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MASTER

STATIC TEST DATA SUMMARY

TUBULAR MODULE

TEM-9U S/N-17

(Title Unclassified)

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INFORMATION CATEGORY

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1.0 INTRODUCTION

TEM-9U S/N-17 is a standard tubular module identical in design to those developed under the Compact Converter Program. Built as part of the Compact Thermoelectric Converter System Technology Program, TEM-9U S/N-17 was subjected to initial testing at WANL for 112 hours. During the heatup and cooldown phases, temperature mapping experiments were carried out to determine the module performance at various specified average clad temperature combinations.

The results of the qualification static testing at WANL will be compared with test data measured at Marshall Spaceflight Center, Huntsville, Alabama, using a WANL provided test stand. Heatup data from this module are also presented ~~in this report~~ and a comparison of the actual measured performance data is made with the corresponding predicted values.

2.0 DESCRIPTION OF TEST APPARATUS

In the static test configuration an electrical "main" heater was placed within the bore of the module, while guard heaters were located on either end of the main heater. The functions of the guard heaters were to bring the end closure temperatures up to the level of the thermoelectric material in order to control heat losses to the end closures from the main heater and to reduce axial temperature gradients. Air flow forced over the fin assembly outside the module maintains a nearly constant cold clad temperature.

Thermocouples were located at thirteen axial positions on both inner and outer clads of the module (see Figure 1). The thermocouples were equally spaced along the active length (the lead telluride region) of the module with thermocouples numbers 1 and 13 located in the planes separating the active length from the end closures.

Average hot and cold clad temperatures ($\bar{T}_H$ and $\bar{T}_C$, respectively) were determined using a standard trapezoidal summation applied to the readings from the thermocouples. Along with the twenty-six thermocouple readings, a data point consisted of simultaneous measurements of module load voltage, instantaneous open circuit voltage, current, circuit-to-clad resistance, main heater power, and guard heater powers.

Figure 1. Instrumentation of Standard Tubular Thermoelectric Module on Static Test

3.0 DESCRIPTION OF HEATUP TEST

Module heatup data provide a comparison between calculated parameters and experimental data over a wide range of temperature from ambient to design operating conditions of $\bar{T}_H = 1000^\circ\text{F}$ (538°C) and $\bar{T}_C = 392^\circ\text{F}$ (200°C).

The heatup of TEM-9U S/N-17 was carried out according to Test Plan No. TETP-035S. A load resistor of approximately 0.075 ohms was placed in series with the module during the heatup cycle. The first data set was recorded at ambient conditions.

During the heatup phase, main heater power input was controlled by a cam driven power supply that was designed to provide a $\bar{T}_H$ ramp rate no greater than $2.5^\circ\text{F}/\text{min.}$, while the guard heaters were maintained at a power level $7.0 \pm .5\%$ of the main heater level. Cooling fan speed was adjusted when necessary to maintain the hot and cold clad temperature relationship specified in the test plan.

The initial heatup of TEM-9U S/N-17 was aborted when a failure in the main heater power supply resulted in an overtemperature trip and a rapid shutdown. During the second heatup, when the module had been heated to $\bar{T}_H = 800^\circ\text{F}$ and $\bar{T}_C = 500^\circ\text{F}$, the heatup temperature mapping experiments were begun. During the mapping experiments, increases in $\bar{T}_H$ were controlled so that a $2.5^\circ\text{F}/\text{min.}$ maximum ramp rate was achieved.

4.0 RESULTS OF HEATUP TEST

Module performance at given operating temperatures can be completely evaluated on the basis of three basic parameters: effective Seebeck coefficient $\bar{\alpha}$; module internal electrical resistance, R_g ; and circuit thermal impedance, TI .

The effective Seebeck Coefficient, $\bar{\alpha}$, is defined as the ratio of the open circuit voltage to the average module radial temperature drop. Hence,

$$\bar{\alpha} = \frac{V_{oc}}{\Delta \bar{T}}.$$

In this equation $\Delta \bar{T}$ is defined as the difference between the average hot clad and average cold clad surface temperatures.

The circuit thermal impedance is defined as the ratio of the average module radial temperature drop to the circuit heat input rate. Hence,

$$TI = \frac{\Delta \bar{T}}{Q_T}.$$

In this equation Q_T is that portion of the main heater power which flows through the thermoelectric circuit. Main heater power losses to the module end closures are determined using a TOSS (Transient Or Steady State heat conduction) computer code.*.

Module internal resistance is determined directly from electrical data for each data point. The relationship used here, which comes directly from an analysis of the module electrical load circuit is

$$R_g = \frac{V_{oc} - V_L}{I_L}.$$

Here V_{oc} is the instantaneous open circuit voltage, V_L is the steady state load voltage, and I_L is the steady state load current.

* D. Bagwell, "Transient and/or Steady State (TOSS) Digital Heat Transfer Cod ", Union Carbide Nuclear Co., K-141, 1961.

These three parameters can be calculated as functions of average module temperature, $\bar{T}$, and are used to evaluate actual module performance during heatup tests. The average module temperature is defined as the average of the hot and cold clad average surface temperatures.

Figure 2 presents the measured effective Seebeck coefficient heatup data of TEM-9U S/N-17, as well as cooldown data, plotted against average module temperature. The calculated effective Seebeck coefficient is shown as a solid line on the figure. The calculated effective Seebeck coefficient curve, hence voltage, agrees very closely with the experimental data from the heatup and cooldown.

Figure 3 presents a comparison of calculated and experimental internal resistance data measured during the heatups and cooldown of TEM-9U S/N-17. All experimental data agree well with the calculated curve with the exception of the first two data points following the cooldown temperature mapping. This anomalous behavior in module internal resistance is felt to be a result of the transient conditions and is not considered indicative of normal steady state operation at those temperatures. The remaining two data points of the cooldown exhibit good correlation with the calculated curve.

Figure 4 presents a comparison of experimental and calculated circuit thermal impedance heatup and cooldown data from TEM-9U S/N-17. Although correlation of experimental with calculated values is not as good for this parameter as was observed for voltage and resistance, the correlation is typical for parameters which are functions of heat input rates which are extremely difficult to measure during transient operation.

Figure 2. A Comparison of Calculated and Measured Effective Seebeck Coefficient Data from TEM-9U S/N-17.

Figure 3. A Comparison of Calculated and Measured Internal Resistance Data from TEM-9U S/N-17.

Figure 4. A Comparison of Calculated and Measured Thermal Impedance Data from TEM-9U S/N-17.

5.0 TEMPERATURE MAPPING EXPERIMENT

As a part of the heatup and cooldown phases of testing, a series of stable data points were taken at nine different average clad temperature combinations. The results of these two mapping experiments are summarized in Table 1. The measured open circuit voltage, internal resistance, electrical power output, and circuit efficiency data presented in the table have been mathematically adjusted to the nominal temperatures and to matched load conditions. In no case was the required temperature adjustment greater than 6°F. Excellent correlation exists between these adjusted measured values and the predictions of the thermoelectric module design code TEMOD for all parameters at all the average clad temperature combinations.

TABLE 1

TEM-9U S/N-17 TEMPERATURE MAPPING

$\bar{T}_H = 800^\circ\text{F}, \bar{T}_C = 500^\circ\text{F}$	V_{oc} (Volts)	R_g (m-Ohms)	P_e (Watts)	η (Pct)
Calculated Heatup	2.59	66.7	25.2	3.42
Calculated Cooldown	2.56	67.2	24.3	3.39
Predicted	2.65	65.9	26.7	3.66
$\bar{T}_H = 800^\circ\text{F}, \bar{T}_C = 392^\circ\text{F}$				
Calculated Heatup	3.30	57.4	47.6	4.52
Calculated Cooldown	3.28	57.3	47.0	4.54
Predicted	3.38	56.6	50.5	4.88
$\bar{T}_H = 800^\circ\text{F}, \bar{T}_C = 300^\circ\text{F}$				
Calculated Heatup	3.80	50.2	72.0	5.36
Calculated Cooldown	3.79	50.2	71.6	5.41
Predicted	3.88	49.1	76.6	5.75
$\bar{T}_H = 900^\circ\text{F}, \bar{T}_C = 300^\circ\text{F}$				
Calculated Heatup	4.82	57.6	100.8	6.27
Calculated Cooldown	4.78	57.1	100.1	6.41
Predicted	4.89	56.7	105.4	6.73
$\bar{T}_H = 900^\circ\text{F}, \bar{T}_C = 392^\circ\text{F}$				
Calculated Heatup	4.31	65.5	71.0	5.46
Calculated Cooldown	4.29	65.2	70.4	5.53
Predicted	4.38	64.8	74.2	5.84
$\bar{T}_H = 900^\circ\text{F}, \bar{T}_C = 500^\circ\text{F}$				
Calculated Heatup	3.58	75.5	42.4	4.42
Calculated Cooldown	3.56	75.5	41.9	4.43
Predicted	3.64	74.7	44.5	4.61
$\bar{T}_H = 1000^\circ\text{F}, \bar{T}_C = 500^\circ\text{F}$				
Calculated Heatup	4.60	83.5	63.5	5.23
Calculated Cooldown	4.59	83.5	63.0	5.29
Predicted	4.63	83.7	64.0	5.32
$\bar{T}_H = 1000^\circ\text{F}, \bar{T}_C = 392^\circ\text{F}$				
Calculated Heatup	5.31	72.8	96.7	6.35
Calculated Cooldown	5.32	73.0	97.0	6.44
Predicted	5.38	73.6	98.5	6.55
$\bar{T}_H = 1000^\circ\text{F}, \bar{T}_C = 300^\circ\text{F}$				
Calculated Heatup	5.82	64.7	130.7	7.12
Calculated Cooldown	5.82	64.8	130.9	7.16
Predicted	5.90	65.0	133.9	7.46

6.0 TEM-9U S/N-17 LIFE TEST DATA

TEM-9U S/N-17 was subjected to 112 hours of life testing at $\bar{T}_H = 1000 \pm 10^\circ\text{F}$ and $\bar{T}_C = 392 \pm 10^\circ\text{F}$. During this time the load resistance was adjusted so that V_L was equal to one half the instantaneous open circuit voltage ± 0.1 volt prior to recording data. Guard heater power levels were held constant at 150 watts throughout the duration of the testing.

The life test data from TEM-9U S/N-17 are presented in Table 2. The experimental data presented in this table establishes the beginning-of-life levels of each of the parameters.

TABLE 2

TEM-9U S/N-17 LIFE TEST DATA

MEASURED									* TEMP AND LOAD		
*****									* ADJUSTED		
*****									* *****		
DP#	TIME	TH	TC	Q	VOC	RG	PE	ETA	VOC	RG	PE
***	HOURS	DEGF	DEGF	WTS	VOLTS	M-OHM	WTS	PCT	VOLTS	M-OHM	WTS
***	*****	****	****	***	*****	*****	***	***	*****	*****	***
1	.0	997	394	1496	5.27	73.1	95	6.35	5.31	73.2	96
2	16.8	1000	397	1495	5.29	73.8	95	6.34	5.32	73.3	97
3	41.3	1000	394	1505	5.30	73.3	96	6.37	5.31	73.2	97
4	112.2	1001	395	1505	5.31	73.6	96	6.35	5.32	73.3	97

7.0 SUMMARY

A complete summary of experimental data from TEM-9U S/N-17 measured during static testing at WANL have been presented in this report. Heatup, cooldown, and life test data have been presented and discussed. The results of this qualification testing will be compared with similar data measured with the same module tested in a static test stand at Marshall Spaceflight Center, Huntsville, Alabama.