RECEIVED BY DTIC NOV 18 1969

~~CONFIDENTIAL~~

MASTER

Gulf General Atomic
Incorporated

AEC RESEARCH AND
DEVELOPMENT REPORT

GA-9501

C-92a, Systems for Nuclear
Auxiliary Power (SNAP) -
Isotopic SNAP Program
(M-3679, 62nd Ed.)

UNCLASSIFIED

PRELIMINARY ANALYSIS AND EXPERIMENTAL INVESTIGATIONS OF THE
TRANSIT/ISOTEC THERMOELECTRIC GENERATOR THERMAL RESPONSE
DURING LAUNCH EVENTS (U)

By:

George Bradshaw

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Prepared Under
Contract AT(29-2)-2564
for the
Albuquerque Operations Office
U.S. Atomic Energy Commission

69 214

~~GROUP-3~~

Downgraded at 12-year intervals;
not automatically declassified

This material contains information affecting the
national defense of the United States within the
meaning of the espionage laws, Title 18, U. S. C.,
Sections 793 and 794, the transmission or revela-
tion of which in any manner to an unauthorized
person is prohibited by law.

~~RESTRICTION OF THIS DOCUMENT IS LIMITED
To Government Agencies and Their Contractors~~

Project 4021

~~CONFIDENTIAL~~

January 1969

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express 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. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

~~CONFIDENTIAL~~

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

Printed in USA. Charge \$1.45. Available from the U.S. Atomic Energy Commission, Division of Technical Information Extension, P.O. Box 62, Oak Ridge, Tenn. 37830. Please direct to the same address inquiries covering the procurement of other classified AEC reports.

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~
Gulf General Atomic
Incorporated

P.O. Box 608, San Diego, California 92112

AEC RESEARCH AND
DEVELOPMENT REPORT

SPECIAL REVIEW
FOUO
DETERMINATION
Class: U
Reviewer: KAW
Class: U
Date: 6/30/82

GA-9501
C-92a, Systems for Nuclear
Auxiliary Power (SNAP) -
Isotopic SNAP Program
(M-3679, 62nd Ed.)

~~UNCLASSIFIED~~
Copy No. **1**

PRELIMINARY ANALYSIS AND EXPERIMENTAL INVESTIGATIONS OF THE
TRANSIT/ISOTEC THERMOELECTRIC GENERATOR THERMAL RESPONSE
DURING LAUNCH EVENTS (U)

by

George B. Bradshaw

Classification cancelled or changed to
by authority of DOE
by ATC - TIC, date SEP 6 - 1973

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express 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.

United
accu
he use
fringe
in the
em
t that
ares,
tract

Prepared Under
Contract AT(29-2)-2564
for the

Albuquerque Operations Office
U.S. Atomic Energy Commission

~~GROUP-3
Downgraded at 12-year intervals;
not automatically declassified~~

This material contains information affecting the national defense of the United States within the meaning of the espionage laws, Title 18, U. S. C., Sections 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

Project 4021

January 1969

~~CONFIDENTIAL~~
DISTRIBUTION OF THIS DOCUMENT UNLIMITED

~~DISTRIBUTION OF THIS DOCUMENT IS LIMITED
To Government Agencies and Their Contractors~~

UNCLASSIFIED

ii

CONTENTS

	Page
1.0 Introduction	1
2.0 Experimental Investigations	2
2.1 1000-Hour Module Tests in Air and Nitrogen	2
2.1.1 Experimental Equipment and Procedures	2
2.1.2 Discussion of Experimental Results	5
2.2 Converter Thermal Tests in Nitrogen, Inert Gasses and Air	15
2.2.1 Experimental System	15
2.2.2 Experimental Procedures	18
2.2.3 Discussion of Experimental Results	21
3.0 Analytical Efforts	32
3.1 Prelaunch and Launch Phase Events	32
3.2 Comparison of Predicted and Experimental Equilibrium Temperatures	35
3.3 Converter Transient Thermal Response During Launch	44
3.4 Predicted Converter Electrical Performance During Environmental Operation	47
4.0 Summary and Conclusions	56
Acknowledgements	58
References	59
Appendix - Experimental Measurements on the GC01 Converter in Various Gases	60

UNCLASSIFIED

LIST OF FIGURES

<u>Figure No.</u>		<u>Page</u>
1.	Thermoelectric Test Station Used on Module Air and Nitrogen Life Tests	3
2.	Power and Temperature Data for Modules Life-Tested in Air	6
3.	Power and Temperature Data for Modules Life-Tested in Nitrogen	7
4.	Power Output of Modules Before and After 1000-Hour Air Tests	8
5.	Power Output of Modules Before and After 1000-Hour Nitrogen Tests	9
6.	Resistance and Seebeck Coefficient Per Couple Before and After 1000-Hour Air Tests	10
7.	Resistance and Seebeck Coefficient Per Couple Before and After 1000-Hour Nitrogen Tests	11
8.	Typical Temperature and Relative Humidity Conditions During the Module Air Tests	14
9.	Experimental Electric Heat Source Assembly Drawing	16
10.	Photograph of the Converter and Heat Source During Integration	17
11.	Schematic Diagram of the Set-Up for Generator Gas Tests	17
12.	Experimental Test Equipment Used for the GC01 Environmental Tests	19
13.	Location of GC01 Inside the Experimental Chamber	20
14.	Comparison of Converter Hot Junction Temperatures in Nitrogen with Power Input and Orientation	24
15.	Comparison of Converter Hot Junction Temperatures in Static Helium and Nitrogen	25
16.	Converter Hot Junction Temperatures in Flowing Gas	26
17.	Comparison of Converter Hot Junction Temperatures In Static Air and Nitrogen	28
18.	Comparison of Experimental Temperatures for Different Cooling Gases	30

UNCLASSIFIED

iv

<u>Figure No.</u>		<u>Page</u>
19.	Payload Field Flow Processing Plan for the SCOUT Vehicle	33
20.	Vandenberg Air Force Base, Western Test Range Launch Site	34
21.	Schematic of the SCOUT Payload Envelope — Showing the Relative Size of the TRANSIT/ISOTEC Generator and Gas Test Chamber	36
22.	Schematic of Events During Typical Orbital Missions for the SCOUT Heat Shield	38
23.	Temperatures Inside the SCOUT Heat Shield	39
24.	SCOUT Heat Shield Temperatures During Flight	40
25.	Typical SCOUT Boost Performance During Orbital Ascent	40
26.	Generator Temperatures During the First 120 Seconds of Vehicle Flight	46
27.	Change in GC01 Internal Resistance With Average Element Temperature	49
28.	Experimental Open Circuit Voltages in Different Prelaunch Coolant Gases	50
29.	GC01 Power Output and Efficiency During Tests in Different Gases	52
30.	Converter Performance Characteristics for Different Pre-launch Hot Junction Temperatures	53
31.	Converter Performance Characteristics During Typical Pre-launch Environmental Operation	54
32.	Hot Junction Temperature Change With Load Variations During Prelaunch Operation	55

APPENDIX

A-1	Schematic of Panel and Thermocouple Locations on the GC01 Generator	61
A-2	Schematic of Thermocouple Location on SCOUT Shroud Simulation Chamber	62
A-3	Thermocouple Location on GC01 Side Panel PE03	63
A-4	Thermocouple Location on GC01 Bottom Panel PE07	64
A-5	Thermocouple Location on GC01 Side Panel PE11	65
A-6	Thermocouple Location on GC01 Top Panel PE02	66

UNCLASSIFIED

LIST OF TABLES

<u>Table No.</u>		<u>Page</u>
1.	Summary of Thermoelectric Property Data at $\bar{T} = 280^{\circ}\text{C}$ Before and After Environmental Tests	12
2.	Summary of GCOI Generator Temperatures During Static and Dynamic Flow Tests in Nitrogen, Helium and Argon	22
3.	Temperatures of GCOI Generator in Static Air	27
4.	Time sequence of Events During Typical Orbital Missions for the SCOUT Vehicle	37
5.	Summary of Computed Temperatures Inside the SCOUT Shroud and Measured Temperatures on GCOI Inside a Simulation Chamber	41
6.	Physical Properties of Candidate Launch Pad Coolant Gases at One Atmosphere Pressure	43
7.	Summary of Worse-Case ISOTEC Generator Temperatures Inside the SCOUT Heat Shield During Launch	45

APPENDIX

A-1	Measured Temperatures on GCOI in Static Nitrogen for Three Different Converter-Chamber Positions	67
A-2	Measured Chamber and Gas Temperatures During Static Nitrogen Tests	68
A-3	Measured Temperatures on GCOI in Static Helium, Bottom-up Position	69
A-4	Measured Temperatures on GCOI in Flowing Gas, Bottom-up Position	70
A-5	Measured Chamber and Gas Temperatures During Flow Tests in Helium, Nitrogen and Argon	71
A-6	Measured Temperatures on GCOI in Static Air, Vertical Bottom-up Position	72

~~CONFIDENTIAL~~

1

1. INTRODUCTION

The TRANSIT/ISOTEC radioisotope thermoelectric power supply will be exposed to ambient environments during launch events. Under the TRANSIT/ISOTEC RTG Program, preliminary analytical and experimental investigations have been performed to assess thermal and electric operating characteristics of the ISOTEC system in different ground support environments, and are reported in this document.

The experimental efforts, which included both module and converter tests, were designed to provide the most accurate quantitative data possible, within existing budgetary and experimental limitations. Accordingly, existing quality control modules were tested in thermoelectric vacuum stations at Gulf General Atomic, while the full size GCO1 developmental converter was used for system tests which were performed inside a steel test chamber. The chamber structure simulated the Scout missile shroud envelope, and a specially designed spherical stainless steel electric heater simulated the radioisotope heat source.

Results of the module tests verified the feasibility of using either nitrogen or air for cooling the generator by operating over 1000 hours at 250°C hot junction temperature with no significant thermoelectric property or power degradation. The converter tests demonstrated the system response to various gases, and investigated their relative merits as cooling media. Experimental results also supported calculations of peak hot-junction temperatures, which were generally below those predicted.

The analytical phase was primarily concerned with evaluating converter and heat source temperatures under static gas conditions inside a Scout missile shroud. Preliminary computations were also performed on the transient thermal response of the generator during the first 120 seconds of flight, while the power supply and satellite are surrounded by the vehicle heat shield. The report summarizes results of these analyses, and briefly discusses the launch operations. The last section presents predicted electrical characteristics of the converter during ground operation.

~~CONFIDENTIAL~~

2. EXPERIMENTAL INVESTIGATIONS

This section of the report describes preliminary tests on individual ISOTEC modules and the GC01^{*} thermoelectric converter in various gases. During these experiments, four thermoelectric couples were heated to hot junction temperatures of 250°C in air, and four in nitrogen, for periods greater than 1000 hours. The converter tests consisted of short-term operation of GC01 at power input levels to 750 watts in nitrogen, helium, argon, and air.

2.1 1000-Hour Module Tests in Air and Nitrogen

2.1.1 Experimental Equipment and Procedures

Four GC02 quality control modules, which had undergone qualification performance tests in vacuum, were selected for the long-term air and nitrogen experiments. Two modules each were installed in special thermoelectric test stations, which consisted of a heater block and water-cooled heat sinks located inside a bell jar chamber, which was connected to a 400-liter/sec ion pump. The stations were designed to accommodate either vacuum or gas environments, permitting a variety of tests without disturbing the experimental system. Figure 1 shows the module test station and support equipment employed for these tests.

For the air environment, the 8-inch x 14-inch bell jar was open directly to the laboratory through a 1-1/2 inch inlet manifold. Air temperatures and relative humidity near the inlet were continuously recorded during the tests. At the nitrogen test station the atmosphere was obtained by backfilling the evacuated test chamber with 99.998% pure nitrogen, from a certified bottle, until reaching an internal pressure of 700 mm/Hg. The pressure was maintained below one atmosphere to seal the bell jar and maintain the high purity environment, which was continuously monitored by an 8-1/2 inch absolute pressure gauge. Each module being tested contained eight 2-mil iron/constantan thermocouples which

* GC01 was the first full-size developmental thermoelectric converter fabricated by Gulf General Atomic under the TRANSIT/ISOTEC RTG Program. The generator has a power output of 26.8 watts at hot junction temperatures of 400°C in vacuum (reference 1).

UNCLASSIFIED

Figure 1. Thermoelectric Test Station Used for Module Air and Nitrogen Life Tests

UNCLASSIFIED

~~CONFIDENTIAL~~

4

were spot welded to each of the element hot and cold caps. The two thermoelectric modules are mounted in series and electrically instrumented to allow measurement of output power, element and circuit resistance, and Seebeck coefficients.

The test procedure for both the nitrogen and air tests first included performance testing each module in 10^{-7} torr vacuum to hot junction temperatures of 450°C . Results from these tests were then compared to the earlier quality control module performance test data to check out the experimental set-up and verify module integrity. Immediately following the vacuum tests, the modules were allowed to cool to 150°C and the test atmosphere was carefully introduced while monitoring the hot junction temperatures. When atmospheric pressure was reached (in the case of air), or 700 mm/Hg (in the case of nitrogen) the heater power was stepwise increased until the planned hot junction temperature of 250°C was attained. Life testing began at this point, with 1000 hours at hot junction temperatures of 250°C being the planned objective. This temperature was the maximum value calculated for the converter in a static ambient environment.

During the 1000-hour test period, continuous recordings were maintained on test atmospheres and element temperatures. Twice weekly measurements were made of element and module resistance, element Seebeck coefficients, load and open-circuit voltage, load and open-circuit temperatures, and module output power. At the duration of the tests, the heater power was reduced to achieve hot junction temperatures of 100°C and the chamber again evacuated to 10^{-7} torr vacuum. Performance tests, identical to the initial ones, were then conducted to allow comparison of thermoelectric properties with those made prior to the air and nitrogen tests.

The performance tests and 1000-hour atmospheric tests were successfully completed and all of the experimental equipment performed flawlessly. During the tests the laboratory equipment was relocated to a new site. However, the transfer was executed with no deleterious effects to the test equipment or specimens.

~~CONFIDENTIAL~~

2.1.2 Discussion of Experimental Results

Quality Control modules number 15 and 20 were life tested in air at hot junction temperatures of 250°C for a total of 1080 hours. Modules AC-17 and 23 were similarly tested for a total of 1155 hours in a 99.998% pure N_2 environment. Figures 2 and 3 present experimental temperature and power output data during these tests. The temperatures are the average of the four hot junction values. Due to characteristics of the experimental system, the temperatures vary slightly and are consequently maintained such that the maximum hot junction temperature is 250°C . The net effect is that the average is slightly below this value and can fluctuate during the experiment. Because of minor temperature variations the experimental power has been normalized to a ΔT of 110°C . No degradation in power output could be observed during the air and nitrogen tests.

Thermoelectric properties and power were also measured over a range of temperatures in vacuum, before and after the 1000-hour tests. Results of the power output measurements for each of the four modules are plotted in figures 4 and 5. For ease of comparison, the experimental data before and after the 1000-hour tests are presented on the same graph. The air test modules had the same power characteristics and showed no significant deviation between the pre and post-test results. The nitrogen environment test modules had slightly different power characteristics, but also showed no variations between before and after results.

However, minor changes were observed in the thermoelectric properties of the elements. For illustration, figures 6 and 7 present the average Seebeck coefficient and internal resistance per couple measured during the before and after vacuum performance tests. From figure 6, the average Seebeck coefficient shows about a 2% increase, while the resistance shows about a 10% increase for the modules tested in air. Figure 7 shows that the Seebeck coefficients are essentially identical in each case, while the resistance varied only one to two percent before and after the nitrogen tests. For a closer examination, table 1 tabulates properties on individual elements at an average element temperature of 280°C measured before and after the air and nitrogen tests. Also included in the table are

~~CONFIDENTIAL~~

Figure 2. Power and Temperature Data for Modules Life-Tested in Air (U)

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

Figure 3. Power and Temperature Data for Modules Life-Tested in Nitrogen (U)

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

8

Figure 4. Power Output of Module Before and After 1000-Hour Air Tests (1)

~~CONFIDENTIAL~~

Figure 5. Power Output of Modules Before and After 1000-Hour Nitrogen Tests (U)

CONFIDENTIAL

~~CONFIDENTIAL~~

Figure 6. Resistance and Seebeck Coefficient Per Couple Before and After 1000-Hour Air Tests (U)

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

11

Figure 7. Resistance and Seebeck Coefficient Per Couple Before and After 1000-Hour Nitrogen Tests (U)

~~CONFIDENTIAL~~

Table 1. Summary of Thermoelectric Property Data at $\bar{T}=280^{\circ}\text{C}$
Before and After Environment Tests (U)

Module No.	Element No.	Seebeck Coefficient		Resistance		α^2/R		Power	
		α_B^*	α_A^*	R_B	R_A	α^2/R_B	α^2/R_A	P_B	P_A
		($\mu\text{V}/^\circ\text{C}$)	($\mu\text{V}/^\circ\text{C}$)	($\text{m}\Omega$)	($\text{m}\Omega$)	($\mu\text{W}/^\circ\text{C}$)	($\mu\text{W}/^\circ\text{C}$)	(mW)	(mW)
QC-15 (AIR)	A-1	236	239	14.3	15.9	3.91	3.56	137	134
	A-2	239	243	15.2	17.1	3.67	3.43		
	B-1	147	149	9.86	10.5	2.18	2.10		
	B-2	146	148	9.5	10.2	2.23	2.15		
QC-20 (AIR)	A-1	220	238	11.1	14.7	4.35	3.86	136	135
	A-2	237	228	12.6	13.5	4.52	3.88		
	B-1	147	149	10.5	10.9	2.07	2.03		
	B-2	141	150	9.8	10.5	1.88	2.14		
QC-17 (N ₂)	A-1	232	231	13.2	12.6	4.09	4.21	142	141
	A-2	234	233	12.4	11.8	4.42	4.60		
	B-1	148	149	10.6	10.2	2.07	2.17		
	B-2	147	147	10.2	9.92	2.11	2.17		
QC-23 (N ₂)	A-1	231	231	13.0	13.0	4.08	4.10	133	134
	A-2	232	231	14.3	14.4	3.75	3.68		
	B-1	150	150	11.2	11.1	2.01	2.02		
	B-2	146	146	10.0	10.0	2.12	2.12		
Average Values Per Couple									
QC-15, 20 (AIR)		379	386	23.2	25.8	6.20	5.79	136.5	134.5
Deviation			+2%		+11%		-6%		-1.5%
QC-17, 23 (N ₂)		380	380	23.7	13.3	6.16	6.27	137.5	137.5
Deviation					-2%		+2%		

* Subscript "B" refers to before gas testing and "A" to after testing in the gas environment.

CONFIDENTIAL

CONFIDENTIAL

~~CONFIDENTIAL~~

13

experimental module power values measured near a hot junction temperature of 400°C and normalized to $\Delta T = 244^{\circ}\text{F}$.

Discrepancies on the order of two or three percent are well within experimental accuracy and typical thermoelectric property reproducibility. In addition, thermal cycling and relocation of the experimental system would enhance the likelihood of measurement uncertainties. However, the greater changes apparent in the elements tested in air over the ones in nitrogen indicate some affect of long-term temperature operation in air. Some of the factors contributing to these apparent changes include:

- Possible oxidation of the lead-telluride, which would increase the measured element resistance.
- Oxidation or redistribution of lead-telluride dopants, which would cause corresponding changes in both α and R .
- Temperature measurement errors due to oxidation of the small 2-mil iron/constantan thermocouple wires.

Other possibilities also exist, such as a return of initial performance characteristics after operation of the modules in vacuum. The small degradation of only 1.5% in power output of the modules tends to discount some of observed property degradation, and supports the hypothesis that temperature probe degradation may have occurred.

Since moisture may effect the experimental results of the air tests, continuous recordings were maintained of the ambient temperature and relative humidity. Typically, the temperature was constant within $\pm 5^{\circ}\text{F}$, however, the relative humidity varied between almost zero and 40%. Figure 8 shows a typical circular chart recording of temperature and relative humidity for a one week period. Although severe, these fluctuations are considered representative of worse-case ambient storage conditions.

From the experimental results, it can be concluded that operation of the ISOTEC modules at 250°C in nitrogen for 1000 hours has negligible effect on thermoelectric properties or power delivery capabilities of the elements. Operation of modules at 250°C in relatively moist air may result in very minor power output degradation, on the order of 2% in

~~CONFIDENTIAL~~

UNCLASSIFIED

14

Figure 8. Typical Temperature and Relative Humidity Conditions During the Module Air Tests

UNCLASSIFIED

~~CONFIDENTIAL~~

15

1000 hours. These conditions are considerably more severe than may actually be encountered during prelaunch hold periods. For instance, temperatures will be closer to 200°C in static air, or as low as 100°C if cooled, and hold periods will probably not exceed 100 or 200 hours.

2.2 Converter Thermal Tests in Nitrogen, Inert Gases and Air

The operation of the GC01 ISOTEC converter in gases is described and discussed in this section. The experimental system was designed to roughly simulate conditions inside the Scout missile shroud, and to allow measurement of system temperatures over a range of thermal inputs by using an electrical heater to simulate the radioisotope heat source. Power inputs from 500 to 750 watts were investigated and resulted in peak hot junction temperatures of up to 257°C .

2.2.1 Experimental System

The GC01 developmental converter (described in references 1 and 2) was used for the thermal environmental tests. It is a full size ISOTEC thermoelectric generator, containing 360 PbTe couples. For the gas tests, thermal input is supplied to the converter by a specially designed resistivity heated stainless steel sphere capable of operating at temperatures of 700°C in air. This heat source, schematically shown in figure 9, consists of two machined hemispheres with a chemically milled helical groove on the surface to locate the wire heating elements. These elements are nichrome wire insulated by MgO and sheathed in Inconel, and are spaced to uniformly distribute the heat flux on the spherical surface. The heat source mass and physical dimensions simulate those of the Gulf General Atomic low-ballistic-coefficient capsule. Support of the sphere inside the converter was provided by a stainless steel quadrupod. Figure 10 is a photograph of the converter and heat source during assembly phases.

The experimental chamber used for the gas tests was a modified 55 gallon steel drum, which physically represents the enclosure inside a Scout missile shroud and contains the desired test gas. Electrical feed throughs for thermocouple and heater leads, support brackets for the generator cage, and gas inlet and outlet lines were installed on the

~~CONFIDENTIAL~~

UNCLASSIFIED

16

UNCLASSIFIED

Figure 9. Experimental Electric Heat Source Assembly Drawing (DRW. NO. GGA 346-SK-232 B)

UNCLASSIFIED

17

UNCLASSIFIED

Figure 10. Photograph of the Converter and Electrical Heat Source During Integration

UNCLASSIFIED

Figure 11 - Schematic diagram of the set-up for gas tests

UNCLASSIFIED

~~CONFIDENTIAL~~

18

tank. The chamber was sand-blasted and coated throughout with Pyromark high emissivity thermal paint, and baked at 150°C for 24 hours. Support of the converter inside the chamber was accomplished by bolting the cylindrical converter cage to special brackets in the metal tank. The converter was located inside the cage by fine wires, which provided structural support in any position, with minimal thermal perturbations. Figure 11 shows a schematic of the test set-up.

Temperatures of the chamber, converter, and heat source were monitored by twenty-six 2-mil iron/constantan thermocouples, and are described in detail in the Appendix. Thermocouple outputs were connected to a digital voltmeter and strip chart recorder for continuous monitoring of experimental temperatures. Probes were also installed to enable measurement of converter open circuit voltage. A gas manifold, which contained a molecular sieve drying unit, was used to connect the chamber to the gas storage bottles, pressure gages and flowmeter regulators. Power for the electrical heat source was provided by a transistor driven regulated D.C. power supply, capable of delivering 750 watts.

The test chamber was supported in a special harness which allowed the tank to be positioned vertically or horizontally for testing the converter in different attitudes. Fans were also provided to convectively cool the outside of the tank. Figures 12 and 13 show the experimental test chamber and the location of the GCOL converter inside.

2.2.2 Experimental Procedures

After installation of the converter and electric heat source inside the experimental chamber, the thermocouples, voltage probes, and heater leads were connected to the electrical feed-throughs and the top of the chamber was secured with a U-shaped brace around the circumference of the tank. The chamber was positioned horizontally or vertically, according to the desired converter attitude, and the electrical instrumentation and gas lines were hooked up and checked out. The gas was supplied from standard cylinders containing high purity certified gas, and was purged through the test chamber at a flow of 2 ft³/min. for about 30 minutes, allowing purge volumes on the order of 10 times the tank volume. During the static gas tests a slightly positive gas pressure of a few centimeters

~~CONFIDENTIAL~~

UNCLASSIFIED

19

Figure 12. Experimental Test Equipment Used for the
GC01 Environmental Tests

UNCLASSIFIED

UNCLASSIFIED

20

Figure 13. Location of GC01 Inside the Experimental Chamber

UNCLASSIFIED

of mercury was maintained inside the chamber to ensure test atmosphere purity.

Once the instrumentation had been checked out and the test atmosphere obtained, power was supplied to the heater in a stepwise fashion, increasing the converter temperature gradually, at a rate of 1 to 2°C per minute. The power was increased until the planned thermal input level was reached. System temperatures were allowed to come to equilibrium, as determined by continuously monitoring temperatures via a digital voltmeter. At power levels of approximately 560, 600, 660, and 750 watts, thermocouple emf's, open circuit voltages, and heater voltage and current were recorded. After maximum power measurements had been made, the heater power was gradually lowered at a rate similar to that used for start-up. One complete test cycle was on the order of 8 to 10 hours.

For the case of nitrogen, tests were performed with the generator in the horizontal and in the vertical position with the top and bottom of the converter up. The remaining gas tests were performed only for the position which resulted in the hottest converter temperatures. The flow tests were performed for volumetric flow rates of up to 3 ft³/min and power inputs of 600 watts, and followed procedures which were identical to the static tests.

2.2.3 Discussion of Experimental Results

The first series of simulated launch pad thermal tests on the GC01 converter included measurement of equilibrium temperatures in static nitrogen, with the generator in three different attitudes -- horizontal, vertical with the bottom of the converter up, and vertical with the top up. Using results from these tests, the remaining experiments were performed with the converter in the worse-case position corresponding to the highest temperatures, and included static tests in helium plus dynamic flow tests in four different cooling gases, nitrogen, helium, argon, and air. Table 2 summarizes the results from these experiments. Detailed test results and temperature probe locations are presented in the Appendix.

~~CONFIDENTIAL~~

TABLE 2. Summary of GC01 Generator Temperatures During Static and Dynamic Flow Tests in Nitrogen, Helium and Argon (U)

~~This table is classified Confidential - Defense Information - Group 3~~

		← EXPERIMENTAL TEMPERATURES °C →						
	Power Input	Peak Hot Cap	Average Hot Cap	Average Cold Cap	Average Heat Source	Average Gas	Average Chamber	
<u>STATIC NITROGEN TESTS</u>								
Horizontal Attitude	561	181	163	119	345	44	33	
	607	189	172	124	358	45	35	
	663	202	184	132	376	46	36	
	738	216	199	141	397	48	37	
Vertical-Bottom up	563	220	175	127	343	53	34	
	600	226	182	134	354	53	35	
	663	242	196	142	374	55	36	
	738	257	211	153	395	59	37	
Vertical-Top up	560	212	167	124	354	51	35	
	603	219	176	128	367	51	34	
	661	234	189	138	385	55	38	
	749	252	209	150	411	--	40	
<u>STATIC HELIUM TESTS</u>								
Vertical-Bottom up	561	175	121	110	271	58	36	
	602	181	125	113	281	58	35	
	661	193	135	127	301	62	40	
	752	207	145	132	325	66	40	
* <u>DYNAMIC NITROGEN TESTS</u>								
0 ft ³ /min	660	241	195	141	374	54	35	
3 ft ³ /min	661	232	183	127	368	51	35	
<u>DYNAMIC HELIUM TESTS</u>								
0 ft ³ /min	661	190	132	119	298	59	34	
3 ft ³ /min	662	184	123	109	295	59	34	
<u>DYNAMIC ARGON TESTS</u>								
0 ft ³ /min	660	255	217	150	394	55	35	
1.5 ft ³ /min	660	249	211	141	392	55	36	

* All Dynamic flow tests are with the generator in the vertical-bottom up attitude, and were limited to a maximum flow rate of 3 ft³/min as measured under ambient conditions.

~~CONFIDENTIAL~~

One of the major objectives of testing an ISOTEC converter in a gas is to evaluate collector and hot junction temperatures during prelaunch storage of the generator assembly. Accordingly, figures 14 through 16 plot hot junction temperatures corresponding to the different cases summarized in table 2. Figure 14 shows the effect of converter attitude on peak and average temperatures in static nitrogen. It indicates that maximum temperatures occur with the converter in the bottom-up position, and that a 5 watt change in power input corresponds to only a 1°C change in hot junction temperature. The peak temperatures, which are as much as 50°C greater than average temperatures, occur in the center of the uppermost panels, apparently due to the natural convection flow of hot gases from the heat source. The disparity between these temperatures could be reduced by preferential cooling of the hotter surfaces. Introducing cooling gas inside the converter may also be considered, but is believed to be impractical due to increased system complexity, the possibility of overpressurizing the converter, and because of the relatively high volume flow rates which would be required.

Figure 15 compares experimental temperatures for nitrogen and helium with the converter in the bottom-up attitude. The experimental data shows that the helium atmosphere is effective in reducing average hot junction temperatures about 60°C , and heat source temperatures about 75°C below values in nitrogen. These temperatures are controlled largely by the natural convection heat transfer and conduction through the gas. The natural convection film coefficient is a function of the gas conductivity, the surface dimensions, the Grashof number, and the Prandtl number.

The effectiveness of forced convection cooling to reduce hot junction temperatures was also investigated for low gas flow rates with the converter in the bottom-up vertical position. Experimental limitations prohibited volumetric flow rates above $3\text{ ft}^3/\text{min}$ for nitrogen and helium, and $1.5\text{ ft}^3/\text{min}$ for argon. Results of the flow tests are also tabulated in table 2 and are plotted in figure 16.

Due to the relatively poor heat capacity ($\text{Btu}/^{\circ}\text{F ft}^3$) of gases, high flow rates are required to significantly reduce temperatures. Because of this fact, use of flowing helium would be economically impractical,

Figure-14. COMPARISON OF CONVERTER HOT JUNCTION TEMPERATURES
IN NITROGEN WITH POWER INPUT AND ORIENTATION (U)

Figure-15. COMPARISON OF CONVERTER HOT JUNCTION TEMPERATURES IN STATIC HELIUM AND NITROGEN (U)

Figure 16. CONVERTER HOT JUNCTION TEMPERATURES IN FLOWING GAS (660 WATTS THERMAL INPUT)

while argon is obviously undesirable as a coolant because it is thermally less efficient than nitrogen or air. If flowing nitrogen is to be considered as a coolant, flow rates on the order of 30 ft³/min (130 lb/hr) would be required to reduce average hot junction temperatures to around 100°C. Another noteworthy point regarding dynamic cooling is that peak temperatures could significantly be reduced by introducing gas onto the hottest panel. However, this was not done during the experiments, which were performed only with the gas inlet at the bottom of the chamber.

Subsequent to the converter nitrogen and inert gas tests, and the module air tests, GC01 was operated in air with thermal inputs up to 750 watts. The purpose of the air test was to compare temperatures in air and nitrogen and verify that hot-junction values do not exceed 250°C under worse-case prelaunch storage conditions. Table 3 summarizes average and peak experimental system temperatures, and figure 17 compares measured hot junction temperatures in air and nitrogen with the converter in the vertical bottom-up position. Average temperatures for the two gases compare to within 3°C - consequently, air and nitrogen are essentially identical from a heat transfer point of view. Slightly lower temperatures measured in air compared to nitrogen are affected by the relative humidity of the gas, which was about 20% during these experiments, which were performed in the sealed test chamber with the vent lines open to the laboratory atmosphere.

TABLE 3. Temperatures of GC01 Generator
in Static Air (U)

(This table is classified Confidential - Defense Information Group 2)

Power Input	Experimental Temperatures, °C*					
	Peak Hot Cap	Aver. Hot Cap	Aver. Cold Cap	Aver. Heat Source	Aver. Gas	Aver. Chamber
499	200	160	117	320	44	31
659	235	193	139	371	51	34
748	253	211	151	396	55	36

* Converter in the vertical bottom-up attitude.

Figure 17. Comparison of Converter Hot Junction Temperatures
In Static Air and Nitrogen (U)

Figure 18 is presented to compare each of the different gases under static conditions. The data clearly indicate that temperatures are hottest with argon, while helium is most effective for obtaining a uniform temperature within the test assembly. This is important in case it is desired to cool only the outside of the shroud.

The only electrical parameter measured during the tests was converter open circuit voltage, due to restrictions imposed by the present experimental set-up. Open circuit data are tabulated in the Appendix and are graphically presented later in section 3.4, which evaluates the electrical performance of the converter during low temperature operation.

In regard to electrical characteristics, consideration has also been given to passing current through the converter to use Peltier cooling for reducing hot junction temperatures. However, since the ΔT across the elements is relatively small, and since most of the heat is pumped through the gas located within the insulation, this method could not be used with satisfactory success. Furthermore, it would probably be impractical to implement such a procedure during the satellite-converter integration and prelaunch phases.

As a final point in this discussion, it is noteworthy that the experimental data can be used to upgrade physical properties of the system which are used for heat transfer analyses. For instance, examination of the thermal conductivity of the elements, at the average element temperature of interest, allows a determination of the fraction of heat transferred through the elements. In the case of nitrogen and air, about 20% of the total heat is conducted through the elements. The remaining 80% is transferred between the collector and radiator through the gas and insulation assembly. Assuming constant temperatures across collector and radiator surfaces, an effective thermal conductivity of the insulation assembly in gas can be computed. At the average temperatures corresponding to 660 watts input, the effective panel insulation conductivity is roughly 0.05 Btu/hr-ft²°F* in nitrogen or air, compared to a conductivity of about

* Actually, this would be slightly smaller since the ΔT across the elements is somewhat less than ΔT between the collectors and radiators.

Figure 18. COMPARISON OF EXPERIMENTAL TEMPERATURES FOR DIFFERENT COOLING GASES (U)

0.02 Btu/hr-ft-°F for the gas alone. In the case of helium, only about 3 to 5% of the total heat is conducted through the elements, resulting in an effective insulation conductivity of roughly 0.26 Btu/hr-ft-°F** at average equilibrium temperatures corresponding to a power input of 660 watts (pure helium conductivity is about 0.1 Btu/hr-ft-°F). Effective conductivities, computed from the data in tables 2 and 3 are also useful for estimating hot junction temperatures as radiator temperatures are reduced.

** Assumes a total converter surface area of 766 in² and effective thickness of 0.165 inches.

~~CONFIDENTIAL~~

3. ANALYTICAL EFFORTS

This section is divided into four parts. The first part briefly reviews some of the constraints imposed on the power supply during the launch operations. Section 3.2 presents predictions of the generator equilibrium temperatures prior to launch and compares them to the simulation test results in different gases. In the third part, launch environmental data was used to determine the transient thermal response of the converter during the first 120 seconds of flight. The last section discusses the generator electrical characteristics during atmospheric operation.

3.1 Prelaunch and Launch Phase Events

Preliminary evaluations of generator response during launch phases have been performed assuming the standard Scout launch vehicle. The Scout missile, which is built by LTV Aerospace Corporation, is a solid propellant, four-stage booster system approximately 72 feet in length with a launch weight of 40,000 pounds and a lift-off thrust of 100,000 pounds. Reference 3 provides a summary description of the system.

A typical payload field flow processing plan is pictorially shown in figure 19. Balancing and integration phases require on the order of four days, and may (but not necessarily) be performed with a fueled heat source. After integration of the payload and vehicle system, anywhere from five hours to five days may elapse prior to lift-off -- indicating a maximum of about nine days or 216 hours that the generator assembly may be exposed to ambient conditions.

After the generator and satellite have been mounted on the vehicle, the system is moved to the launch complex. Figure 20 shows the launch facilities for the Western Test Range at Vandenberg Air Force Base, California. The vehicle is erected at the launch complex, where precooled and filtered gas can be supplied to the payload through umbilical lines connected to special doors in the heat shield.

The major thermal control problems will occur once the generator is enclosed by the heat shield and shroud assembly. The heat shield is a 34-inch diameter fiberglass laminate and honeycomb composition structure with a stainless steel nose cap. A schematic of the heat shield,

~~CONFIDENTIAL~~

UNCLASSIFIED

UNCLASSIFIED

Figure 19. Payload Field Flow Processing Plan for the SCOUT Vehicle (Ref. 3)

UNCLASSIFIED

Figure 20. Vandenberg Air Force Base, Western Test Range Launch Site (Ref. 3)

UNCLASSIFIED

indicating the payload envelope, is shown in figure 21. Also shown is the relative size of the simulation chamber used for testing the generator in gas, and the converter shell. Considering the fact that the satellite will occupy a large portion of the available envelope space, the simulation chamber volume is comparable to that inside the shroud.

Cooling can be supplied to the payload up to the time of lift-off. After lift-off, the heat shield remains in place until burn-out of the second stage, when it is ejected into space. The time sequence of launch phase events are shown in table 4, and figure 22 schematically shows the major vehicle events for orbital missions. The launch phase transient thermal environment inside and outside the heat shield are shown in figures 23 and 24. Corresponding profiles of altitude, velocity, range, and dynamic pressure are presented in figure 25.

The heat shield provides environmental protection to the satellite and converter for the first 120 to 130 seconds of flight. At this time, the vehicle altitude is on the order of 300,000 ft, the velocity is 10,000 fps, and the corresponding dynamic pressure is 0.11 psf. Personal communication with APL indicated that aerodynamic heating has not been a problem with their satellites, which have been launched by the Scout missile. Absence of surface thermal property changes on their system has qualitatively indicated that frontal surface temperatures are below about 200°C. The ISOTECH panels could withstand short-term exposure even at this upper predicted temperature, although this effect should receive further consideration.

3.2 Comparison of Predicted and Experiments Equilibrium Temperatures In Air and Helium

Prior to conducting the GC01 converter tests in nitrogen and inert gases, hand and computer computations were performed to assess the equilibrium thermal environment of a fueled ISOTECH generator enclosed within a Scout missile shroud. The analysis assumed typical shroud dimensions of 30-inch diameter and 36-inch height, and a heat source power of 660 watts. Natural convection and radiation of heat from the shroud to 100°F ambient conditions were assumed for the outside boundary conditions. Table 5 summarizes results of the thermal analysis, which

UNCLASSIFIED

Figure 21. Schematic of the SCOUT Payload Envelope — Showing the Relative Size of the TRANSIT/ISOTEC Generator and Gas Test Chamber (Ref. 3)

UNCLASSIFIED

UNCLASSIFIED

TABLE 4

TIME SEQUENCE OF EVENTS DURING TYPICAL ORBITAL MISSIONS FOR THE SCOUT VEHICLE
(Ref. 3)

(This Table is classified Unclassified)

TIME (SEC.)	EVENT	TIME (SEC.)	EVENT
0.00	LIFT-OFF	122.22	STG. 3 IGNITION
0.03*	START TIMER		SEPARATE STG. 2
	(6) PITCH RATES	157.72	STG. 3 BURNOUT
76.57	STG. 1 BURNOUT		(2) PITCH RATES
78.32	STG. 2 IGNITION	162.72	ACTIVATE CONTROLS
	ACTIVATE "B"	713.52	SPIN & SQUIB IGN.
	SEPARATE STG. 1		
	(2) PITCH RATES	715.02	SEPARATE STG. 3
117.22	STG. 2 BURNOUT	716.02	RETRO
120.52	SEPARATE H/S	719.52	STG. 4 IGNITION
	ACTIVATE "C"	742.72	STG. 4 BURNOUT

* PREDICTED LIFT-OFF OCCURS 0.08 SECONDS AFTER IGNITION

UNCLASSIFIED

UNCLASSIFIED

UNCLASSIFIED

Figure 22. Schematic of Events During Typical Orbital Missions for the SCOUT Vehicle (Ref. 3)

UNCLASSIFIED

UNCLASSIFIED

Figure 23. Temperatures Inside the SCOUT Heat Shield

UNCLASSIFIED

40

Figure 24. SCOUT Heat Shield Temperatures During Flight (Ref. 3)

Figure 25. Typical SCOUT Boost Performance During Orbital Ascent (Ref. 3)

UNCLASSIFIED

TABLE 5. Summary of Computed Temperatures Inside the Scout
Shroud and Measured Temperatures on GCOL Inside a Simulation Chamber* (U)

~~This table is classified CONFIDENTIAL - Do not release without approval of the~~

Average Temperature	Computed, Scout Shroud - Air -	Experimental*	Computed, Scout Shroud - Helium -	Experimental*
		GCOL, Simulation Chamber - Air -		GCOL, Simulation Chamber - Helium -
Heat Source	378°C (712°F)	371°C	350°C (664°F)	301°C
Hot Junction	247°C (476°F)	193°C	193°C (380°F)	135°C
Cold Junction	168°C (336°F)	139°C	168°C (336°F)	127°C
Shroud	82°C (180°F)	34°C	82°C (180°F)	40°C
Ambient	38°C (100°F)	21°C	38°C (100°F)	21°C

* Converter tested in the vertical attitude with the bottom up.
660 Watts Power Input
Experimental Temperatures are average values

~~CONFIDENTIAL~~

42

were performed by the TAP-3F digital computer program, for the cases of static air and helium in the shroud cavity. Also tabulated are experimentally measured temperatures presented earlier in Section 2.2.3.

Examination of the data in table 5 shows that in all cases, computed temperatures were higher than average measured values. Reasons for the variations include; (1) differences between the ambient conditions, which affect the shroud temperature, (2) differences between the assumed insulation assembly conductance and that determined experimentally, (3) variations between actual and assumed gas conductivities due to temperature dependence, and (4) differences between the shroud and simulation chamber thickness, material, and emissivity and physical size. Although calculated and measured hot junction temperatures varied 50 to 60°C, both of the values are below the safe temperature limit indicated by the successful 1000-hour tests of modules in air at 250°C. One important conclusion from the above comparisons is that for the case of converter storage in static air or helium, hot junction temperatures can be maintained below safe limits during fueled converter storage in a static gas environment.

It has been demonstrated that the thermal performance of the converter is essentially identical in either nitrogen or air. For the purpose of comparing properties of these gases as well as helium and argon, table 6 tabulates pertinent physical properties. The experimental converter temperatures in nitrogen, helium and argon are consistent with the thermal conductivities of these gases, where the conductivity of helium is about five times that of nitrogen and eight times greater than argon at 100°C. However, the heat capacity (product of specific heat and density) of helium and argon are nearly identical at atmospheric pressure, and both are less than nitrogen. This illustrates that flowing nitrogen can remove more heat for a given temperature rise than either helium or argon. The Prandtl number ($\mu C_p / K$) is also a physical property of the gas and is used to evaluate film coefficients. However, for the gases considered, the Prandtl numbers are all similar and the film coefficient will be dependent on the Grashof number in the case of static gas, or the Reynolds

~~CONFIDENTIAL~~

TABLE 6. Physical Properties of Candidate Launch Pad
Coolant Gases at One Atmosphere Pressure (U)

~~This table is classified Confidential - Defense Information Group 5~~

Property	Temp.	Air	Nitrogen	Helium	Argon
	$^{\circ}\text{C}$				
Molecular Weight		29	28	4	40
Density (lb/ft^3)	20	.07528	.07274	.01039	.1037
	100	.1045	.101	.0144	.144
Thermal (Btu/hr $\text{ft}^{\circ}\text{F}$) Conductivity	20	.015	.0145	.078	.01
	100	.0184	.0181	.0988	.0123
Specific Heat ($\text{Btu}/\text{lb}^{\circ}\text{F}$)	20	.241	.247	1.25	.124
	100	.25	.25	1.25	.124
Heat Capacity ($\text{Btu}/\text{ft}^3^{\circ}\text{F}$)	20	.0181	.0180	.0130	.0129
Prandtl Number	100	0.69	0.70	0.71	0.66

~~CONFIDENTIAL~~

44

number in the case of flowing gas. Both of these dimensionless quantities depend on viscosities, gas temperatures, system dimensions, and flow rates of the gases.

If flowing gas is used to reduce shroud and converter temperatures, the amount of heat removed will depend on the gas, its flow rate, and the inlet temperature. During the experiments of GCOI in flowing nitrogen at 660 watts, the average hot junction temperature was reduced 12°C which corresponded to a reduction in power input of 58 watts. At $3\text{ ft}^3/\text{min}$, this corresponds to a nitrogen temperature rise of 31°C , which is nearly equivalent to the difference of inlet and gas bulk temperatures measured inside the chamber. It is likely that this temperature rise will decline as flow rates are increased. The example serves only to illustrate that the temperature rise of flowing coolant gas on the outside of the converter will be small -- consequently, high volumetric flow rates will be required to achieve significant cooling.

Actual launch pad cooling techniques will depend on satellite requirements as well as the missile systems requirements. In some cases it may be desirable to have static conditions within the shroud, hence cooling systems will be external to the shroud surface. In this event special thermal baffles or fins can be designed inside the shroud or a high conductivity gas, such as helium, can be used to minimize system temperature gradients. Most probably, however, air conditioning will be used and the coolant gas will be introduced at reduced temperatures.

3.3 Converter Transient Thermal Response During Launch

A transient thermal analysis was performed to assess the temperature rise of the generator assembly inside the heat shield during the first 120 seconds of flight. The analysis was performed using the TAP-3F Thermal Analyzer Program on the UNIVAC 1108 Computer at GGA. TAP solves transient and steady-state heat transfer problems and will accommodate a network of 500 nodes and 999 connectors. Calculations were performed for time intervals of one second and printed every ten seconds.

The transient thermal analyses assumed a heat source power of 660 watts, and were performed for three different launch environment cases:

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

45

(1) the shroud contains air at one atmosphere during the flight period, (2) the shroud cavity is evacuated at time >0 , and (3) the shroud was assumed to be evacuated except for the presence of air in the insulation assembly which is at the density of the surroundings. Other pertinent assumptions used in the analysis include the following:

1. Just before lift-off, natural convection and radiation cooling of the heat shield was assumed with an ambient temperature of 70°F . After lift-off, the heat shield was treated as an infinite heat sink whose temperature was estimated from aerodynamic heating data, such as that presented earlier in figure 23.
2. The heat shield was assumed to be a 0.21-inch thick structure of aluminum honeycomb covered with 0.020-inch thick fiberglass on each side. The inside surface of the shield is assumed to have $\epsilon = 0.88$, according to LTV data. K (heat shield) = $1.41 \text{ Btu/hr-ft}^2\text{ }^{\circ}\text{F}$.
3. Heat Source: Diameter = 8 in.
 $\epsilon = 0.8$
4. Generator: ϵ Collector = 0.85
 ϵ Radiator = 0.8
 K Elements = $1.16 \text{ Btu/hr-ft}^2\text{ }^{\circ}\text{F}$
Collector and Radiator fin efficiency - 100%

Figure 26 plots the computed temperatures based on the above assumptions, and table 7 summarizes the maximum temperatures for case No. 2.

TABLE 7. Summary of Worse-Case ISOTEC Generator Temperatures Inside the Scout Heat Shield During Launch (U)

(~~CONFIDENTIAL~~)

	Temperatures* at Time = Zero	Worse-Case Temperatures at Time = 120 sec.
Heat Source	376°C (706°F)	404°C (758°F)
Collector (Hot Junction)	240°C (465°F)	324°C (616°F)
Radiator (Cold Junction)	162°C (324°F)	163°C (325°F)
Inside Heat Shield	61°C (142°F)	89°C (192°F)

* Assumes equilibrium thermal conditions at launch (i.e., no air conditioning) and considers only radiation heat transfer.

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

46

Figure 26. Generator Temperatures During the First 120 Seconds of Flight (U)

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

The three different cases of thermal analysis bracket the range of possible system temperatures under actual launch conditions. Case 1, which assumes both natural convection and radiation heat exchange, is presented as a reference case only since complete evacuation of the shroud would be assured after 120 seconds of normal flight. Case 2 assumes the same initial conditions as 1, but considers only radiation heat transfer within the shroud and insulation assembly. This is obviously pessimistic since the trapped air within the shroud and generator assembly will also remove heat and reduce temperature gradients. Peak hot junction temperatures for case 2 reach 324°C prior to ejection of the heat shield, which is 76°C below the design value.

Collector temperatures are extremely sensitive to the conductivity of the insulation assembly, which is dependent on the pressure of trapped gas. By folding air conductivity and pressure characteristics with the altitude-time relations for the Scout missile, it was possible to more closely simulate the expected thermal characteristics of the system. Case 3, shown in figure 26, examines this condition -- showing that after 50 seconds (corresponding to an altitude on the order of 75,000 feet) the insulation conductivity approaches that in a vacuum environment. Computed hot junction temperatures are 254°C and 315°C after 50 and 120 seconds of flight time, respectively. For conservatism, convection to the air inside and outside the converter panels was neglected.

As previously mentioned, generator temperatures can be reduced by air conditioning the assembly prior to launch. However, this does not appear to be necessary based on the present transient thermal analysis of generator temperatures.

3.4 Predicted Converter Electrical Performance During Environmental Operation

During the launch events, the TRANSIT/ISOTEC generator will be at temperatures considerably below operational values. However, once the converter and heat source have been integrated some electrical power can be extracted. At equilibrium ambient conditions the power out is small, although it may be sufficient for relaying checkout data, local thermal control, powering timers, etc.

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

48

As noted in Section 2.2.3, the only electrical parameter recorded during the GC01 tests in different gases was the open circuit voltage, which can be related to maximum power output as follows:

$$P = \left[\bar{\alpha}_L \Delta T_L \right]^2 / 4R$$

where,

P = maximum thermoelectric power,

$\bar{\alpha}_L$ = average Seebeck coefficient,

ΔT_L = temperature difference across the elements under load, and

R = converter internal resistance.

For the Gulf General Atomic modules $\bar{\alpha}_L \Delta T_L \approx \bar{\alpha}_O \bar{T}_L$ (reference 7), where α_O is the open circuit Seebeck coefficient and is equal to $V_O/\Delta T_O$. With these substitutions, the power equation becomes,

$$P = \left[V_O \left(\frac{\Delta T_L}{\Delta T_O} \right) \right]^2 / 4R$$

where,

V_O = open circuit voltage, and

ΔT_O = temperature difference across the elements under open circuit conditions.

If $\Delta T_L \approx \Delta T_O$, then $P \approx V_O^2/4R$. The latter assumption is valid only if the Peltier cooling can be neglected. For launch pad conditions, when $\Delta T \leq 60^\circ\text{C}$ and load resistance is similar to converter resistance, this is believed to be a valid assumption, although slightly optimistic since ΔT_L is always somewhat less than ΔT_O . Thus the maximum power output of the converter (corresponding to a load matching factor of 1.0) is simply the open circuit voltage squared divided by four times the converter internal resistance.

The internal resistance of the converter (R) can be evaluated at the average element temperature ($\bar{T}$). Since R has not been measured at intermediate temperatures, data from the module tests in air were utilized to compute internal converter resistances. Figure 27 is a plot of the predicted GC01 internal resistance with average element temperature. The other variable, open circuit voltage, varies with both ΔT and $\bar{T}$, although values can be compared for the different test gases as shown in figure 28.

~~CONFIDENTIAL~~

Figure 27. Change in GC01 Internal Resistance With Average Element Temperature ($\bar{T}$)

~~CONFIDENTIAL~~

CONFIDENTIAL
Defense Information
GROUP 3

Figure 28. EXPERIMENTAL OPEN CIRCUIT VOLTAGES IN DIFFERENT PRELAUNCH COOLANT GASES (U)

Figure 29 presents the computed maximum converter power output and efficiency using measured open circuit voltages and power input data from the GC01 gas tests, and internal resistances corresponding to the average experimental element temperature. The power output in helium is essentially negligible, while argon gas allows the highest power because of the increased ΔT in this gas. In air or nitrogen, the ΔT across the elements will be on the order of 50°C at 660 watts input. This corresponds to a converter power delivery capability of 1.2 to 1.6 watts. The efficiency is extremely low due to the presence of gas in the insulation assembly which reduces the amount of heat pumped through the elements by more than a factor of four in the case of air or nitrogen.

The electrical characteristics discussed apply for matched load conditions ($m=1$), and do not completely describe the electrical performance. Therefore, computer analyses were performed to evaluate the low temperature electrical characteristics under various temperature and load conditions. Figure 30 shows results of power and load voltage as a function of ΔT across the elements. Voltage is also shown for various hot junction temperatures, while power was found to be relatively independent of hot junction temperature over the range investigated. The calculated power compares with that determined from open circuit data, although the latter is slightly greater due to the assumption of equal load and open circuit ΔT 's.

Figure 31 presents the converter electrical characteristics for a range of load conditions at $T_H = 200^{\circ}\text{C}$ and $T_C = 150^{\circ}\text{C}$. The curves assume that the temperatures remain constant, although Peltier cooling effects would cause some changes in the physical system. For the conditions shown, the load voltage will be 0.7 volts at 1.2 watts.

Lastly, figure 32 shows the effect of load resistance on hot junction temperatures for typical static gas equilibrium conditions, illustrating that these temperatures vary only about 15°C between open and short circuit conditions.

~~CONFIDENTIAL~~

Figure 29. GC01 POWER OUTPUT AND EFFICIENCY DURING TESTS IN DIFFERENT GASES (POWER COMPUTED FROM EXPERIMENTAL OPEN CIRCUIT VOLTAGES) (1)

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

Figure 30. Converter Performance Characteristics for Different Prelaunch Hot Junction Temperatures (U)

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

54

Figure 31 . Converter Performance Characteristics During Typical Prelaunch Environmental Operation (U)

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

55

Figure 32. Hot Junction Temperature Change With Load Variations During Prelaunch Operation (Calculated Based on GCO2 Data and Hot Junction Temperature of 200°C) (U)

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

4. SUMMARY AND CONCLUSIONS

The experimental results presented in this report allow an assessment of the integrity of the TRANSIT/ISOTEC thermoelectric generator in different environmental control gases. Some of the major conclusions from these experiments, conducted on modules and the GC01 generator, include the following:

- Two ISOTEC thermoelectric modules were tested for over 1000 hours at hot junction temperatures of 250°C in nitrogen, and showed no degradation in power delivery capabilities in vacuum. Two modules tested under similar conditions in air showed minor changes in thermoelectric properties with an average degradation of 1.5% over the entire test period.
- Thermal tests were performed on the GC01 generator in nitrogen, helium, argon, and air over a range of thermal inputs between 500 to 750 watts. Hottest collector temperatures resulted with the converter in the vertical position with the bottom up, and reached average values in static air of 193 and 211°C , for 660 and 750 watts input, respectively. Temperatures in air and nitrogen were identical, while values were highest in argon and lowest in helium. Dynamic gas tests with volumetric flow rates of $3\text{ ft}^3/\text{min}$ reduced average collector temperatures only 12°C .

Module environmental tests were performed for temperatures and times greater than those which would be experienced during worse-case prelaunch hold periods. The apparent degradation of modules tested in air may have been due to oxidation of the lead telluride or instrumentation thermocouples, as these effects were not observed during tests in nitrogen. Life testing of the air test modules in vacuum is currently underway to further evaluate these effects.

Thermal tests of the GC01 ISOTEC converter verified that equilibrium temperatures in a static ambient gas environment are below safe short-term operational limits. Helium, which limits peak collector temperatures to below 200°C , would be the most efficient gas for static prelaunch storage conditions, although nitrogen or air would also be satisfactory. The converter can be successfully cooled by flowing gas around the outside surface; however, high flow rates ($> 30\text{ ft}^3/\text{min}$) and low inlet temperatures would be required to significantly reduce temperatures.

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

57

Computed converter temperatures within the Scout missile shroud are similar to corresponding temperatures measured during the converter experiments in the simulation chamber. Thus illustrating that generator temperatures inside the missile shroud will be comparable to those measured on the experimental system; consequently, launch pad air conditioning will be optional.

Transient thermal analysis of the generator was also performed for the first 120 seconds of flight, while the heat shield is surrounding the generator and satellite. Results indicated that the maximum possible hot junction temperature rise will be below safe design values, assuming static equilibrium thermal conditions inside the shroud at launch. Again indicating that launch pad precooling, by the use of air conditioning, is not a requirement of the thermoelectric power supply.

During equilibrium thermal conditions of the fueled converter in air, 1.0 to 1.5 watts of power will be generated. The power output will not change significantly during cooling operations as long as the ΔT across the elements remains constant. Changing the load will affect the power output, voltage, and hot junction temperatures. However, due to the presence of gas in the insulation assembly, most of the heat is transferred through the insulation, with the result that conversion efficiencies in gas are very low and temperatures change only 10 to 20°C between full open and short circuit load conditions.

The present preliminary investigations of launch pad environmental effects on the ISOTEC modules and converter have indicated that special cooling provisions are not required to ensure integrity of the TRANSIT/ISOTEC generator during launch events.

~~CONFIDENTIAL~~

UNCLASSIFIED

58

ACKNOWLEDGEMENTS

The author gratefully acknowledges the contributions of the following people: R. L. Leedy, W. B. McKinney and the members of the thermoelectric test group for performing the module and converter gas tests; C. Q. Torrijos and R. J. Brislin for performing the thermal analysis; and J. E. Cruver and E. J. Steeger for their valuable technical assistance.

UNCLASSIFIED

REFERENCES

1. Bradshaw, G. B., "Test Results for the Developmental ISOTEC NAVSAT Thermoelectric Generators GCO1 and GCO2 (U)", Report No. GA-8972 (Draft), November 1968.
2. "Radioisotope Space Power Generator (U)", Twelve-Month Annual Summary, July 1, 1967 through June 30, 1968, Report No. GA-8928 (Draft), November 1968.
3. "SCOUT Planning Guide", Missiles and Space Division, LTV Aerospace Corporation, October 1968.
4. Leedy, R. L., "Performance Testing Flat-Plate Thermoelectric Generators (U)", Report No. GA-7652.

APPENDIX

Experimental Measurements on the GCO1
Converter in Various Gases

This Appendix presents details on the experimental thermocouple location throughout the generator test assembly, and presents individual thermocouple readings. Data has been extracted directly from test summary memorandums submitted by the Thermoelectric Test Group at Gulf General Atomic.

Figures A-1 and A-2 schematically show the test configuration and the approximate location of thermocouples on the converter and on the surface and inside the simulation chamber. Figures A-3 through A-6 show the detail location of thermocouples on individual panels. In each case, the couples are located on either hot caps (which are shown on the left side of the schematic) or cold caps. A total of 13 thermocouples, 9 hot and 4 cold, were placed on the converter; 3 on the heat source and support; and 10 on and inside the chamber.

Tables A-1 and A-2 present the individual thermocouple data recorded during the static nitrogen tests of the converter in different positions. Also tabulated are open circuit voltages, which was the only converter electrical parameter measured. Table A-3 presents the thermal performance data in static helium, for the maximum temperature case of the converter located vertically with the bottom panel facing upward. Results of measurements during the dynamic gas flow experiments are tabulated in tables A-4 and A-5. Lastly, table A-6 presents data from the static air tests.

UNCLASSIFIED

UNCLASSIFIED

Figure A-1 SCHEMATIC OF PANEL AND THERMOCOUPLE LOCATIONS
ON THE GCOL GENERATOR

UNCLASSIFIED

62

UNCLASSIFIED

Figure A-2 SCHEMATIC OF THERMOCOUPLE LOCATION ON SCOUT SHROUD SIMULATION CHAMBER

UNCLASSIFIED

Generator Bottom

63

A	1 A	2 A	3 A	4
B	1 B	2 B	3 B	4
A	5 A	6 A	7 A	8
B	5 B	6 B	7 B	8
A	9 A	10 A	11 A	12
B	9 B	10 B	11 B	12
A	13 A	14 A	15 A	16
B	13 B	14 B	15 B	16
A	17 A	18 A	19 A	20
B	17 B	18 B	19 B	20
A	21 A	22 A	23 A	24
B	21 B	22 B	23 B	24
A	25 A	26 A	27 A	28
B	25 B	26 B	27 B	28
A	29 A	30 A	31 A	32
B	29 B	30 B	31 B	32
A	33 A	34 A	35 A	36
B	33 B	34 B	35 B	36

UNCLASSIFIED

A	4	A	3	A	2	A	1
B	4	B	3	B	2	B	1
A	8	A	7	A	6	A	5
B	8	B	7	B	6	B	5
A	12	A	11	A	10	A	9
B	12	B	11	B	10	B	9
A	16	A	15	A	14	A	13
B	16	B	15	B	14	B	13
A	20	A	19	A	18	A	17
B	20	B	19	B	18	B	17
A	24	A	23	A	22	A	21
B	24	B	23	B	22	B	21
A	28	A	27	A	26	A	25
B	28	B	27	B	26	B	25
A	32	A	31	A	30	A	29
B	32	B	31	B	30	B	29
A	36	A	35	A	34	A	33
B	36	B	35	B	34	B	33

(RADIATOR)

Generator Top

(COLLECTOR)

Figure A-3 Thermocouple Location on GC01 Side Panel - PEO3

UNCLASSIFIED

UNCLASSIFIED

64

A 1 A 2 A 3 A 4

B 1 B 2 B 3 B 4

A 5 A 6 A 7 A 8

B 5 B 6 B 7 B 8

A 9 A 10 A 11 A 12

B 9 B 10 B 11 B 12

A 13 A 14 A 15 A 16

B 13 B 14 B 15 B 16

A 17 A 18 A 19 A 20

B 17 B 18 B 19 B 20

A 21 A 22 A 23 A 24

B 21 B 22 B 23 B 24

A 25 A 26 A 27 A 28

B 25 B 26 B 27 B 28

A 29 A 30 A 31 A 32

B 29 B 30 B 31 B 32

A 33 A 34 A 35 A 36

B 33 B 34 B 35 B 36

(RADIATOR)

UNCLASSIFIED

(COLLECTOR)

Figure A-4 Thermocouple Location on GC01
Bottom Panel - PEO7

UNCLASSIFIED

UNCLASSIFIED

Generator Bottom

65

A 1 A 2 A 3 A 4

B 1 B 2 B 3 B 4

A 5 A 6 A 7 A 8

B 5 B 6 B 7 B 8

A 9 A 10 A 11 A 12

B 9 B 10 B 11 B 12

A 13 A 14 A 15 A 16

B 13 B 14 B 15 B 16

A 17 A 18 A 19 A 20

B 17 B 18 B 19 B 20

A 21 A 22 A 23 A 24

B 21 B 22 B 23 B 24

A 25 A 26 A 27 A 28

B 25 B 26 B 27 B 28

A 29 A 30 A 31 A 32

B 29 B 30 B 31 B 32

A 33 A 34 A 35 A 36

B 33 B 34 B 35 B 36

A 4 A 3 A 2 A 1

B 4 B 3 B 2 B 1

A 8 A 7 A 6 A 5

B 8 B 7 B 6 B 5

A 12 A 11 A 10 A 9

B 12 B 11 B 10 B 9

A 16 A 15 A 14 A 13

B 16 B 15 B 14 B 13

A 20 A 19 A 18 A 17

B 20 B 19 B 18 B 17

A 24 A 23 A 22 A 21

B 24 B 23 B 22 B 21

A 28 A 27 A 26 A 25

B 28 B 27 B 26 B 25

A 32 A 31 A 30 A 29

B 32 B 31 B 30 B 29

A 36 A 35 A 34 A 33

B 36 B 35 B 34 B 33

UNCLASSIFIED

Generator Top

Figure A-5 Thermocouple Location on GC01
Side Panel - PE-11

UNCLASSIFIED

UNCLASSIFIED

66

A 1 A 2 A 3 A 4

B 1 B 2 B 3 B 4

A 5 A 6 A 7 A 8

B 5 B 6 B 7 B 8

A 9 A 10 A 11 A 12

B 9 B 10 B 11 B 12

A 13 A 14 A 15 A 16

B 13 B 14 B 15 B 16

A 17 A 18 A 19 A 20

B 17 B 18 B 19 B 20

A 21 A 22 A 23 A 24

B 21 B 22 B 23 B 24

A 25 A 26 A 27 A 28

B 25 B 26 B 27 B 28

A 29 A 30 A 31 A 32

B 29 B 30 B 31 B 32

A 33 A 34 A 35 A 36

B 33 B 34 B 35 B 36

A 4 A 3 A 2 A 1

B 4 B 3 B 2 B 1

A 8 A 7 A 6 A 5

B 8 B 7 B 6 B 5

A 12 A 11 A 10 A 9

B 12 B 11 B 10 B 9

A 16 A 15 A 14 A 13

B 16 B 15 B 14 B 13

A 20 A 19 A 18 A 17

B 20 B 19 B 18 B 17

A 24 A 23 A 22 A 21

B 24 B 23 B 22 B 21

A 28 A 27 A 26 A 25

B 28 B 27 B 26 B 25

A 32 A 31 A 30 A 29

B 32 B 31 B 30 B 29

A 36 A 35 A 34 A 33

B 36 B 35 B 34 B 33

27

UNCLASSIFIED

Figure A-6 Thermocouple Location on GC01
Top Panel - PE02

UNCLASSIFIED

TABLE A-1. Measured Temperatures ($^{\circ}\text{C}$) on GC01 in Static Nitrogen for Three Different Converter-Chamber Positions (U)

~~This table is classified Confidential - Defense Information Group 3~~

TEST 1: GC01 HORIZONTAL

Power Input (Watts)	T/C No. (T_H)									T/C No. (T_c)				Average Source Temp.		Average Generator Temp.				V_0
	PEO7			PE-11			PEO3		PE-11	PEO3		PEO7	1	SPHERE		T_H	T_c			
	3	4	5	6	7	8	9	10		11	12			13	14			2		
561	140	180	181	170	175	164	153	144	126	113	107	129	345	345.5	346	163	119	1.31		
607	148	189	189	179	184	172	162	152	132	118	112	134	358	358	358	172	124	1.422		
663	160	202	202	191	196	184	174	164	140	125	120	142	376	376	376	184	132	1.59		
738	175	218	216	205	211	198	188	178	148	135	129	152	397	396.5	397	199	141	1.80		

TEST 2: GC01 VERTICAL, BOTTOM UP

Power Input (Watts)	T/C No. (T_H)														T/C No. (T_c)				Average Generator Temp.							
	PEO2			PEO7			PE-11			PEO3		PE-11		PEO3		PEO7		Average Source Temp.		SPHERE		LEG		T_H	T_c	V_o
	27	3	4	5	6	7	8	9	10	11	12	13	14	1	2	25	1	2	25	1	2	25	1	2	25	
563	160	174	220	186	153	171	179	152	176	123	100	129	154	343	339	346	209	175	127	1.32						
600	167	181	226	193	160	178	185	160	184	128	114	133	159	354	350	357	217	182	134	1.42						
663	183	194	242	207	174	192	200	174	196	136	123	141	169	374	371	377	232	196	142	1.61						
738	199	210	257	223	190	208	215	189	212	146	133	152	179	395	392	398	248	211	153	1.84						

TEST 3: GC01 VERTICAL, TOP UP

Power Input (Watts)	T/C No. (T_H)													T/C No. (T_c)				Average Generator Temp.		
	PEO2			PEO7			PE-11			PEO3			Average Source Temp.	SPHERE		LEG 25	T_H	T_c	V_o	
	27	3	4	5	6	7	8	9	10	11	12	13		14	1					2
560	212	146	173	158	182	156	149	181	148	128	131	108	127	354	360	348	162	167	124	1.33
603	219	153	180	165	189	181	155	183	155	132	135	112	131	367	373	361	166	176	128	1.42
661	234	160	198	183	205	—	169	200	166	143	145	121	143	385	392	379	184	189	138	1.60
749	252	188	217	201	223	217	189	210	187	155	156	133	157	411	417	405	204	209	150	1.87

UNCLASSIFIED

68

TABLE A-2. Measured Chamber and Gas Temperatures
During Static Nitrogen Tests

(This Table is Unclassified)

TEST 1: GC01 HORIZONTAL											
Power Input	N ₂ Temp. °C		Chamber Surface Temp. °C								
	T/C. No.		T/C No.								
	15	16	17	18	19	20	21	22	23	24	T̄
561	41	46	37	--	--	30	--	33	--	33	33
606	42	47	37	32	33	37	32	34	40	34	35
663	43	49	38	33	34	38	33	35	42	35	36
738	45	51	39	34	35	39	33	36	42	36	37
TEST 2: GC01 VERTICAL, BOTTOM UP											
563	33	72	33	30	36	28	36	36	34	40	34
600	33	73	35	30	36	28	38	38	33	41	35
663	33	77	36	31	37	28	40	38	34	41	36
738	35	83	37	31	39	29	40	40	35	42	37
TEST 3: GC01 VERTICAL, TOP UP											
560	68	33	37	34	37	37	36	34	33	30	35
603	69	33	37	34	37	36	36	34	32	29	34
661	74	36	40	37	42	40	40	37	35	32	38
749	80	38	42	38	48	43	42	38	36	34	40

UNCLASSIFIED

~~CONFIDENTIAL~~

69

TABLE A-3. Measured Temperatures on GC01 in
Static Helium, Bottom-Up Position (U)

~~This table is classified Confidential - Defense Information Group 3~~

P_{IN} (Watts)	V_o (Volts)	PE02	PE07			PE11			PE11		
		27	3	4	5	6	7	8	9	10	
561	.36	90	132	175	141	88	112	127	90	130	
602	.38	93	137	181	146	91	116	132	93	134	
661	.43	103	148	193	156	100	125	142	102	145	
752	.50	114	161	207	170	111	138	154	112	139	
		PE11	PE03		PE07	HS	Sphere		Leg	$\bar{T}_h$	$\bar{T}_c$
		11	12	13	14	Av.	1	2	25		
561	96	79	114	151	271	263	279	150	121	110	
602	100	81	117	155	281	273	290	154	125	113	
661	108	89	126	184	301	292	309	167	135	127	
752	118	97	136	177	325	317	334	181	145	132	
		He		Chamber Surface Temp. °C							
		15	16	17	18	19	20	21	22	23	24
561	30	85	30	31	36	29	36	41	36	47	
602	29	86	30	31	35	29	36	39	36	47	
661	31	93	33	33	37	30	38	44	38	69	
752	33	99	34	35	40	31	41	46	40	53	

~~CONFIDENTIAL~~

TABLE A-4. Measured Temperatures on GC01 in Flowing Gas
Bottom Up Position (U)

(This table is classified Confidential - Defense Information)

Gas Flow Rate	V_o	TEST 1 HELIUM - 660 WATTS INPUT																T_s	LEG 25	Generator	
		Hot Junction Temperatures								Cold Junction Temperatures				T_h	T_c						
		PE02	PE07		PE-11		PE03		PE-11	PE03		PE07									
		27	3	4	5	6	7	8	9	10	11	12	13			14					
Static	0.430	99	145	190	153	97	122	139	98	142	105	86	123	163	298	164	132	119			
3 ft ³ /min	0.422	92	134	184	148	87	108	125	97	132	85	84	113	155	295	156	123	109			
		TEST 2 NITROGEN - 660 WATTS INPUT																			
Static	1.605	180	194	241	207	174	192	200	173	196	135	122	141	167	374	230	195	141			
3 ft ³ /min	1.577	170	183	232	196	160	176	186	162	183	114	109	127	156	368	220	183	127			
		TEST 3 ARGON - 660 WATTS INPUT																			
Static	2.048	209	213	255	225	200	---	218	200	215	146	135	149	171	394	243	217	150			
1.5 ft ³ /min	2.067	206	208	249	221	193	---	209	195	208	132	128	139	165	392	237	211	141			

CONFIDENTIAL

CONFIDENTIAL

~~CONFIDENTIAL~~

71

TABLE A-5. Measured Chamber and Gas Temperatures
During Flow Tests in Helium, Nitrogen, Argon
(Generator Vertical with the Bottom Up) (U)

~~This table is classified CONFIDENTIAL - Defense Information~~

Test Gas	Flow Rate ft ³ /min	Gas Temp.		Chamber Surface Temp. °C									$\bar{T}$
		15	16	17	18	19	20	21	22	23	24		
Helium	0	28	90	30	29	35	27	34	40	35	44	34	
Helium	3	49	69	41	32	33	28	35	36	32	35	34	
Nitrogen	0	32	75	35	32	36	28	35	40	34	39	35	
Nitrogen	3	50	51	43	33	34	29	35	36	32	34	35	
Argon	0	34	75	36	33	36	28	35	40	34	37	35	
Argon	1.5	49	60	42	34	36	29	38	40	34	36	36	

~~CONFIDENTIAL~~

TABLE A-6. Measured Temperatures on JC01 in Static
Air - Vertical, Bottom Up Position

~~This table is classified Confidential - Defense Information Group 1-5~~

Power Input (Watts)	PE02	PE07			PE11			PE03		PE11	PE03		PE07	Sphere		Leg	Average Generator	
	27	3	4	5	6	7	8	9	10	11	12	13	14	1	2	25	T _H	T _C
499	152	158	200	167	140	158	164	139	161	112	100	118	138	316	324	192	160	117
659	180	191	235	201	172	197	196	171	193	135	122	140	160	369	374	228	193	139
748	199	209	253	219	190	---	216	190	211	147	133	151	173	393	399	247	211	151
		Gas Temp.		Chamber Surface Temp.												Open Circuit Voltage		
		15	16			17	18	19	20	21	22	23	23	T				
499		29	59			29	27	33	27	30	34	32	32	31			1.136	
659		33	68			33	30	37	25	34	39	37	35	34			1.581	
748		35	75			35	33	40	27	36	42	39	37	36			1.822	

CONFIDENTIAL