loading. Assembly, outgassing and initial performance testing of the EDU were completed during June 1985. Table IV-8 compares the performance prediction with the initial power checks performed after outgassing for both 100% Xe and 100% Argon gas fills. The 4.13 watt power output was within 3% of the nominal prediction.

The initial parametric performance test on the EDU was completed after final sealing with a 95% Xe/5%He gas fill. The 5% He was added to facilitate helium leak check operations. Performance results are shown in Figure IV-12. Power output was

FIGURE IV-11. SPECIAL APPLICATIONS EDU

TABLE IV-7**LEGEND**

ITEM NO	DESCRIPTION	MAT'L
1.	*HOUSING	BeCu
2.	*DOME	BeCu
3.	END COVER	BeCu
4.	*CABLE HOUSING, POWER OUTPUT	BeCu
5.	FIN PLATE	BeCu
6.	HEAT DISTRIBUTION CUP	MOLYBDENUM
7.	THERMOELECTRIC MODULE	PbTe/TAGS
8.	ELECTRICAL HEAT SOURCE	GRAPHITE BODY, TUNGSTEN BALLAST, WATLOW CARTRIDGE
9.	GETTER & GETTER HOUSING	Zr IN Pd HOUSING
10.	THERMAL INSULATION, NON LOAD BEARING	MIN-K TE 1800
11.	*HI-PRESS. MARINE ELEC. RECEPTACLE, O-RING SEALED	BeCu, VITON O-RINGS
12.	LOAD RING	6061-T6 AL ALLOY
13.	LOAD DISC	HARD COATED, 6061-T6 AL ALLOY
14.	SPRING (6), HEAT DIST. CUP RETAINER	CrV STEEL
15.	*SPRING, HEAT SOURCE RETAINER	CrV STEEL
16.	*SPRING SPACER SLEEVE	HARD COATED, 6061-TE AL ALLOY
17.	SPRING GUIDE PIN	CRES STEEL
18.	*ELECTRICAL RECEPTACLE, O-RING SEALED	CRES SHELL, VITON O-RING
19.	*POWER OUTPUT PLUG & CABLE ASSY.	AL ALLY SHELL
20.	*HEATER POWER INPUT PLUG & CABLE ASSY.	AL ALLY SHELL
21.	THERMAL INSULATION, LOAD BEARING	MIN-K TE 1400
22.	*O-RING SEALS, CABLE HOUSING	PRP #19277
23.	THERMAL GREASE	DOW CORNING #340
24.	ELECTRICAL INSULATION WAFER .025 THK.	AL ₂ O ₃
25.	ELECTRICAL INSULATION WAFER .025 THK WITH THERMAL GREASE	AL ₂ O ₃ WITH DOW CORNING #340
26.	*O-RING SEAL FIN GREASE RETAINER	PRP #19277
27.	*O-RING SEALS, DOME SEAL	PRP # 19277
28.	*VENT TUBE, OUTGASSING	BeCu

* SAME AS 5-WATT ETG PART.

TABLE IV-8**ENGINEERING DEMONSTRATION UNIT PERFORMANCE AT OUTGASSING STATION**

	<u>EDU Prediction @ 100 Hours</u>		<u>EDU Performance</u>	
	<u>(100%Xe)</u>	<u>(100%A)</u>	<u>100%Xe (5/17/85)</u>	<u>100%A (5/16/85)</u>
Power Output (W(e))	4.26	4.26	4.13	4.13
Power Input (W(t))	67.3 ⁽¹⁾	70.8 ⁽¹⁾	68.0	72.5
Hot Junction (°F)	925	925	929	923
Cold Junction (°F)	160	160	162	155
Open Circuit Voltage (V)	15.68	15.68	15.53	15.26
Load Voltage (V)	8.79	8.79	9.09	9.07
Internal Resistance (ohms)	14.22	14.22	14.18	13.58

---

(1) Prediction includes heater lead thermal losses and Min-K insulation configurations peculiar to the EDU. Equivalent RTG thermal inventory requirement would be approximately 62.5 watts(t).

FIGURE IV-12
EDU PARAMETRIC PERFORMANCE DATA

4.12 watts at 9.0 volts, and was almost identical with the power checks at the outgassing station. It was noted that the addition of 5% He to the Xe gas fill required an additional 3 watt(t) input. Thus, for an RTG, either a lesser quantity of helium would be considered or a residual gas analyzer, tuned to detect Xe gas, employed for leak detection.

After outgassing and parametric performance testing, the EDU was then subjected to the scheduled dynamic tests. During qualification level vibration testing of the EDU on June 6, 1985, an open circuit condition was experienced in the power output. The condition occurred during the 3rd sweep from 7 to 200 Hz at 1-1/2 G in the X-axis. Previous tests had included a resonance sweep from 7 to 50 Hz at 1/4 G and 2-hour dwell at 25 Hz at 1/2 G. A diagnostic disassembly of the EDU was conducted. No visible damage to the EDU internals (i.e., Min-K, heat source and preload springs) was noted during disassembly. However, after disassembly down to the T/E module, it was found to have a high resistance although externally it showed no signs of physical damage. Subsequent metallography on the module revealed breakage in about 2/3 of the T/E elements at the module cold side approximately 0.1 inch above the cold side bond (see Figure IV-13). Generally, both the hot and cold side bonds were intact (see Figure IV-14).

Stress analyses and supporting structural testing of the T/E elements were performed to determine the cause of the module mechanical failure. Table IV-9 summarizes the results of these evaluations. The natural frequency of the module and 5.5 pound heat source system is estimated at about 200 Hz or less (for assumed T/E materials mechanical properties). Thus, the module and heat source system is believed to have experienced resonance in the 5 to 200 Hz X-axis sweep with calculated element bending tensile stresses in the 7000 psi range. This is in

FIGURE IV-13. TYPICAL EDU COLD SIDE CRACKING

FIGURE IV-14. TYPICAL EDU HOT SIDE BONDS

TABLE IV-9
MODULE DYNAMIC ANALYSIS RESULTS

No. Couples	No. Acting**	Effective Length (in.)	Element Cross Section (each side) (in.)	Heat Source Weight (lbs.)	Resonant Frequency (Hz)	Vibration Tensile Stress (psi)
98	100%	.675	.077	5.5	223	115
98	50%	.675	.077	5.5	157	7210*

CANTILEVER ELEMENT TEST RESULTS

(Cantilever Tests Performed on Individual Elements)

Type Element	Sample Size	Bending Tensile Stress at Failure (psi)***	Observations
TE1006(N)	10	avg. = 2501 low = 1142 high = 3766	All failed in element at "cold" side
TAGS(P)	10	avg. = 2617 low = 1698 high = 3923	All failed in element at "cold" side

* 1.5g's (amplified by factor of 10 at resonance).

** Percent of couples assumed to be reacting the dynamic load.

*** Room temperature tests.

excess of the T/E material capability. Room temperature tests performed on both N and P elements (see Table IV-9) showed the average bending tensile stress at failure to be in the 2500 to 2600 psi range. Typical location of failure in the test elements was approximately 0.1 inch above the cold bond, the same point as for the EDU element failures.

3. Modifications Resulting from PbTe/TAGS CPA Module Testing

After evaluation of test results from the two life test modules and EDU generator, the following module modifications were made to correct the deficiencies in the thermoelectric module design and update the module to reflect changes in program objectives resulting from on-going heat source studies and interfacing activities with potential users:

- a. The module design effort was reoriented towards a 2-watt minimum power level module with a 15-year life objective (the Special Applications Contract requirement is for a 5-year life). This required a module with an initial power output of 3.5 to 4.0 watts. A 10 to 15-year life requirement became apparent after interfacing with potential users of this technology.
- b. The heat source weight was reduced from 5.5 lbs. to 1.5 lbs. to reflect to adoption of the 3-layer capsule heat source technology which had transpired in the heat source evaluation effort. The 5.5 lb. heat source reflected a design intended for use in a high temperature, cascaded RTG system, and utilized a GPHS Fueled Clad inside a heavy strength member to effect a sealed heat source design.
- c. The design voltage was reduced from 9 volts to the range of 5 volts, which was the voltage level consistent with potential user requirements. This reduction permitted an increase in the cross section of the thermoelectric elements and a decrease in the number of thermoelectric couples
- d. A PbSnTe hot segment was incorporated in the TAGS P-leg (similar to SNAP-19 type couple construction) to reduce the operating temperature of the TAGS hot side and minimize sublimation of the TAGS material.
- e. The operating hot junction temperature was decreased from 925°F to 850°F, a temperature more consistent with a 15-year life objective considering sublimation effects on the relatively small cross section

thermoelectric element legs.

- f. The series electrical circuit of the thermoelectric couples within the module was retained but Schottky diodes were included across the couples to protect against an open circuit failure. This permitted attainment of user-specified reliability goals for the RTG.
- g. The Synthane eggcrate was eliminated from the design and the minicouples arrayed with sufficient spacing to prevent circuit shorting due to T/E sublimation products. The Synthane was replaced with powdered Min-K thermal insulating material to not only reduce thermal losses, but to provide a more effective sublimation barrier around the thermoelectric elements due to the intimate "packing effect" of the Min-K powder.

The resulting module design is discussed in Section V.

4. Component Verification Tests

Component testing was performed to verify that the changes in the module design would accomplish their objectives. Two module segments were fabricated, one to evaluate the performance of the minicouple with a PbSnTe at the hot side of the P-leg. This module also included increased couple spacing and application of powdered Min-K insulation.

The second module evaluated the effect of increased leg spacing and Min-K insulation in reducing electrical shorting but was operated at an accelerated temperature. The test articles made maximum use of components and tooling for the CPA module in order to expedite initiation of the tests.

a. Performance Demonstration Module

A demonstration module was fabricated to provide early verification of the module design. The module contained six couples with an element size of 0.077 inch square. This was the first module fabricated with a spacing of 0.095 inch between adjacent couples, with powdered Min-K used to fill the voids and with a PbSnTe segment at the P-leg hot end. Table IV-10 presents results of performance testing of the demonstration module. The performance prediction, based on a computer prediction model for PbTe/TAGS-PbSnTe materials, is also included for comparison. The measured performance of the module at 100 hours of operation agreed closely with the prediction. There was no evidence of electrical

TABLE IV-10**6-COUPLE DEMONSTRATION MODULE PERFORMANCE**

	<u>Prediction @ 100 Hrs.</u>	<u>Normalized Test Data</u>	
		<u>@ 100 Hrs.</u>	<u>@ 1900 Hrs.*</u>
Power Output (W(e))	0.162	0.163	0.162
Hot Junction ($^{\circ}$ F)	850	850	850
Cold Junction ($^{\circ}$ F)	210	210	210
Load Voltage (V)	0.462	0.462	0.462
Open Circuit Voltage (V)	0.798	0.799	0.820
Internal Resistance (ohms)	0.958	0.957	1.023

---

* End of test.

shorting during the test, and examination of the test hardware after the 1900-hour test did not reveal observable T/E material sublimation products. Also the electrical performance of the module verified the prediction model for the segmented couple design.

b. Accelerated Temperature Test

A test module was fabricated to determine the effectiveness of increased couple spacing in the module design to inhibit electrical shorting. The module had three rows of P-legs and three rows of N-legs with each row consisting of identical type legs connected in parallel. This configuration permitted monitoring of the electrical insulation between element rows to detect any tendency for shorting. The P-legs had the PbSnTe segment at the hot end. Each leg, both within a row and between rows, was separated by 0.095 inch. A machinable ceramic cold plate supported the legs, and powdered Min-K filled the space around the legs. This "string" module is shown in Figure IV-15. The test was initiated with a hot junction temperature of 850°F and a cold junction temperature of 200°F. The electrical isolation resistance between adjacent rows was measured periodically. After 1750 hours of operation, the hot junction temperature was increased to 950°F. No evidence of electrical shorting was observed between adjacent element rows over the 17,000-hour test period for this module, thus demonstrating the effectiveness of the design changes to eliminate the electrical shorting experienced on CPA modules S/N 001 and S/N 002.

5. Structural Analysis Summary

A structural evaluation of a modified module was performed to consider the effects of voltage reduction from 9 volts to approximately 5 volts (larger but fewer couples), and the reduction in heat source weight from 5.5 lbs. to 1.5 lbs. The assumed module consisted of approximately 66 couples with 0.106 inch square element legs. The results are shown in Table IV-11. The resonant frequency of the heat source/module system more than doubled and was well above the 200 Hz upper limit for vibration test frequency, and the resulting thermoelectric element stress levels are greatly reduced, exhibiting values well below the measured room temperature strength values given in Table IV-9. With slight modifications, this assumed module was the basis for the selected module design discussed in Section V.

FIGURE IV-15. "STRING" MODULE IMPREGNATED WITH POWDERED MIN-K INSULATION

TES-32115-194

TABLE IV-11
MODULE DYNAMIC CHARACTERISTICS

<u>No.</u> <u>Couples</u>	<u>No.</u> <u>Acting</u>	<u>Effective</u> <u>Length</u> <u>(in.)</u>	<u>Element</u> <u>Size</u> <u>(in.)</u>	<u>Heat</u> <u>Source Wt.</u> <u>(lbs.)</u>	<u>Resonant</u> <u>Frequency</u> <u>(Hz)</u>	<u>Tensile Stress (psi)</u> <u>Vibration*</u>	<u>Shock**</u>
66	100%	.675	.106	1.5	664	-201	437

-----
* 1.5g's

** 18g's (15g shock amplified by 10% via half-sine shock profile)

V. SELECTED PbTe/TAGS MODULE TECHNOLOGY

The technical approach selected for the Special Applications thermoelectric module consists of individual minicouples arrayed in a circular configuration to form a cylindrically-shaped module assembly nominally 3 inches in diameter by 7/8 inch thick. Two module designs employing the selected technical approach have been assembled and tested during the development program. The first module design has a disc-shaped configuration with an installed configuration in an RTG as shown in Figure V-1. In this installation the heat source preload spring force and heat source weight are reacted through the individual module thermoelectric elements. Thus, the elements must be capable of withstanding vibration and shock dynamic loads to which the heat source and support system might be subjected.

The second module configuration is ring-shaped with an installed configuration as shown in Figure V-2. In this instance the heat source and spring preload are reacted through a separate heat source support which is located in the center hole of the ring module. This arrangement minimizes dynamic loads on the thermoelectric module in shock and vibration environments. The latter module configuration was developed for a potential user application which required that the RTG be capable of withstanding a 100 g axial and 50 g lateral shock load, the two loads applied simultaneously. The only other significant difference between the disc and ring modules is that the ring module incorporates a bismuth telluride (Bi_2Te_3) segment at the cold end of the P-leg to take advantage of direct exposure to a subsea environment to enhance electrical power conversion efficiency.

The two module designs are discussed in detail in the following sections.

FIGURE V-1. TYPICAL RTG CONFIGURATION WITH DISK-TYPE THERMOELECTRIC MODULE

FIGURE V-2. TYPICAL RTG CONFIGURATION WITH RING-TYPE THERMOELECTRIC MODULE

A. PbTe/TAGS Disc-Type Thermoelectric Module

1. Module Design

The disc-type thermoelectric module consists of 68 thermoelectric couples assembled to a cold side printed circuit board (refer to Figure V-3). The module is approximately 3 inches in diameter by 0.875 inch thick. The individual legs of each couple are soldered to the board by means of a copper pin brazed to the cold shoe of each leg. The double-sided copper foil pattern on the board is configured to connect the couples electrically in series. The circuit board is the prime structural member for the thermoelectric module.

Open circuit protection is provided by 26 Schottky diodes connected to the board in parallel with 26 couple groups; a single Schottky diode parallels either two or three couples, the number depending on the board location. The forward conduction voltage of the Schottky diode (approximately 0.3 volt at operating temperature) is such that no current flows through a diode unless the resistance of the parallel couple group increases to the point that the voltage drop across the couple (and diode) exceeds approximately 0.3 volt. At this point the diode becomes operational. Module thermal insulation between the thermoelectric couple legs is provided by powdered Min-K insulation. A vacuum impregnation process is used to assure that the powder is solidly packed around the thermoelectric elements, thus enhancing sublimation suppression. A circular glass fiber-based synthane skirt retains the Min-K powder at the circumference of the module.

The individual thermoelectric couples, shown in Figure V-4, consist of a PbTe N-leg and segmented TAGS P-leg; the P-leg is segmented at the hot end with PbSnTe. The N and P thermoelectric elements are 0.104 inch square by 0.625 inch long. Iron is used for both the hot and cold shoe material. A copper pin is

FIGURE V-3. SPECIAL APPLICATIONS DISC-TYPE MODULE DESIGN

P AND N-LEGS: .104 IN. SQ. x .625 IN. LG.

FIGURE V-4. PbTe/TAGS MINICOUPLE CONFIGURATION

brazed to each cold shoe to permit solder attachment to the printed circuit board. Ceramabond is used at the cold side of the board to permit sanding of the soldered copper pins so that they lie in a flat plane parallel to the hot shoe.

Figures V-5 through V-11 show the module during various steps of the assembly process. Figure V-5 is a view of the as-received printed circuit board. Figure V-6 shows the board after installation of the 1N5817 Schottky diodes. Figure V-7 depicts the board after soldering the thermoelectric couple cold shoe copper pins to the board. (Note that the thermoelectric couples are inserted from the backside of the board in the same manner as the diodes, and therefore, are not seen in this view.) Figure V-8 shows the module after application, curing and sanding of the Ceramabond. The Ceramabond is sanded to the level that a majority of the copper pin ends are visible. Figure V-9 shows the module inverted so that the hot shoes of the thermoelectric couples can be seen. The diodes are visible between the couple legs at the backside of the circuit board. The circumferential Synthane skirt, installed in preparation for the powdered Min-K impregnation process, is also visible in this view. Figure V-10 is a view of the module in the vacuum impregnation tooling after filling the void volume around the thermoelectric couples with powdered Min-K insulation. And finally, Figure V-11 pictures a completed module ready for testing or installation in a generator.

As a side discussion, prior to selection of the PC board as the means to complete the electrical circuit and support the couples at the module cold end, a machineable ceramic (Macor) was evaluated for this application. A prototype module was assembled to evaluate this design approach. Figure V-12 depicts the machined cold end plate for the module showing the holes for the couple legs and recesses for the Schottky diodes. Figure V-13 shows the diodes and couple cold caps in position for the soldering of the diodes. (Note that the couple

FIGURE V-5. THERMOELECTRIC MODULE PC BOARD

**FIGURE V-6. THERMOELECTRIC MODULE PC BOARD AFTER
SOLDERING PROTECTION DIODES**

**FIGURE V-7. THERMOELECTRIC MODULE AFTER SOLDERING
OF DIODES AND COUPLES**

FIGURE V-8. THERMOELECTRIC MODULE COLD SIDE VIEW

**FIGURE V-9. THERMOELECTRIC MODULE PRIOR TO POWDERED
MIN-K IMPREGNATION**

**FIGURE V-10. THERMOELECTRIC MODULE AFTER POWDERED MIN-K
VACUUM IMPREGNATION**

**FIGURE V-11. COMPLETED THERMOELECTRIC MODULE
HOT SIDE VIEW**

FIGURE V-12. MACHINED MACOR PLATE

FIGURE V-13. PROTOTYPE MODULE AFTER DIODE SOLDERING

interconnect straps are installed subsequent to this operation, and therefore, are not seen in this view.) Figure V-14 shows the module after completing the soldering operations. (The diodes are installed on the opposite side of the cold plate from that previously discussed for the selected PC board approach.) Figure V-15 presents the completed module after using Ceramabond to fill the voids around the diodes and couple leg cold caps. This approach was abandoned because of the fabrication cost of the complex cold plate and element cold caps, the relatively difficult soldering operation and repair considerations. The PC board approach simplified most of these operations.

A total of 12 thermoelectric modules of the disc-type design were fabricated to support the program module testing requirements and generator assembly activities. Table V-1 summarizes the usage and test status of these modules as of the preparation of this report.

2. Module Testing

Three modules, S/N 6, S/N 7 and S/N 12, have been tested for long-term in a bell jar environment. Six modules are installed in three life test fixtures (2 modules per fixture) and have each accumulated approximately 20,000 hours of operation. Two modules have been used in the assembly of two electrically-heated generators (ETGs) and have accumulated 8,000 to 12,000 hours of operation. All module testing is continuing with the exception of S/N 7 and S/N 6 which were removed from test after approximately 1 year and 2 years of operation, respectively, for evaluation.

a. Bell Jar Tests

Table V-2 presents initial data for the three modules tested in the bell jar. All modules were very close to the performance prediction. Note that the design point for the disc-type module is 850/210°F hot/cold junction temperatures

FIGURE V-14. PROTOTYPE MODULE AFTER SOLDERING OPERATIONS

FIGURE V-15. PROTOTYPE MODULE AFTER APPLICATION OF CERMABOND FILLER

TABLE V-1
TEST/USAGE STATUS SUMMARY
FOR DISC-TYPE THERMOELECTRIC MODULES

<u>Module S/N</u>	<u>Status/Comments</u>	<u>Usage</u>
6	. On test 20544 hours***	Bell Jar Test
7	. On test 9384 hours, removed from test on 4/7/87*	Bell Jar Test
8 & 9	. On test 20450 hours	Life Test (Fixture STA 1)
10	. Room temperature vibration/shock test completed; on test 19467 hours. Life Test (Fixture STA 3)	Room Temperature Vibration/Shock Test; Life Test (Fixture STA 3)
11 & 13	. On test 20124 hours	Life Test (Fixture STA 2)
12**	. On test 11688 hours	Room Temperature Vibration Test (alt.); Bell Jar Test
14	. On test 19467 hours	Life Test (Fixture STA 3)
15	. Assembly completed	Spare
16	. On test 12669 hours	Ground Demonstration System (GDS #1)
17	. On test 8711 hours	Engineering Demonstration Unit (EDU)

* Module S/N 7 was cooled down on 4/7/87 after 9384 hours of operation for evaluation. Module S/N 12 was installed in the test station previously occupied by S/N 7.

** On module S/N 12, the hot side alumina insulator is bonded to the thermoelectric couple hot shoes. This module was used as an alternate design backup for the room temperature dynamic test.

*** Module S/N 6 was cooled down on 7/27/88 after 20544 hours of operation for evaluation. Module S/N 101 (ring module) was installed in the test station previously occupied by S/N 6.

NOTE: Times are as of 9/2/88 on Fixtures STA 1, 2 and 3; 7/27/88 on module S/N 6; 8/2/88 on module S/N 12; 9/2/88 on the EDU; 9/2/88 on GDS #1.

TABLE V-2MODULE INITIAL PERFORMANCE SUMMARYBELL JAR TESTS

	Prediction @ 100 Hrs.	Normalized Test Data		
		Module S/N 6 @ 115 Hrs.	Module S/N 7 @ 114 Hrs.	Module S/N 12 @ 504 Hrs.
Power Output (W(e))	3.66	3.69	3.70	3.72
Hot Junction ($^{\circ}$ F)	850	850	850	850
Cold Junction ($^{\circ}$ F)	210	210	210	210
Load Voltage (V)	5.25	5.25	5.25	5.25
Open Circuit Voltage (V)	9.04	8.83	8.83	8.91
Internal Resistance (ohms)	5.43	5.09	5.08	5.16

Module Configuration Summary

- . Disc-type module.
- . Element size: 0.104 in. sq. x 0.625 in. lg.
- . 68 couples connected electrically in series.
- . PbTe N-leg; TAGS P-leg with 0.075 in. lg. PbSnTe segment at hot side.
- . Vacuum impregnated powdered Min-K insulation.
- . Schottky diode open circuit protection.
- . PC board cold side electrical straps.

and 5.25 V load voltage.

Figure V-16 shows the power output of the three modules with operating time. Module S/N 7 was tested for 9384 hours before removal from test for diagnostic inspection to permit assessment of the module condition after approximately one year of operation. Module S/N 6 was tested for 20544 hours before removal from test for diagnostic evaluation.

As shown in Figure V-16, the junction temperatures on modules S/N 6 and S/N 12 were reduced from 850/210°F to 800/200°F during the test. The reasons for this reduction were two-fold. Firstly, diagnostic disassembly data from module S/N 7 as well as component couple tests showed unacceptable sublimation of the TAGS segment and oxidation of the N-leg (at their hot sides) for a 15-year mission. A reduction in the hot junction temperature of approximately 50°F appeared warranted based on examination of available TAGS sublimation test data and examination of the TAGS element surface recession from the long-term test samples. Secondly, at this point in the program a Bi_2Te_3 cold segment was being added to the P-leg cold side. A 68-couple module with this type couple would operate at a nominal 800°F hot junction temperature with the thermal inventory capacity of the 3-layer fuel capsule being developed jointly with MRC/Mound Plant. Therefore, in October 1987 the hot junction test temperature was reduced to 800°F and the load voltage changed to 5.0 V to be consistent with the modified junction operating temperatures. Also, as a result of the observed oxidation of the N-leg at the hot end, outgassing procedures for ring-type module hardware have been modified to assure a more thorough outgassing of the powdered Min-K insulation within the module assembly.

b. Module Life Test Fixtures

Six disc-type modules are being life tested in three test fixtures (two modules per fixture). Figure V-17 shows the test setup for the three life test fixtures.

FIGURE V-16
MODULE BELL JAR TEST DATA

(continued next page)

FIGURE V-16 (CONTINUED)

FIGURE V-17. THERMOELECTRIC MODULE LIFE TEST SETUP

Table V-3 presents the initial performance for these modules; the performance prediction is included for comparison. All modules agreed with the performance power prediction within 4%.

Figures V-18, V-19 and V-20 show the test data for Life Test Fixtures Nos. 1, 2 and 3, respectively. All fixtures have accumulated approximately 20,000 hours of operation.

As with the bell jar tests previously discussed, in October 1987 the hot junction operating temperatures of the life test fixtures were reduced. Two operating conditions were simulated by the revised operating temperatures. Life Test Fixture No. 1 was reduced to 750/150°F hot/cold junction temperatures to simulate "worst case" conditions for a subsea application where the RTG would be exposed directly to the seawater environment. Life Test Fixture Nos. 2 and 3 are being operated at 800/200°F hot/cold junction temperatures to simulate "worst case" air operation or a subsea application in which the RTG might be buried or silted over. All module life tests are continuing to permit accumulation of data for performance assessment of long-term applications.

c. Generator Testing

Testing of disc-type modules in generator hardware has been on two units. The EDU (rebuilt after removal of the CPA module previously discussed in Section IV) and GDS #1 (shown in Figure V-21) generators have been assembled and tested with results as reported under separate cover (refer to "Special Applications Summary Test Report for Engineering Demonstration Unit (EDU)," TES-32115-150 dated September 1987 and "Special Applications Summary Test Report for Ground Demonstration System (GDS)," TES-32115-151 dated October 1987).

TABLE V-3

MODULE INITIAL PERFORMANCE SUMMARY

LIFE TEST FIXTURES

	Bell Jar Test		STA Fix. No. 1		STA Fix. No. 2		STA Fix. No. 3	
	Prediction	MOD S/N 6	MOD S/N 7	MOD S/N 8	MOD S/N 9	MOD S/N 11	MOD S/N 13	MOD S/N 14
	@ 100 Hrs	@ 115 Hrs	@ 114 Hrs	@ 98 Hrs	@ 98 Hrs	@ 111 Hrs	@ 111 Hrs	@ 94 Hrs
Pwr. Output (W(e))	3.66	3.69	3.70	3.53	3.67	3.71	3.71	3.65
Hot Junc. ($^{\circ}$ F)	850	850	850	850	850	850	850	850
Cold Junc. ($^{\circ}$ F)	210	210	210	210	210	210	210	210
Load Volt. (V)	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25
Open Cir. Volt. (V)	9.04	8.83	8.83	8.79	8.80	8.82	8.85	8.84
Inter. Resis. (Ohms)	5.43	5.09	5.08	5.25	5.07	5.05	5.10	5.16

Module Configuration Summary

- . Disc-type module.
- . Element size: 0.104 in. sq. x 0.625 in. lg.
- . 68 couples connected electrically in series.
- . PbTe N-leg; TAGS P-leg with 0.075 in. lg. PbSnTe segment at hot side.
- . Vacuum impregnated powdered Min-K insulation.
- . Schottky diode open circuit protection.
- . PC board cold side electrical straps.

* Module subjected to room temperature qualification level vibration/shock testing prior to life test.

FIGURE V-18
LIFE TEST FIXTURE NO. 1 DATA

FIGURE V-19
LIFE TEST FIXTURE NO. 2 DATA

FIGURE V-20
LIFE TEST FIXTURE NO. 3 DATA

**SPECIAL APPLICATIONS
GROUND DEMONSTRATION SYSTEM (GDS)
S/N 301**

Engineering Tests Initiated: March 25, 1987

Nominal Power Output: 3.4 W(e) @ 5.00 VDC

Nominal Input Power: 60.5 W(e)

Hot Junction Temperature: 750°F

Cold Junction Temperature: 150°F

FIGURE V-21. SPECIAL APPLICATIONS GDS #1

AIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

Centimeter

Inches

MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.

---

2 of 2

**SPECIAL APPLICATIONS
GROUND DEMONSTRATION SYSTEM (GDS)
S/N 301**

Engineering Tests Initiated: March 25, 1987

Nominal Power Output: 3.4 W(e) @ 5.00 VDC

Nominal Input Power: 60.5 W(e)

Hot Junction Temperature: 750°F

Cold Junction Temperature: 150°F

FIGURE V-21. SPECIAL APPLICATIONS GDS #1

The initial performance of these units is shown in Table V-4, and the long-term test results in Figure V-22. As with the other test modules discussed in this section the power performance of the EDU and GDS #1 agreed well with the performance prediction.

Referring to Figure V-22, initially the two generators were both operated at 850/210°F hot/cold junction temperature and 5.25 V load voltage. However, as with the other test hardware, in October 1987 the operating temperatures were reduced. The EDU has since been operating at 800/200°F junction temperatures, and GDS #1 at 750/150°F temperatures; load voltage for both units is 5 V. As discussed previously, the present test temperatures are "worst case" for an in-air or sea burial condition and subsea operation, respectively.

B. PbTe/TAGS-Bi₂Te₃ Ring-Type Thermoelectric Module

1. Module Design

The basic construction and assembly techniques for the ring-type thermoelectric module differ from the disc-typed module discussed previously as follows:

- 1) A 1.25 inch diameter center hole has been added to accommodate a heat source support.
- 2) A Bi₂Te₃ segment has been added to the cold side of the P-leg to improve power conversion efficiency.
- 3) The powdered Min-K thermal insulation is subjected to a more thorough outgassing schedule to maximize removal of contaminants.
- 4) 1/4 inch diameter holes (baffled with microquartz fiber insulation to prevent loss of powdered Min-K insulation) have been added in the outer Synthane circular skirt to improve gas exchange from the module powdered Min-K insulation during outgassing operations.
- 5) The module OD has been increased to 3.42 inches to accommodate the center hole while still including the 68 minicouples.
- 6) The minicouples have been arrayed in concentrated circles around the center hole.

TABLE V-4

EDU AND GDS INITIAL PERFORMANCE

	<u>Prediction @ 100 Hrs.</u>	<u>EDU (S/N 201) @ 99 Hrs. (9/15/86)</u>	<u>GDS (S/N 301) @ 100 Hrs. (3/28/87)</u>
Power Output (W(e))	3.63	3.65	3.67
Power Input (W(t))*	59.6 (EDU) 64.6 (GDS)	60.1	64.2
Hot Junction ($^{\circ}\text{F}$)	850	845	847
Cold Junction ($^{\circ}\text{F}$)	210	210	210
Load Voltage (V)	5.25	5.25	5.25
Open Circuit Voltage (V)	9.04	8.83	8.85
Internal Resistance (Ohms)	5.48	5.14	5.14
System Efficiency (%)*	6.09 (EDU) 5.62 (GDS)	6.07	5.72

Configuration Summary

- Disc-type module.
- Element size: 0.104 in. sq. x 0.625 in. lg.
- 68 couples connected electrically in series.
- PbTe N-leg; TAGS P-leg with 0.075 in. lg. PbSnTe segment at hot side.
- Vacuum impregnated powdered Min-K insulation.
- Schottky diode open circuit protection.
- PC board cold side electrical straps.
- Fill gas: 100% Xe.
- EDU assembled into Five-Watt RTG configured housing; GDS housing 4.5 in. dia. x 10.1 in. lg.

---

* RTG equivalent thermal input.

FIGURE V-22
EDU AND GDS #1 LIFE TEST DATA

Figure V-23 shows both a partially completed and completed ring module assembly.

The design of the minicouple employing the Bi_2Te_3 cold segment on the P-leg is shown in Figure V-24. Fabrication of this couple requires three bonding steps instead of the two necessary with the straight PbTe/TAGS minicouple. The fabrication steps for the two minicouple assemblies are included in Figure V-25.

A total of six ring thermoelectric modules has been fabricated with dispositions as shown in Table V-5. Since the ring modules were fabricated near the end of the Special Applications program, only short-term test data were available as of the preparation of this report. However, modules will continue on test to accumulate time to permit performance evaluation.

2. Test Results

Testing has been initiated on two ring modules, including one module (S/N 101) in a bell jar environment and another (S/N 105) in the GDS #2 generator. Two additional modules (S/N 102 and S/N 103) were being assembled into a life test fixture for long-term testing at the time this report was being prepared.

a. Bell Jar Test

Module S/N 101 was placed on test in July 1988 to permit assessment of the ring module performance and comparison with the performance prediction. Table V-6 shows the available test data as of the preparation of this report (accumulated module operating time of 745 hours). Two test conditions were evaluated. The first test point was a power check at a 200°F cold junction temperature. This cold junction temperature is considered a "worst case" test condition for in-air operation or for operation in a subsea burial environment. A second power check was performed at a 100°F cold junction temperature. This latter temperature is considered a "typical" cold junction temperature for an application in which the RTG is exposed directly to the seawater environment. The power output of the module

THERMOELECTRIC MODULE DURING COLD
END SOLDERING OPERATION

COMPLETED MODULE (HOT SIDE VIEW)

FIGURE V-23. RING-TYPE THERMOELECTRIC MODULE

P and N Legs: .104 in. sq. x .625 in. lg.

FIGURE V-24. MINICOUPLE CONFIGURATION WITH Bi_2Te_3 SEGMENT

1st Bond 2nd BondPbTe/TAGS MINICOUPLE 1st Bond 2nd Bond 3rd BondPbTe/TAGS-Bi₂Te₃ Minicouple

FIGURE V-25. MINICOUPLE ASSEMBLY STEPS

TES-32115-194

TABLE V-5
FABRICATION/TEST STATUS SUMMARY
OF RING-TYPE MODULES

<u>Module S/N</u>	<u>Status/Comments</u>	<u>Usage</u>
101	. On test 1753 hours	Bell Jar Test
102	. Initiated fixture assembly	Life Test (Fixture STA 4)
103	. Initiated fixture assembly	Life Test (Fixture STA 4)
104	. Assembly completed	Spare
105	. On test 448 hours	Ground Demonstration System #2 (GDS #2)
106	. Assembly completed	Spare

NOTE: Test times are as of preparation of this report.

TABLE V-6RING-TYPE MODULE S/N 101 PERFORMANCE

	<u>Predicted</u>		<u>Module S/N 101</u>		
	<u>@ 100 Hrs.</u>		<u>@ 91 Hrs.</u>	<u>@ 171 Hrs.</u>	<u>@ 745 Hrs.</u>
Power Output (W(e))	3.37	3.79	3.31	3.70	3.40
Hot Junction ($^{\circ}\text{F}$)	800	706	792	707	782
Cold Junction ($^{\circ}\text{F}$)*	200	100	200	100	200
Load Voltage (V)	5.00	5.00	5.00	5.00	5.00
Open Circuit Voltage (V)	8.80	8.40	8.48	8.13	8.52
Internal Resistance (Ohms)	5.61	4.49	5.24	4.23	5.18

Module Configuration Summary

- Ring-type module.
- Element size: 0.104 in. sq. x 0.625 in. lg.
- 68 couples.
- PbTe N-leg; TAGS P-leg with 0.090 in. lg. PbSnTe hot segment and 0.312 in. lg. Bi_2te_3 cold segment.
- Vacuum impregnated powdered Min-K insulation.
- Series circuit with Schottky diode open circuit protection.
- PC board cold side electrical straps.

* 200°F - typical of "worst case" in-air or subsea burial operation; 100°F - representative cold junction for subsea application.

NOTE: Time is as of 9/2/88 at 745 hours.

was within 2% of the prediction at these test conditions. The module is continuing on long-term test at the 800/200°F operating condition.

b. Generator Testing

Fabrication, assembly and initial performance testing of the electrically-heated GDS #2 were completed just prior to the preparation of this report. Figure V-26 depicts the GDS #2 generator on its support stand. The topical report for this generator giving details of the generator test program and resulting test data will be issued in a separate report. However, the initial performance check for this unit is included in Table V-7. The power output of the generator agreed well with the prediction, however, the required thermal input was 3.3 watts greater than that predicted. It should be pointed out that the GDS #2 generator incorporates a metallic "hard" mount for the heat source that fits in the thermoelectric module center hole, thus increasing the heat losses substantially above those typical of GDS #1. This hard mount was incorporated to satisfy the 100 g axial, 50 g lateral (both applied simultaneously) shock requirement for a specific mission for which the Special Applications RTG technology is being considered. For applications not requiring the hard mount, a material with better thermal insulating properties would be used in lieu of the metallic support to substantially reduce heat losses.

After completion of the parametric performance, vibration and shock dynamic tests this unit will be placed on life test to accumulate operating time and permit assessment of long-term performance stability.

c. Component Dynamic Tests

To assess the capability of the ring module and heat source support structure to withstand the anticipated dynamic test requirements of potential near-term applications (including the 100 g shock requirement previously

FIGURE V-26. SPECIAL APPLICATIONS GDS

mentioned), a test fixture containing an all-up ring module and simulated heat source with its associated support structure, was assembled and subjected to a dynamic test program as outlined in Table V-8. All tests were conducted at room temperature (non-operational). The details of this dynamic test program are included in a separate report (refer to "Special Applications Module Cold Shock Test Report," STA-DST-120 dated October 20, 1988) but are summarized below.

The room temperature transportation level vibration and functional shock tests were performed at MRC/Mound during the April 1988 time period. The transportation level vibration and functional shock tests were considered to be successful with one exception. During the initial assembly of the module into the dynamic test fixture, five of the 68 total thermoelectric couples were damaged. The thermoelectric module resistance at the initiation of the dynamic test was measured to be 9.2 ohms. At the conclusion of the test the module resistance was unchanged. Therefore, the vibration and shock tests did not result in any additional damage over that experienced during initial assembly. After disassembly of the test fixture and return of the test module to TES, diagnostic evaluation of the module showed five couples to be cracked and that the probable cause was that the uneven plane of the hot shoes resulted in the couples being damaged during assembly. As a result of this experience the module assembly tooling and procedure were modified to assure that the minicouple hot shoes of the completed module all lie in the same plane.

The 100 g shock test was conducted at the Naval Surface Weapons Center in White Oak, Maryland in May 1988. The test was performed at room temperature using a test fixture which permitted simultaneous application of the 100 g axial and 50 g lateral shock on the test hardware. The test consisted of applying a simultaneous 100 g axial and 50 g lateral shock load on the simulator in first the +X and then

TABLE V-8DYNAMIC TEST REQUIREMENTSVibration

Basic Transportation

MIL-STD-810D (19 July 1983), Method 514.3, Category 1 (Figures 514.3-1, 514.3-2 and 514.3-3). Two-hour test duration in each of the three axes (equivalent to 2000 miles of expected overland transportation).

Shipboard

MIL-STD-167-1 (SHIPS) (1 May 1974), Type I, Consisting of resonance search from 4 Hz to 50 Hz (para. 5.1.3.3.1), vibration from 4 Hz to 50 Hz (para. 5.1.3.3.2), and resonance dwell (para. 5.1.3.3.3).

Shock

Functional

MIL-STD-810D (19 July 1983), Method 516.3, Procedure I, Figure 516.3-4 (20 g, 11ms). Applied three times in each direction of each axis (18 shocks total).

Mission Specific

100g axial, 50g lateral 50ms shock applied simultaneously in one axial direction (+Z) and each of two orthogonal lateral directions (+X and +Y) (two shocks total).

the +Y directions. The shock test in the +X axis was completed successfully with no change in thermoelectric module electrical resistance. However, after the shock in the +Y axis the module resistance was very high. On disassembly of the test fixture, the cause for the failure in the +Y axis was determined to be that the Macor ceramic heat source support sleeve had shattered, allowing the heat source simulator to displace and strike the thermoelectric module, damaging a number of couples.

Structural and thermal analyses were performed to select a revised support sleeve design incorporating new material for the heat source support. A metallic support was preferable due to the difficulty in assessing the adequacy of inherently brittle materials (such as ceramics) to survive the shock loading. A titanium alloy was selected for the support material.

In July 1988 the room temperature shock test was repeated at the Naval Surface Weapons Center to verify the adequacy of the modified heat source support design to withstand the 100 g axial, 50 g lateral shock load requirement. The heat source support and all-up thermoelectric module survived the simultaneous axial and lateral shock impulses in both the X and Y lateral axes (two shocks total). Electrical resistance measurements performed on the thermoelectric module demonstrated that the module and its support system had also survived the shock test. There was no significant change in the total module resistance or individual minicouple resistances as a result of the test. GDS #2 is scheduled to be subjected to the same dynamic test environments as the test fixture to permit assessment of structural capability of the module and heat source support at normal RTG operating conditions.

**DATE
FILMED**

9/22/93

END