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TESTING OF THE SNAP-27
TEN-COUPLE MODULES

Engineering Memo 342-93

G. Stapfer

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SUMMARY

The life and performance testing of two thermoelectric modules is described. The two identical modules consist of ten lead-telluride thermoelectric couples of 3P-3N type material. The modules were manufactured and procured from the 3M Company. The construction of the module is of the SNAP-27 type technology, and a combined operating time of 27,000 hours has been recorded. The report briefly describes the thermoelectric elements, the module construction, and the test equipment utilized for the life and performance tests. The recorded data is then discussed and analysed.

The output power degradation rate of module No. 1 was found to be 0.3%/1000 hours for the initial 16,000 hours of operation, at which time the degradation rate increased to 3.12%/1000 hours. It is postulated, that the decrease of the internal argon pressure is responsible for the increased degradation rate of module No. 1. An increase of internal resistance was found to be responsible for both modules overall output power decrease.

1. INTRODUCTION

The success of future space explorations will in part depend on the long term performance of the electrical power source to be used for these missions. An investigation of the continuous performance of thermoelectric materials to be utilized for power generation is therefore not only desirable but necessary. As a result, a portion of the Nuclear Power Sources Group objectives, is to perform life and endurance tests of the various proposed thermoelectric materials.

Two lead-telluride ten-couple thermoelectric modules were procured from the 3M Company for life-test evaluation. Both modules are similar in construction to the SNAP-27 thermoelectric generator presently being evaluated by the Nuclear Power Sources Group.

This report describes the life-tests performed on these modules, the equipment utilized for these tests, and analyses the resultant test data.

2. DESCRIPTION OF THERMOELECTRIC MODULE

Since both thermoelectric modules procured from the 3M Company are identical in design and content, a description of only one module is given.

The basic module contains the thermoelectric elements, an electrical heater and a heat exchanger, all enclosed within an hermetically sealed canister. Figure 1 shows a pictorial view of the final assembly in the test station.

A total of ten thermoelectric couples are connected in two series circuits of five couples each. The electrical leads for the two circuits are brought out separately through the canister on metal-to-ceramic feed throughs. This arrangement allows the module to be operated in an all series or series-parallel combination. For the purpose of the described life-testing, both modules were operated with all ten thermocouples wired in series.

The modules temperature profile is measured by Iron-Constantan thermocouples which are attached to the hot and cold shoes. Figure 2 shows an electrical schematic of the thermoelectric module, including the thermocouple location.

The thermoelectric elements are fabricated from 3P lead-tin-telluride material for the P-legs, and 3N lead-telluride for the N-legs. The thermoelectric materials are pressure contacted to the common hot shoe while the cold side is soldered to individual domed cold shoes (figure 3). The dome of the cold shoe, through a spring follower, provides a heat path from the cold end of the couple to the module's cold frame. Excess heat is then removed from the cold frame by water cooling coils, located between the cold frame and the canister walls.

The thermoelectric couples are thermally insulated from the housing by means of powdered MIN-K-1301. The same material is used for insulation between the modules hot and cold shoes. To remove any possible contaminants, the MIN-K-1301 is thoroughly outgassed prior to final assembly. A bottom and top plate is welded to the cylindrical assembly, to obtain an hermetic enclosure. All the input and output connections for the heaters, instrumentation etc. are brought through the canisters bottom plate.

The whole assembly is then purged and pressurized with Argon to an internal pressure of approximately 2 PSIG at ambient temperature. This pressure is calculated to increase to about 8 PSIG during normal operating condition. A Bourdon gauge, mounted on the top plate, is used to continuously monitor the modules internal pressure. A summary of the modules specification is shown in Table 1.

Table 1. Ten-Couple Module Specification

Thermoelectric Material:	N-LEG Lead-Telluride (3N) P-LEG Lead-Tin-Telluride (3P)
LEG Dimensions:	0.207 in Diameter 0.400 in Length
Operating Temperature: Hot Side Cold Side	600°C Nominal 260°C Nominal
Thermal Insulation:	MIN-K-1301
Fill Gas:	Argon

3. MODULE TEST

a) Test Equipment

The equipment utilized to test the modules is shown in figure 4. Both test stations are identical, and a functional diagram depicting the major components is shown in figure 5.

The input power to the thermoelectric module is controlled and maintained constant by an SCR power control circuit. A power input mode select switch, maintains either the power input or the hot junction temperature constant. The output of the power controller is rectified and filtered before being applied to the module heater. This not only reduces AC noise throughout the test system, but also increases the accuracy of the data to be recorded.

The output power of the module is continuously adjustable from zero voltage to open circuit voltage, by an electronic load. The modules output voltage is maintained constant (± 10 mv) at the desired voltage level.

The temperatures of the module are monitored by a ten-channel thermocouple scanner. This temperature scanner also provides an over temperature guard interlock, which protects the module from extreme temperatures by turning off all input power, should any temperature exceed a pre-determined value.

A digital voltmeter (DVM) is used to measure all input and output voltages and currents. The module temperatures are also measured with this DVM. The front panel meters are thus utilized only for visual reference and observations.

b) Life Tests

Both modules were installed in the life-test equipment and the tests initiated in September, 1966. Since that time, module No. 1 has accumulated over 19,000 hours of operation and is at the present continuing to operate. Module No. 2 developed an open circuit after slightly more than 8000 hours of operation. One-half of the module (5 couples) is presently continuing the life-test. For this report, however, only the data obtained prior to the open circuit is considered.

During the early test period, the internal pressure of both modules continuously decreased, indicating a loss of the hermetic seals. As a result of this, the modules were returned to the manufacturer (3M Company) for reprocessing and sealing. The subsequent life-tests indicated a constant pressure for a portion of the operation, however, afterwards the pressure again began to decrease. Figure 6 shows the internal pressure of the two modules as a function of operating hours. It can be seen from this figure, that the internal pressure of module No. 1 has reduced from an average of 8 PSIG to 2.5 PSIG, while module No. 2's pressure has decreased to atmosphere. No further attempt has been made to repurge either module.

Throughout the life-test, numerous thermal cycles were experienced by the two modules. The thermal cycles were caused either by equipment failures, or electrical power outages. In both cases, the modules were slowly brought back to the same operating condition as recorded previous to the shut-down. The modules electrical power output was then compared with the previously recorded power output, to verify the modules continuing performance. Any performance change directly attributable to the thermal cycling, could thus be easily detected. However, at no time was such a performance change noted.

c) Test Data

Throughout the major portion of the modules life-test, only limited attention was paid to the operation of the test. As a result, data was recorded at approximately 50 hours intervals under varying conditions. Neither the input power to the modules, nor the hot junction temperature was maintained constant. The modules output voltage and current was allowed to vary over a large range of values.

The pertinent performance parameters of the two modules as a function of operating time are shown in figures 7 through 14. The data for these curves were obtained, by selecting representative performance points from the recorded raw data at 1000 hour intervals.

The input power and output power for both thermoelectric modules are presented in figures 7 and 8. The actual voltage and current measurements were used to derive the corresponding input and output power. Figures 9 and 10 show the modules output voltage and output current. The large variation of

these parameters occurring throughout the test can be seen from these figures. The module's average hot junction temperature and open circuit voltage is shown in figures 11 and 12. The cold junction temperature was fairly constant for both modules. An average cold junction temperature of 250°C was recorded for module No. 1, while the average cold junction of module No. 2 was 270°C. The open-circuit voltage was recorded automatically after the load circuit was interrupted (20-100 millisecond time delay). This insured a fair degree of accuracy in recording this voltage since operator errors were eliminated.

Figures 13 and 14 show the module efficiency and the internal resistance as a function of operating hours. The module efficiency is defined as the ratio of the electrical power output divided by the total electrical power input.

The internal resistance was determined by:

$$R_i = E_{oc} - E_{out}/I_{out}$$

Where

E_{oc} is the measured open-circuit voltage E_{out} and I_{out} are the modules output voltage and output current.

4. ANALYSIS OF DATA

To establish meaningful performance results from the modules life-tests, some normalizing of the recorded raw data had to be done. This was necessitated by the fact that throughout most of the module's life-testing, none of the input or output parameters were held constant.

The initial normalizing consists of adjusting the modules output power as a function of input power. Since the modules output power is proportional to the applied input power a correction constant may be found and applied to this parameter. Figure 15 shows the modules output power as a function of small changes in input power. The output voltage of the module was held constant at 0.8 volts. This voltage corresponds to the voltage observed at maximum power output. From this curve it was found that the power output will change by 0.031 watts for each watt of input power change.

The module's power output (P_{norm}) normalized to a constant input power of 62 watts is shown in figure 16. Although the normalized power output (P_{norm}) compared to the raw data (figure 7) shows a smoother curve, variations due to different voltage operating points still exist and distort the actual output power profile.

To establish a true power degradation rate for these modules, it was necessary to determine the output power at a constant output voltage. It is advantageous to use a reference voltage which will correspond to the module's maximum power output point. The value of 0.8 volts was selected. From a recent volt-ampere curve (figure 17, 18,) recorded with a constant input power of 62 watts, the ratio of the power at a specified output voltage to the power at the reference voltage (0.8 volts) was established. The corresponding ratio is then applied to the normalized output power (P_{norm}) of the module. The resultant voltage normalized power output ($P_{\text{v.n.}}$) will thus represent the power output of the module had it been operated at the reference output voltage with a constant input power of 62 watts.

Figure 18 shows the output power ($P_{\text{v.n.}}$) of the two modules which have been normalized to a constant voltage and input power, as a function of operating time. It can be seen from this figure that the output power of module No. 1 decreased very little for the initial 16'000 hours of operation, however a noticeable increase in the degradation rate is apparent beyond this point.

The initial power degradation rate of module No. 1 is 0.1 watts for the first 16'000 hours or 0.3%/1000 hours. This rate subsequently increased to 0.25 watts/4000 hours or 3.12%/1000 hours.

The tenfold increase in the module's power degradation may be caused by the small leak in the module's hermetic seal. The pressure (previously shown in figure 6) decreased to about 4 PSIG at the 16'000 hours operating point. Since the module's internal gas pressure is 4-6 PSI lower in its cold (shutdown) state, it becomes possible that during an inadvertent shutdown, air was introduced into the module. The thus resulting presence of Oxygen would seriously effect the module's subsequent performance.

The power output of module No. 2 is also continuously decreasing. A change of degradation rate becomes apparent after approximately 5500 hrs of operation.

The power degradation rate up to this point is 0.045%/1000 hours, after this, the rate increases to 6%/1000 hours. Again referring to figure 6, it is seen that at this point (5500 hrs) the module's internal pressure is decreasing below 6 PSIG.

The degradation rate of both modules are in fair agreement, and it appears that the same process is responsible for No. 2 module's degradation rate change as was discussed for the No. 1 module.

To establish whether the observed output power degradation is due to either a change, in the seebeck voltage or internal resistance both of these parameters need to be further examined.

Making use of the relationship

$$E_{oc} \approx \alpha(T_H - T_C)$$

where, α , is the seebeck coefficient in $\mu V/^{\circ}C$, the open-circuit voltage can be normalized to an average hot junction temperature.

Using a value of 5MV/ $^{\circ}C$ as a temperature correction factor, it was found that the open-circuit voltage remained fairly constant at 1.45 volts throughout the tests. This indicates that the change of internal resistance is solely responsible for the modules output power degradation.

The internal resistance of the module is composed of the actual thermoelectric material resistance in addition to the interconnecting contact resistance. It is very difficult to determine which of the two resistances changed during operation. It is possible, however, since the contact arrangement uses spring tension, that this tension is changing as a function of operating time, thus contributing in part to the overall internal resistance increase.

5. CONCLUSIONS

The two ten-couple thermoelectric modules procured from the 3M Company have successfully operated for a total of 27,000 hours of combined

operating time and their overall performance was found to be very stable. The observed output power degradation, inherent with thermoelectric power sources, was found to be due to an increase of the module's internal resistance. With the available test data it is difficult if not impossible to determine whether the observed increase of internal resistance is due to a deterioration of the contacts or caused by a change of the thermoelectric module's physical properties.

The change in the power degradation rate of both modules is possibly due to the introduction of air within the module during inadvertent shutdowns. This becomes a possibility when the normal operating pressure falls below 4-6 PSIG. It was found, however, that this change of degradation rate will be completely masked, unless the test parameters are held extremely constant, or some normalizing of the raw data is performed.

Figure 1. Ten-Couple Module

Figure 2. Electrical Schematic 3M Thermoelectric Module

Figure 3. Single Thermoelectric Couple

Figure 4. Ten-Couple Test Station

Figure 5. Test Equipment Block Diagram

Figure 6. Ten-Couple Thermoelectric Module, Pressure vs. Hours

Figure 7. Module No. 1 Input and Output Power

Figure 8. Module No. 2 Input and Output Power

Figure 9. Module No. 1 Output Voltage and Output Current

Figure 10. Module No. 2 Output Voltage and Output Current

Figure 11. Module No. 1 Hot jct Temp. and Open ckt Voltage

Figure 12. Module No. 2 Hot jct Temp. and Open ckt Voltage

Figure 13. Module No. 1 Efficiency and Internal Resistance

Figure 14. Module No. 2 Efficiency and Internal Resistance

Figure 15. Ten-Couple Module No. 1, Input Power vs. Output Power

Figure 16. Normalized Output Power, Modules No. 1 and No. 2

Figure 17. Volt-Ampere Curve, 3M T/E Module I

Figure 18. Volt-Ampere Curve, 3M T/E Module II

Figure 19. Voltage Normalized Output Power, Modules No. 1 and No. 2