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AEC Research And
Development Report

Phase II-B

COMPACT THERMOELECTRIC CONVERTER (U)

Quarterly Progress Report

January 1 - March 31, 1968

April 12, 1968

Westinghouse Astronuclear Laboratory

P.O. Box 10864 Pittsburgh, Pa. 15236

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PREFACE

This Quarterly Report is submitted in response to the terms of Atomic Energy Commission Contract AT(30-1)-3584, Phase II-B, Compact Thermoelectric Converter Program. The Phase II-B Program, which spans from January 1, 1967 through June 30, 1968, is being conducted by the Astronuclear Laboratory of the Westinghouse Electric Corporation under the direction of the Atomic Energy Commission.

This Quarterly Report for Phase II-B presents the significant progress on the Compact Thermoelectric Converter Program for the period from January 1 through March 31, 1968. Also included are the pertinent results of certain other programs being performed in parallel with this contract. Such items are noted as they are reported.

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ABSTRACT

Performance information is presented for twenty-four tubular thermoelectric modules tested during the reporting period. TEM-1 S/N-1, the first module fabricated under the Compact Converter Program, has accumulated over 21,000 hours of successful operation under matched load conditions.

Methods of reducing degradation are discussed. Data from TEM-9U and TEM-9AC series modules, using tungsten foil barriers and molybdenum inner conductor rings to prevent TEGS-2P degradation, continue to exhibit effective operation.

High temperature data from modules employing TEGS-3P material indicate that, within experimental accuracy, there is no increase in degradation rate as hot clad temperatures are increased. These data include peak temperatures as high as 1370°F.

The TEM-9S series of modules are discussed and evaluation of the data from S/N-1 indicates a reduction of nearly 50 percent in end closure heat losses. The TEM-9T thin mica module is discussed and the data presented show that it had the highest beginning-of-life circuit efficiency of any module tested at standard operating conditions.

A new series of modules, TEM-10, was designed and fabricated. The new module has an I. D. of approximately 1 inch and an O. D. of approximately 2 1/2 inches. This module is a high efficiency design, which is suitable for heat pipe application to supply module heating, and demonstrates a marked advance in tubular module technology.

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INTRODUCTION AND SUMMARY

INTRODUCTION

The specific objectives of Phase II-B, Process and Module Development, include the definition of the processes and materials required to assure reproducible module performance characteristics, the continuation of effort directed toward defining contributions to module performance degradation, the development of analytical methods to predict module behavior, the verification of problem solutions by means of capsule experiments and module testing, the investigation of heat pipe applications to tubular modules, and the definition of a module design suitable for prequalification testing.

SUMMARY

A variety of proof-test modules, part of a program to develop modules with up to 70 percent better performance than the TEM-9C, -9E, and -9I series modules now being endurance tested, have been placed on test. These modules were designed to test separately each module improvement needed to achieve a performance gain prior to incorporation of the changes into the redesigned power modules. Initial study modules of inner clad, outer clad, and end closure redesigns are on test and are yielding valuable information to guide the optimized design being sought. In addition, the improvement of the high temperature capabilities of tubular modules through the use of improved thermoelectric materials and diffusion barriers to reduce module degradation has been established. The results of all module improvement tests conducted to date at WANL are discussed in this report.

Test data during this Quarter indicate continuing successful operation of a number of modules designed to control performance degradation. These modules were designed to eliminate degradation by reducing or eliminating direct contact to TEGS-2P material with iron. Performance data are presented for TEM-9U S/N-1, a tungsten barrier module, which shows degradation reduced to an extremely low level for operation at 1000°F as a direct result of the diffusion barriers placed between the inner iron conductor rings and the TEGS-2P thermoelectric washers.

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Testing of materials modules containing stoichiometric n-type and TEGS-3P thermoelectric materials, at hot clad temperatures up to 1370°F, has proceeded without indication of abnormal behavior of any type. The use of new barrier materials and stoichiometric lead telluride has improved the elevated temperature capability of the module. Over 2700 hours were logged with no measurable degradation at a peak temperature of 1340°F for a module containing stoichiometric n-type lead telluride. A TEGS-3P material module has operated for over 500 hours at a peak temperature of 1370°F with no signs of degradation. A TEGS-2P material module with an experimental tungsten barrier was operated for 1000 hours at a peak temperature of 1270°F with reduced degradation. In no cases have circuit-to-clad resistances dropped significantly.

An analysis of experimental temperature data from the first module constructed with redesigned end closures (TEM-9S S/N-1) indicates a reduction of nearly 50 percent in end closure heat losses as compared to the standard design. Excellent agreement was achieved between preliminary design calculations and final calculations, using measured temperature profiles.

Test data from a module designed with thin (0.0015 inch) mica insulating washers are presented and discussed. This module, as a result of reduced shunt heat losses, had the highest beginning-of-life circuit efficiency of any module tested at standard operating conditions ($\bar{T}_H = 1000^\circ\text{F}$ and $\bar{T}_C = 392^\circ\text{F}$).

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I. DESIGN AND ANALYSIS

The principal objectives of the thermoelectric module design and analysis effort during Phase II-B are to obtain an understanding of module degradation, to develop and confirm design tools and computer programs capable of optimizing the tubular module, to identify the materials properties and experimental information required to effectively implement these design tools, and to complete the design of a tubular module that will reflect the attainment of these objectives.

Effort during the first Quarter of 1968 was focused on improving the performance of the TEM-9 module, analytically and experimentally to define methods for controlling performance degradation. These modules were then fabricated into proof modules which are now on test. Additional work was concentrated on the low heat loss end closure experiments, and on the design and analysis of heat pipes for use in heat pipe tubular module systems.

A. DESIGN AND ANALYSIS PROGRAM

Significant improvements in tubular thermoelectric module design have been made through the evaluation of module experiments. Module technology continues to develop through the identification of potential design and processing improvements, the incorporation of these improvements into module experiments, and the analysis of the test data from the experiments.

The close reproducibility of operation exhibited thus far in the program, by all modules fabricated and processed, similarly permits the evaluation of the success of module experiments based on experimental data which are not significantly different from data from the base modules. A deviation of as little as ± 3 percent in any parameter from the average of the data gathered from the "base" modules is readily apparent.

A complete discussion of all module tests conducted or evaluated during this Quarter is given in this report.

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B. MECHANICAL DESIGN AND STRESS ANALYSIS

During this period progress was made toward developing a low end heat loss TEM-9 module with a near-uniform outside diameter after processing. Modules were built with different radial clearances of the end components to allow for Alsimag compactions of 5 to 10 percent. Measurement of the TEM-9S S/N-4 module indicates that the design objective has been very nearly achieved.

In addition, a major step forward was taken with the design and apparently successful fabrication of a new module of increased size, TEM-10 S/N-1. The design of the module and the processing cycle selected were based on results of analytical parametric studies. Module compaction during processing agreed with predictions and the "as-processed" circuit resistance of the module indicates good electrical contact. It is presently anticipated that this module will perform properly at operating temperature.

Low Heat Loss Module Experiments (TEM-9S Series)

TEM-9S S/N-2. Experience has shown that TEM-9L and -9S modules with the thin Inconel 718 outer clads have low room temperature contact pressure after gas-pressure-sintering at 20,000 or 30,000 psi and 650°C. The TEM-9S S/N-1 module, processed at 30,000 psi, had a slightly higher Seebeck coefficient than TEM-9L S/N-2, processed at 20,000 psi (as well as TEM-9I S/N-1 and -2). This indicates that the average contact pressure in these TEM-9L and -9S modules is higher when they are processed at 30,000 psi.

Because of the high circuit resistance in TEM-9S S/N-1, processing of TEM-9S S/N-2 was discontinued after cold autoclaving. An investigation was made to determine how to change the autoclave cycle for modules using Inconel 718 outer clads. It was decided that gas-pressure-sintering should be accomplished at a higher temperature based on an analysis which indicated that better "as-processed" contact pressure would be obtained.

Figure 1-1 shows the results of stress calculations for TEM-9S S/N-2. Processing at both 20,000 and 30,000 psi, 650°C, results in modules with internal gaps at room temperature. Good contact pressures should be obtained at either pressure if the processing temperature is increased to 750°C. Therefore, this module should be gas-pressure-sintered at 750°C to verify

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Figure 1-1. TEM-9L and TEM-9S Pressure Profiles at Room Temperature

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the calculations even if the lead-telluride to iron degradation reaction is amplified by raising the autoclave temperature. Circuit resistance of this module will be increased but a gross reduction in internal gap should be achieved. If the autoclave cycle produces adequate contact pressures as indicated by electrical circuit resistance as a function of temperature, the test purpose of determining an adequate autoclaving cycle has been achieved.

TEM-9S S/N-3. The third low end heat loss module (TEM-9S S/N-3) was redesigned in an attempt to eliminate the end closure distortions experienced in the first such module design. Severe depressions occurred in the ends of the first module design, indicating that Alsimag compaction ranged from 9 to 17 percent (except in the cap area). Accordingly, TEM-9S S/N-3 was dimensioned to allow for 10 percent Alsimag compaction. After autoclaving, measurements indicate about 3 to 4 percent compaction except for a slightly higher value at the retainer ring (based on the assumption that the notch provided in this area filled with Alsimag from adjacent areas).

Figure 1-2 shows the S/N-3 outside diameter as assembled and after cold autoclaving and gas-pressure-sintering. Note that the ends did not reduce in diameter as much as the active section. The calculated points are discussed elsewhere in this report.

TEM-9S S/N-4. TEM-9S S/N-4 is being built as the next step in the development process to achieve an approximately uniform outside diameter after processing in a low end heat loss TEM-9 module. The module is identical to TEM-9S S/N-3 except for radial clearances in the end closure region. The positive end is identical to that of TEM-9S S/N-3 except for enlarged clearance under the retainer ring flange (the notch has essentially been extended the full length of the stretch neck). The negative end has radial clearances which lie midway between the TEM-9F and the TEM-9S S/N-3 clearances. Even though the radial clearances are different at each end and some differences should be expected in the diametral reductions, these differences should not affect the module performance.

The module has now been assembled and cold autoclaved. During cold autoclaving the end closure diameter reduction was less on the positive end than on the negative end. The positive end diameter reduction was about 0.010 to 0.018 inch less than in the active section,

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Figure 1-2. TEM-9S S/N-3 Diameter During Processing

while the negative end reduced about 0.002 to 0.010 inch less than the active section. It would appear that the end closure design objective has been very nearly achieved on the negative end. However, gas-pressure-sintering must be accomplished before final conclusions can be drawn.

Alsimag Compaction

An analysis of the TEM-9I end cap was performed with the stress code, to determine Alsimag compaction constants which would analytically reproduce the dimensional changes of the cap. Measurements of the TEM-9I cap were used to obtain experimental data. It was assumed that the center of the cap behaved independently of the ends.

Dimensional data were used from both end caps of the TEM-9I S/N-1, -2, -3, and -4. The average diametral reduction measured after cold autoclaving was 0.0382 inch, and after gas-pressure-sintering at 20,000, 25,000, and 30,000 psi was 0.0464, 0.0494, and 0.0550 inch, respectively. Using the selected compaction constants, the calculated values after cold autoclaving and 30,000 psi gas-pressure-sintering are 0.0364 and 0.0520 inch.

These constants were used in an analysis of the TEM-9S S/N-3 end to determine if the observed dimensional behavior in this area can be analytically reproduced. The results of the analysis of three planes of TEM-9S S/N-3 are shown on Figure 1-2. The solid dots are based on drawing clearances at assembly and no axial movement of the Alsimag during the processing. The agreement is good except at the retainer ring plane. If it is assumed that the notch under the retainer ring is completely filled by axial movement of Alsimag, very little diameter reduction occurs (the other point at the retainer ring). Obviously the notch in this area was not effective, but it also appears that Alsimag did not freely fill the notch since the module behavior is between the two analytical points.

Attempts will be made to apply the code to other module end closures. Results for this module, though encouraging, are not conclusive. Unfortunately, this type of analysis could not be performed for TEM-10 before release of hardware for S/N-1.

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Extension of Tubular Module Technology (TEM-10 Module)

One important objective of the program is to define new TEM designs suitable for extending tubular module technology. As a first step in defining these modules, the TEM-10 module with a 1.1 inch ID and 2.6 inch OD was conceived, incorporating the results of analytical and experimental design evaluations. The module diameters are sized from a parametric study, while the axial dimensions are essentially the same as in the TEM-9S module. Specific mechanical design features demonstrated in the TEM-9 module series are discussed below.

- 1) Reduced Heat Loss End Closure. The TEM-10 module incorporates the end closure design of TEM-9S by scaling up the radial and axial dimensions. (Refer to Figure 1-3 for a size comparison of TEM-10 with a TEM-9S S/N-3.)
- 2) Diffusion Barriers. The tungsten foil diffusion barriers of the most recent TEM-9U module design were included to eliminate degradation caused by the interaction of iron and TEGS-2P lead telluride.
- 3) Elimination of Circuit-to-Clad Shorting. The use of GE n-type material in place of TEGS n-type lead telluride extends the high temperature capability of modules so that successful operation should be possible at hot clad temperatures as high as 1300°F. Therefore, GE n-type material was incorporated in the TEM-10 module design.
- 4) Clad Geometries. Various clad geometries were chosen for analysis with the stress code. Four scaled TEM-9 outer clads were investigated:
 - a) TEM-9L - Inconel 718
 - b) TEM-9F - Type 316 Stainless Steel
 - c) TEM-9I - Type 316 Stainless Steel
 - d) Intermediate Type 316 Stainless Steel

The two Inconel 718 inner clads investigated were (1) scaled TEM-9Y, and (2) a reduced thickness clad.

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Figure 1-3. Comparison of End Closure Regions of TEM-10 and TEM-9S S/N-3

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In all cases the cold autoclaving pressure was 50,000 psi and the gas-pressure-sintering cycle was 30,000 psi and 650°C. Results for the selected design with the scaled TEM-9Y Inconel 718 inner clad and the intermediate-thickness stainless steel outer clad are shown in Figure 1-4. These results include initial operation at $\bar{T}_H = 1100^\circ\text{F}$ and $\bar{T}_C = 400^\circ\text{F}$, and operation after 1000 hours at this condition. Also shown are results of operation at $\bar{T}_H = 1100^\circ\text{F}$ and $\bar{T}_C = 600^\circ\text{F}$, both with and without prior operation at $\bar{T}_C = 400^\circ\text{F}$. The results at 1100-400°F after an over-temperature condition of 1300-400°F are also included. It appears that this module should be able to tolerate all of these conditions, although the 1100-600°F operation after 1100-400°F operation may be marginal.

The selected TEM-10 clads do produce higher calculated contact pressure at 1100-400°F operation than any of the others considered. It should be emphasized that the inner clad is a direct scaleup of a demonstrated thin clad TEM-9 design, while the outer clad was selected conservatively as a reasonable balance between two demonstrated TEM-9 designs.

At this point the module design was established. The clearances were adjusted somewhat to meet manufacturing requirements, the boron nitride rings at the inside were added, and numerous small changes were made. The revised geometry was input to the stress code and somewhat lower contact pressures resulted under operating conditions. It was concluded that a processing parameter study was required in addition to the above clad parameter study.

Figure 1-5 shows the results of the processing study. The contact pressures at the $\bar{T}_H = 1100^\circ\text{F}$, $\bar{T}_C = 600^\circ\text{F}$ operation condition are shown after four gas-pressure-sintering cycles. It was concluded that the 20,000 psi 650°C cycle should be adequate.

Considerable difficulty was encountered in determining the proper Alsimag clearances for the end closure. Early modules such as the TEM-9F, -I, and -L appear to have experienced much more Alsimag compaction during processing than the more recent TEM-9S S/N-3 and -4 modules. Figure 1-6 shows a summary of the Alsimag compaction experienced by various modules. Also shown are the selected design values for TEM-10 based on a review of the other changes.

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Figure 1-4. TEM-10 Pressure Profiles (Heavy Inner and Intermediate Outer Clads)

Figure 1-5. TEM-10 Pressure Profiles During Operation at $\bar{T}_H = 1100^\circ\text{F}$ and $\bar{T}_C = 600^\circ\text{F}$

PLANE	GAS - PRESSURE - SINTERED AT 650°C AND					9 S-4 COLD		SELECTED FOR TEM-10 DESIGN
	30,000 PSI			20,000 PSI		AUTOCLAVE ONLY + END	- END	
	9S-1	9I-3	9L-2	9F-1	9S-3			
A	10.1 %	10.4 %	8.9 %	11.7 %	3.6 %	2.81 %	3.05 %	7.0 %
B	9.3 %	10.1 %	13.3 %	10.4 %	3.4 %	4.93 %	5.03 %	7.0 %
C	17.7 %	37.1 %	30.8 %	21.3 %	9.8 %	9.41 %	9.31 %	10.9 %
D	7.4 %	6.4 %	6.7 %	7.5 %	2.9 %	2.12 %	4.87 %	4.0 %

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Figure 1-6. Alsimag Compaction Summary (Percent Compaction That Occurred at Various Planes)

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Figure 1-7 shows the recorded dimensions of the module before and after processing. The end closures did reduce in diameter, but not quite as far as anticipated. It appears that the Alsimag compaction design values in Figure 1-6 are slightly higher than those that actually occur.

The average module diameter reduction in the active length is essentially as predicted by the stress code. The prediction was 0.0502 inch during cold autoclaving and 0.0723 inch total after gas-pressure-sintering. Electrical measurements of the various module parameters made after end cap removal indicate proper processing of the module.

Module and Heat Pipe Integration

Part of the effort to develop technology for future module applications includes integrated testing of a tubular module/heat pipe system. The TEM-10 module with its larger inner clad ID (1.092 inch) is an attractive candidate for testing in such systems.

To date one heat pipe from a Westinghouse-funded program has been tested and has successfully demonstrated the capability of delivering the necessary power for the TEM-10 module at an operating temperature of 1100°F. Module performance, however, will be contingent upon the design of an interface that will provide good thermal contact between the module and heat pipe.

The concept proposed for this interface solution makes use of a split boron nitride sleeve located between the module and heat pipe, and designed and fabricated to provide minimum assembly clearances and to maintain intimate contact between adjacent surfaces at operating temperatures.

The feasibility of this concept is dependent upon the stringent dimensional requirements which must be met in the processing and machining of the primary components. These requirements are reflected in the close tolerances demanded for both straightness and roundness for the inner clad ID and the heat pipe OD.

Hardware has been designed and fabricated for a Westinghouse-funded program to evaluate this interface scheme and the prototype heat pipe. An assembly of an Inconel sleeve, a boron nitride sleeve as described above, and a gas film calorimeter was prepared to simulate

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Figure 1-7. TEM-10 S/N-1 Processing Dimensions

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actual assembly interfaces and the module thermal load. Evaluation of this test assembly is continuing.

Degradation Study Modules

TEM-9AC S/N-2 and -3. Two additional TEM-9AC modules, containing molybdenum hot-side conductor rings as in TEM-9AC S/N-1, were released for assembly and processing to evaluate the conductor ring/lead telluride interface at higher temperature operation. The TEM-9AC S/N-2 module has recently been placed on test at $\bar{T}_H = 1200^\circ\text{F}$. The other module (S/N-3) will be tested at $\bar{T}_H = 1100^\circ\text{F}$.

TEM-9U S/N-4, -5, -6, -7, and -8. The successful static testing of the TEM-9U S/N-1 module has shown that the inclusion of a tungsten diffusion barrier between the hot-side iron conductor rings and lead telluride washers can greatly reduce the degradation observed in the TEM-9I type module. To accumulate more data on the effects of barrier materials on module performance, the TEM-9U S/N-4, -5, -6, -7 and -8 modules were released for fabrication.

C. THERMAL AND THERMOELECTRIC ANALYSIS

Continuing progress has been made in the definition and evaluation of module improvements through the analysis of module heatup and life test data. Because of the extremely small variance in the performance data from identically constructed modules, it has been possible to evaluate the effectiveness of minor design changes.

Heat pipe tests being conducted at WANL have established the long-term performance capabilities of the Westinghouse-built heat pipe and methods of fabricating heat pipe/thermoelectric systems are under study.

Selection of New Technology Module Dimensions

Design of the latest series of TEM modules, the TEM-10 series, represents a marked advance in tubular module technology. A module with a 1.1-inch ID and 2.6-inch OD was chosen based on analysis of module performance parameters, technology considerations, and potential applications. Three goals to be met with this new series of modules are as follows:

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1) This module design will furnish a vehicle for determination of processing cycles as a function of module size. Module design problems and predictions of module compaction and performance will be explored.

2) More watts per module will be obtained with little sacrifice in module specific power. Thus, this design has the potential for simpler systems with fewer tubular units and a lower converter system cost.

3) Studies of potential applications including reactor power conversion systems, heat pipe heated systems, and internally fueled isotope systems indicate the desirability of larger module inner diameters. In fact, the 1-inch ID appears well suited for use with heat pipe heated systems. There may be considerable gains in system simplicity and cost when more power per module is obtained in a reactor conversion system. Also, this new design is much closer to the design requirements of internally fueled isotope systems.

Determination of the inner and outer diameters best suited for these considerations was made from the parametric study, reported previously. Calculations performed for a 15-inch long module circuit assumed to be operating with $\bar{T}_H = 1200^\circ\text{F}$ and $\bar{T}_C = 400^\circ\text{F}$ will be discussed here as indicative of the results obtained. It must be pointed out that although the transport and thermoelectric data used for lead telluride temperatures above 1000°F are extrapolations of experimental data, these are the best available data and should be valid to determine trends associated with increasing the inner or outer diameters.

An example of module efficiency for various module inner diameters is shown in Figure 1-8. In this figure, it can be seen that identical efficiency can be obtained for modules with inner diameters ranging from 0.375 to 1 inch and above, within the range of module outer diameters considered in this study. It can be noted, therefore, that no penalty in module efficiency needs to be experienced when going to larger module inner diameters. The next consideration is what will happen to module specific power (watts per pound) for modules of larger size. Figure 1-9 shows specific power as a function of module outer diameter for various inner diameter sizes. Lines of constant overall module efficiency, cross-plotted on per pound), there appears to be, in fact, an advantage in going to a module of approximately 1-inch ID.

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Figure 1-8. Circuit Efficiency Versus Outer Diameter

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Figure 1-9. Specific Power Versus Outer Diameter

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Power output for a 15-inch module with an open circuit voltage of 14 volts operated between $\bar{T}_H = 1200^\circ\text{F}$ and $\bar{T}_C = 400^\circ\text{F}$ is plotted as a function of OD for various inner diameters in Figure 1-10. For the designs considered here, the power output increases with increasing inner diameter and decreases with increasing outer diameter. Cross-plotted on this figure are lines of constant overall module efficiency. For any constant efficiency curve, power output per module increases nearly linearly with an increase in inner diameter. For completeness, Figure 1-11 shows total module weight for the module designs considered in this comparison.

From the parametric study of various module sizes and operating conditions, a typical section of which is presented here, an inner diameter of approximately 1 inch has been chosen for the TEM-10 module. This size appears to be suitable for operation with heat pipes in initial units 7 inches long and for second-generation units 15 inches long, having power outputs of approximately 150 and 300 watts, respectively. The outer diameter of this module was chosen to increase the circuit efficiency somewhat above that obtained in the present TEM-9 design and, in fact, at a level projected for a redesigned version of the TEM-9 module. The outer diameter, approximately 2.45 inches, was chosen as the best trade-off between maximum efficiency and maximum power per module without an excessive cost in specific power. Initial TEM-10 modules are being made with a stainless steel outer clad; therefore, the specific power forecast shown here will not be achieved until the thinner Inconel 718 outer clad is incorporated into the TEM-10 design.

Thin Mica Insulator Experiment (TEM-9T S/N-1)

TEM-9T S/N-1 was the first TEM module fabricated with thin 0.0015-inch mica insulating washers. All other previously built TEM modules employ 0.005 inch mica washers. The thin mica washers were designed to improve module performance by the following means:

- 1) By reducing shunt heat losses through the mica washers, thereby reducing the heat required to operate the module. (The thermal conductivity of mica is greater than that of lead telluride by approximately a factor of two in the operating temperature range of TEM modules.) A reduction in heat throughput required to maintain the module at normal operating conditions ($\bar{T}_H = 1000^\circ\text{F}$, $\bar{T}_C = 392^\circ\text{F}$) of 2.5 percent was calculated for the thin mica modules as compared to a standard TEM-9I type module.

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Figure 1-10. Power Output Versus Outer Diameter

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Figure 1-11. Module Weight Versus Outer Diameter (15-Inch Active Length)

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2) By increasing the axial length of each of the T/E washers to compensate for the reduction in mica thickness, the internal resistance of the module is reduced. A reduction of 4.0 percent in internal resistance at standard operating conditions was calculated for the TEM-9T design as compared to TEM-9I.

3) A second order effect of replacing a portion of the mica with lead telluride of lower thermal conductivity is an increase in the portion of the module radial temperature drop which is impressed across the T/E material. This increased temperature drop across the lead telluride produces a small increase in Seebeck voltage in the thin mica module. An increase of 0.2 percent in open circuit voltage was calculated for a TEM-9T module operating at standard clad temperatures.

4) The net effect of the reduction in resistance and heat throughput and increase in open circuit voltage was a calculated increase in circuit efficiency from 5.94 in TEM-9I modules to 6.24 percent for the TEM-9T design for standard operating conditions (538°C to 200°C).

To evaluate the actual effectiveness of the thin mica washers, a comparison was made of TEM-9T heatup data with the data of two "standard" TEM-9I series modules. Both TEM-9T and TEM-9I series modules employ single-piece TEGS 2N and 2P T/E washers and are identical in every way except for the axial thicknesses of the lead telluride and mica washers.

A comparison of effective Seebeck coefficient (defined as the ratio of open circuit voltage to average module radial temperature drop), internal resistance, and module thermal impedance (defined as the ratio of average module radial temperature drop to heat throughput) is presented for the three modules. These three parameters are all relatively insensitive to radial temperature drop which varies from module to module during heatup due to differences in cooling fan speed. TEM-9T S/N-1 was heated to $\bar{T}_H = 978^{\circ}\text{K}$ (1300°F), whereas the other two modules were heated to $\bar{T}_H = 811^{\circ}\text{K}$ (1000°F). Heatup data for TEM-9T extend, then, to an average module temperature of 725°K (846°F) and data for the two TEM-9I series modules extend only to $T = 644^{\circ}\text{K}$ (696°F). Since all three modules use the standard TEM end closure

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design, standard and identical end closure heat losses were assumed to apply to each.

Figure 1-12 presents the effective Seebeck coefficient data from the three modules as well as calculated curves for the TEM-9T and -9I designs. The calculated curves can be seen to be nearly identical, whereas the TEM-9T data are about 3.0 percent (near standard operating conditions) below the calculated curves and the TEM-9I data. A discussion of the reduction in TEM-9T effective Seebeck data is given below.

Internal resistance data for the same three modules are presented in Figure 1-13 along with the calculated curves for the two different module designs. For module average temperatures below 500°K , the internal resistance data vary due to the lack of sufficient circuit interface pressures. In the temperature range from 500°K to 645°K , the TEM-9I and TEM-9T data agree excellently with the predicted curves for these designs. However, as the TEM-9T temperature is increased from 645°K to 700°K , the data begin to deviate from the calculated curve. Discrepancies between predicted and experimental performance for modules operated at hot clad temperatures higher than 811°K (1000°F) have been noted before, and is felt to be brought about through the use of lead telluride properties (Seebeck coefficient, electrical resistivity, and thermal conductivity) which have not been adequately characterized at these higher temperatures.

Figure 1-14 presents a comparison of calculated and experimental thermal impedance heatup data for the TEM-9I series modules and TEM-9T S/N-1. Good agreement between TEM-9I series module data and calculated curves was achieved for average module temperatures above 500°K . However, a greater than expected increase in experimental thermal impedance for TEM-9T S/N-1 was measured at standard operating conditions.

Table 1-1 lists three experimentally measured parameters at the beginning-of-life ($\bar{T}_H = 1000^{\circ}\text{F}$) test point: heat throughput, open circuit voltage, and internal resistance, for TEM-9T S/N-1 and TEM-9I S/N-1. The percent decrease measured as well as calculated for each of these parameters is also tabulated. In addition, the circuit efficiencies calculated from the experimental data as well as from the calculated parameters are presented. All calculated and observed parameters agree to within the ± 3 percent calculated versus observed performance tolerances seen in the analysis of TEM-9 module data.

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Figure 1-12. A Comparison of Calculated and Experimental Effective Seebeck Coefficient Data for TEM-9T and -9I Series Modules During Heatup

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Figure 1-13. A Comparison of Calculated and Experimental Internal Resistance Data for TEM-9T and -9I Series Modules During Heatup

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Figure 1-14. A Comparison of Calculated and Experimental Thermal Impedance Data for TEM-9T and -9I Series Modules During Heatup

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TABLE 1-1

COMPARISON OF BOL TEM-9T PERFORMANCE WITH
THAT OF TEM-9I S/N-1 AT STANDARD OPERATING CONDITIONS

	<u>TEM-9T</u>	<u>TEM-9I</u>	<u>Difference</u>	<u>Observed Percent Decrease</u>	<u>Calculated Percent Decrease</u>
Heat Throughput (watts)	1034	1100	76	6.85	2.52
Open Circuit Voltage (volts)	5.49	5.66	0.17	3.00	-0.18
Internal Resistance (ohms)	0.0799	0.0817	0.0018	2.20	4.02
Circuit Efficiency (percent)	6.13	5.95	0.18	-3.03	-5.06

The possibility of explaining the reduction in open circuit voltage measured in TEM-9T S/N-1 as a result of an intercouple short has been considered. Destructive examination of modules employing standard thickness (0.005 inch) mica insulating washers revealed an axial deformation of the mica washers in the vicinity of the end closure region. This deformation is caused by axial movement of the lead telluride washers relative to the iron conductor rings during fabrication and processing of the module. This movement is caused by the axial compaction of the lead telluride washers. Since the iron conductors do not compact the same as the lead telluride, there is movement of the end washers relative to the conductor rings, causing a shear load and shear deformation in the mica washers at the thermoelectric washer-conductor ring interface.

If one of the 0.0015-inch mica washers in TEM-9T failed, a one-couple short circuit would result. An electrical analysis of a module with a shorted couple produces the following relationships:

$$V'_{oc} = V_{oc} - V_{pc} \left(\frac{R_{pc}}{R_{pc} + R_s} \right)$$

and

$$R'_{gen} = R_{gen} - R_{pc} \left(\frac{R_{pc}}{R_{pc} + R_s} \right),$$

where V_{oc} and R_{gen} are the open circuit voltage and internal resistance of the module with no shorts, V'_{oc} and R'_{gen} are the measured open circuit voltage and internal resistance for a module with a one-couple short of resistance R_s through the mica insulating washers, and V_{pc} and R_{pc} are the open circuit voltage and internal resistance of the shorted couple, respectively.

In the case of a completely shorted couple ($R_s = 0$), the open circuit voltage would be reduced by the voltage generated in the shorted couple. Since the modules have thirty-eight couples, the voltage would be reduced by the fraction 1/38. However, accompanying this would be a reduction (by the same fraction 1/38) in internal resistance. No reduction in internal resistance was measured for TEM-9T S/N-1, aside from the reduction resulting from the increase in axial length of the T/E washers as explained above.

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In addition, if an intercouple short existed, there would be a current flow through the shorted couple. The peltier heat pumping from the hot junction to the cold junction would increase heat transfer through the shorted couple. Approximately twice the amount of heat could be transferred across a totally shorted couple as compared to a non-shorted couple. If a shorted couple existed in TEM-9T S/N-1, the thermal impedance would be lower than the calculated value for this module. (Figure 1-17 shows that this is not the case.)

The assumption that an intercouple short exists in TEM-9T S/N-1 as a result of the failure of a mica washer does not satisfactorily explain the performance of this module. An examination revealed that the thermoelectric washers were pressed from the same batch of lead telluride as the washers used for TEM-9U S/N-4. This module, too, exhibited lower open circuit voltage data (hence effective Seebeck coefficient) than anticipated. The lower than normal open circuit voltage of both of these modules is felt to be caused by an unexplained variation in material properties (namely Seebeck coefficient) in the material used to fabricate the lead telluride washers. However, TEM-9T S/N-1 was removed from test and will be destructively examined to determine the condition of the mica washers. Despite the fact that the experimentally measured open circuit voltage of TEM-9T S/N-1 was 3 percent below the expected level for this module design, the thin mica washer module had the highest measured BOL efficiency, 6.14 percent, of any TEM-9 module tested at standard operating conditions ($\bar{T}_H = 538^\circ\text{C}$ and $\bar{T}_C = 200^\circ\text{C}$).

Analysis of Heatup Data from Tungsten Barrier Modules

During the past Quarter three additional modules employing 0.001 inch tungsten foil were placed on test. Heatup data for these three modules (TEM-9U S/N-2, S/N-3, and S/N-4) have been analyzed along with data previously presented for TEM-9U S/N-1* to study the effects of the tungsten foil on initial module performance and to display the reproducibility of operation of these modules.

One of the modules, TEM-9U S/N-3, was heated directly to an average hot clad temperature, $\bar{T}_H = 922^\circ\text{K}$, affording an opportunity to examine module heatup data that extend

* Quarterly Progress Report: NYOO-3584-9, January 12, 1968, p 1-53

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beyond the normal operating level, $\bar{T}_H = 811^\circ\text{K}$ (1000°F). The most recent TEM-9U series module (TEM-9U S/N-4) differs from the others in that tungsten foil was used as a barrier both at the hot junction and cold junction.

Figure 1-15 presents experimental effective Seebeck data from all TEM-9U series modules plotted as a function of average module temperature which is defined as the arithmetic average of $\bar{T}_H$ and $\bar{T}_C$. Very good reproducibility can be observed for all modules with the hot junction tungsten foil barriers (i.e., TEM-9U S/N-1, S/N-2 and S/N-3). Excellent agreement is achieved between the calculated effective Seebeck values and experimental data from these modules.

TEM-9U S/N-4 Seebeck data can be seen to be about 4 percent lower than that of the other modules. This reduction is felt to be primarily due to a variation in material properties (specifically Seebeck coefficient) of the materials used in this module. The thermoelectric materials used in the fabrication of lead telluride washers may vary by ± 3 percent from the norm without cause for rejection. The only other module constructed with washers pressed from the same batch of lead telluride, TEM-9T S/N-1, also exhibited a reduction of 3 percent in effective Seebeck coefficient data when compared to similar modules. A reduction of 3 percent in any experimentally measured parameter is considered significant only because all modules of identical design previously exhibited variations in performance of only 1 percent. This indicates that material properties have been well within the tolerance limits.

Electrical internal resistance data during the heatup cycles of the TEM-9U series modules are presented in Figure 1-16. The scatter in internal resistance data at low temperatures is due to the fact that insufficient contact pressures are developed in the low temperature range. For average temperatures above 550°K , the internal resistances of the first three TEM-9U series modules are in excellent agreement. The solid line is the calculated curve for the TEM-9U series.

TEM-9U S/N-4, as expected, had a lower internal resistance than the other modules. The data from this module can be seen to agree quite well with TEMØD calculations made by setting the interface resistivity at zero.

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Figure 1-15. A Comparison of Calculated and Experimental Effective Seebeck Coefficient Data for TEM-9U Series Modules Measured During Heatup

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Figure 1-16. A Comparison of Calculated and Experimental Internal Resistance Data for TEM-9U Series Modules Measured During Heatup

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Figure 1-17 presents thermal impedance data from TEM-9U series modules. Thermal impedance TI is defined as

$$TI = \frac{\bar{T}_H - \bar{T}_C}{Q_T},$$

where Q_T is the heat throughput. Unlike heat throughput data, the thermal impedance is not a strong function of the module radial temperature drop and the calculated values for this parameter do not vary from module to module.

As seen in Figure 1-17, the thermal impedance data are very reproducible and agree well with the calculated curve. The deviation at lower temperatures is caused by the insufficient interface pressures necessary to produce good thermal contacts.

End Closure Heat Loss Experimental Analysis (TEM-9S S/N-1)

An analysis of experimental temperature data from TEM-9S S/N-1 was performed to determine the effectiveness of the redesigned end closure in reducing end heat losses. This analysis was performed to substantiate the method used to design end closures based on isothermal clad temperature profiles. Excellent agreement was achieved between the preliminary design calculations and final calculation using measured temperature profiles.

TEM-9S S/N-1 was the first module tested with a redesigned end closure to reduce end heat losses. In this analysis of the end closure heat losses, the experimental inner clad temperature data were specified as input to the TØSS model. It was assumed that there exists an overall effective heat transfer coefficient $\bar{h}$ for the entire outer surface of the module.

The magnitude of the effective heat transfer coefficient for the outer surface was determined by accounting for radiation and forced convection heat transfer from the fins attached to the outer clad. Given in Table 7-2 of Macadam* is an overall (radiation plus free convection) heat transfer coefficient for a temperature difference of 400°F from surface to ambient and an outer diameter of 1.75 inches. The value was found to be $(h_c + h_r) = 4.22 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$. Correcting the value by the factor $(1 + \frac{A_f}{A_s})$, where A_f and A_s

* Macadam, Heat Transmission, McGraw-Hill, 1954, Page 179.

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Figure 1-17. A Comparison of Calculated and Experimental Thermal Impedance Data for TEM-9U Series Modules Measured During Heatup

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are the surface areas of the fin and outer clad, respectively, an overall effective heat transfer coefficient $h_{oc} = 45.8 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$ was calculated.

It must be emphasized here, that because of the approximations necessary to calculate an effective heat transfer coefficient the result must be treated merely as effort to determine the order of magnitude. This parameter may be determined empirically as that value which yields the best correlation of calculated and experimental surface temperatures. For the TØSS calculations presented herein, a value of $h_{oc} = 50 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$ was used.

In the stretch-neck region of the end closure, the modules are insulated with fiberfrax thermal insulation. In this region an effective heat transfer coefficient was used which accounts for the insulation. This stretch-neck region heat transfer coefficient is determined from the following relationship:

$$h_{sn} = \frac{h_{oc}}{1 + h_{oc} \left(\frac{r_o \ln r_o / r_i}{k_f} \right)}$$

Here, h_{oc} is the overall heat transfer coefficient previously calculated for the outer clad, r_o and r_i are the outer radius of the outer clad and stretch neck, respectively, and k_f is the thermal conductivity of fiberfrax insulation. With this relationship, a stretch-neck region effective heat transfer coefficient $h_{sn} = 3.0 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$ was calculated.

Figure 1-18 shows a plot of experimental and calculated temperature profiles for TEM-9S S/N-1. Superimposed on the graph is a sketch of the module drawn to scale and indicating the position of the thermocouples on the module.

Because no hot clad temperature data were measured in the end closure region of TEM-9S S/N-1, it was necessary to extrapolate using the data in the active region of the module. This extrapolation caused a deviation of outer clad temperatures calculated for the outer surface of the stretch-neck portion of the end closure. However, because of the insulation, heat losses for these surfaces are negligible and the error in calculated temperatures

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Figure 1-18. Axial Temperature Profile of TEM-9S S/N-1

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does not greatly affect the calculation of end closure heat losses.

Table 1-2 presents the results of the TØSS heat transfer calculations, using the experimentally measured inner clad temperature profile and the outer clad effective heat transfer coefficients discussed above. The surfaces A through E are shown in the sketch of the module in Figure 1-18. As can be seen, the major contribution to the total heat loss is from surface D, from the outer clad in the end closure region.

The total heat loss rate for TEM-9S S/N-1 at standard operating conditions ($\bar{T}_H = 1000^\circ\text{F}$, $\bar{T}_C = 392^\circ\text{F}$) was 101 watts per end. This is in excellent agreement with preliminary calculations performed after the end closure was designed, but before experimental temperature data were available. In these calculations, the outer and inner clad temperatures were assumed to be isothermal to 1000°F and 392°F , respectively.* In addition, the surfaces covered by the fiberfrax insulation were assumed to be adiabatic (effective heat transfer coefficient of zero). In this preliminary analysis, a total end heat loss rate of 104 watts was predicted.

TABLE 1-2
END CLOSURE HEAT LOSSES FOR TEM-9S S/N-1

Surface**	Effective Heat Transfer Coefficient (Btu/hr-ft ² -°F)	Heat Loss Rate	
		(Btu/hr)	(Watts)
A	0	0	0
B	3	7.3	2.1
C	3	1.6	0.5
D	50	274.4	80.3
E	--	63.1	18.5
Total	--	346	101

* NYOO-3584-7, July 12, 1967

** See Figure 1-18 for the location of each surface.

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The accuracy to which heat losses can be calculated by assuming isothermal clad temperatures justifies the use of this procedure for the design of end closures. In addition, thermal analysis of experimental TEM-9S S/N-1 temperature data indicates that this end closure design is a significant improvement over the standard design. End heat losses for the standard design for operation at $\bar{T}_H = 1000^\circ\text{F}$ and $\bar{T}_C = 392^\circ\text{F}$ are 195 watts per end.

The TØSS model used to calculate end heat losses is being revised, so that heat generation rates in the main and guard heaters can be used as input rather than hot clad temperature data. This will eliminate the necessity of extrapolating or interpolating on experimental hot clad temperature data in regions where no thermocouples exist.

Heat Pipe Studies

The Westinghouse-funded heat pipe test program has demonstrated that a 1-inch outer diameter heat pipe subjected to a simulated T/E module loading will function with an isothermal module hot-side temperature, i. e., a uniform heat pipe condenser temperature. With sodium as the heat pipe working fluid, isothermal condenser temperatures have experimentally been shown for temperatures above 500°C . The range for heat flow and condenser temperature of the present investigation is illustrated in Figure 1-19. No heat pipe failure or performance limit was encountered during these studies. Higher power levels were not examined since temperature limits for the heat source (Watlow heaters) were attained, i. e., 800°C .

One heat pipe was tested for 1700 hours with 2300 watts heat transport. During this time, no significant change occurred in the axial temperature profile or power output. The test established the long-term performance capabilities of the Westinghouse-built heat pipe and provides support for the methods used in designing and fabricating heat pipe/thermoelectric systems.

Concurrent with the life test program, additional 1-inch diameter heat pipes have been fabricated and will be tested to demonstrate the reproducibility of the existing designs and to investigate possible performance improvements that may result from using a two-component

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Figure 1-19. Preliminary Isothermal Condenser Operating Region
for Sodium Heat Pipes

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wick* for liquid circulation. These latter investigations are intended to show heat pipe/thermoelectric compatibility for modules of lengths greater than the 7-inch active module length currently considered as the state-of-the-art.

Analytical studies of heat pipes have been directed toward defining evaporator performance limits of the heat pipe and toward preliminary examination of heat rejection systems, which use vapor chamber fins that are suitable for an isotope fueled tubular thermoelectric module.

Heat pipes which can be built with today's technology will satisfy the basic needs for thermoelectric system requirements (2500-5000 watts in a 1-inch diameter pipe), but optimized T/E systems will need several times this capability and will require further refinement of heat pipe performance limits. At present, an understanding of the fluid flow and heat transfer mechanisms which may limit the continuous circulation of working fluid inside the heat pipe is not complete. The original performance limit proposed by Cotter** and experimentally verified by Kemme,⁺ which considers a capillary pressure limit, has been circumvented to some extent by introducing a refined wick construction which permits nearly unlimited capillary pressure while, at the same time, minimizing the drag of the wick structure on the returning liquid.

The technology advancements in capillary wick design have brought into the forefront new heat pipe performance limits which may be encountered when large heat transport rates are desired for the high system performance requirements just mentioned. These limits include 1) vapor-liquid interaction caused by high vapor velocity, and 2) boiling in the liquid-filled wick.

The intention of the description which follows is to outline the behavior of vapor velocity and boiling limits as they are influenced by heat pipe operating temperature. Since

* NYOO-3584-9, January 12, 1968

** Cotter, T. P., "Theory of Heat Pipes," Los Alamos Scientific Laboratory, LA-3246-MS.

⁺ Kemme, J. E., "Heat Pipe Capability Experiments," LA-3585, 1967

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these limits may influence the choice of heat pipe working fluid, experimental measurements of these performance limits is essential to the design of optimized heat pipe systems.

Description of High Performance Heat Pipe Limits. The basic assumption for the performance limit of a heat pipe is the continuity of pressure required for the circulation of working fluid, i.e.,

$$\Delta P_{cap} = \Delta P_{liq} + \Delta P_{vap} \quad (1)$$

The components of the liquid and vapor pressure drops can be further distinguished as

$$\Delta P_{cap} = (\Delta P_{liq})_f + (\Delta P_{liq})_g + (\Delta P_{vap})_f + (\Delta P_{vap})_{acc} ,$$

where

f is the friction or drag loss

g is the hydrostatic loss

and

acc is the acceleration or momentum loss.

The frictional pressure loss in the liquid results from resistance to liquid flow through the capillary wick and from liquid-vapor interfacial shear forces. The frictional forces and the vapor flow are the result of drag on the liquid-vapor interface and any part of the wick structure which is exposed to the vapor. The hydrostatic losses are attributed to the orientation of the heat pipe axis with respect to gravitational acceleration. Vapor acceleration is significant in heat pipes operating with a working fluid vapor pressure which is low. From the viewpoint of vapor acceleration, the static pressure at the exit of the evaporator becomes a minimum, i.e., where vapor velocity is a maximum, and pressure recovery takes place in the condenser section as the vapor flow decelerates. The larger the heat flow demand imposed on the heat pipe, the greater will be the magnitude of the vapor velocity or pressure drop at the exit of the evaporator. Thus, liquid-vapor interaction is most severe at this section.

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Figure 1-20 illustrates heat flow per unit vapor cross section as a function of sodium saturation temperature with vapor velocity (in the form of Mach number) at the exit of the evaporator section as a parameter. Mach numbers near unity can be encountered during startup (i. e., as saturation temperature is increased from room temperature) and, in the case of optimized heat pipe designs, at operating conditions. For a constant vapor cross section at the exit of the evaporator, a Mach number of one will limit vapor mass flow rate to the condenser and, therefore, axial heat transport. Even before this condition is achieved, however, high vapor flow rates may entrain liquid from the wick and thereby limit heat pipe performance.

In contrast to a vapor velocity which increases with the saturation temperature (Figure 1-20), an increase of saturation temperature enhances the thermal conditions necessary to commence nucleate bubble formation.

A vapor bubble could nucleate from the heat pipe inner wall surface and produce a blockage of the liquid return path, thereby reducing the heat flow capability of the heat pipe. The precise thermal conditions which will initiate nucleate bubble formation are poorly understood, particularly for the case of liquid metal working fluids. Therefore, Cotter* suggested a conservative limit to the heating rate according to the equation

$$P_{\text{vap}}(T) - P_{\ell} = \frac{2\sigma}{r_c},$$

where P_{ℓ} is the pressure in the liquid phase, $P_{\text{vap}}(T)$ is the pressure in the vapor above the liquid-vapor interface, σ is the liquid vapor surface tension, and r_c is the size of the nucleation cavity from which a vapor bubble can grow. The unknown magnitude which must be assigned to the nucleating cavity size, r_c , makes a precise determination of incipient boiling conditions difficult. Cotter recommended using the wick pore radius as a conservative limit; however, this permits extremely small values of liquid superheat temperature and corresponding wall heat flux, which have been experimentally exceeded in several tests. In reality, a nucleation site results from microscopic pits or scratches present on the heat pipe inner wall,

* Kemme, J. E., "High Performance Heat Pipes," from a rough draft of the heat pipe discussion for the Los Alamos Advanced Reactor Technology Report for the period ending September 30, 1967.

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Figure 1-20. Sodium Vapor Mach Numbers

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which are not filled with liquid during heat pipe processing. As liquid floods the wick, "pockets" of vapor collect in these pits and scratches. In some cases the vapor pocket is unstable and the liquid entirely wets the cavity, thereby eliminating that site as a possible nucleate bubble formation site. This is not the case, however, for sufficiently small cavities which remain unwetted and form potential nucleation sites. To activate these sites so that a vapor bubble is generated, the liquid temperature must be superheated with respect to the liquid pressure. The parameters which influence bubble formation that have been identified to date include:

- 1) Saturation temperature of the liquid in the wick
- 2) The dimension of the largest unwetted cavity on the heated inner wall surface
- 3) Evaporator heat flux
- 4) Liquid superheat temperature, $T_{\text{wall}} - T_{\text{saturation}}$
- 5) The environment that the heated surface has been subjected to during processing of the heat pipe, including vapor pressure, temperature, cover gas (if any) pressure and temperature
- 6) The depth of liquid covering the heated surface

Parameters (1) through (4) have been widely recognized in the literature as significant to incipient bubble formation. The importance of pressure-temperature history and depth of liquid covering the heated surface, however, have received little recognition to date. Pressure-temperature history was discussed by Holtz* for studies of predicting incipient boiling in liquid metals. He noted that by subjecting the system to a cover gas pressure and temperature prior to heating the test surface, incipient boiling was suppressed to a higher value of heat flux and corresponding wall superheat temperature. It is believed that this procedure reduced the maximum unwetted nucleating cavity size mentioned in (2) above.

The effect of liquid depth upon incipient bubble formation remains almost completely uninvestigated. For a thin liquid layer, a preliminary study of evaporation rates** showed that a small value of superheat temperature in the liquid will result in a large value of free

* Holtz, R. E., "The Effect of the Pressure-Temperature History Upon Incipient Boiling Superheats in Liquid Metals," Argonne National Laboratory, ANL-7184, 1966.

** NYOO-3584-9, January 12, 1968.

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surface evaporation. Since the evaporation heat flux was extremely sensitive to the liquid superheat, predictions of incipient nucleate boiling by means of this theory are complicated by uncertainties in inner heat pipe wall temperature, working fluid vapor temperature, and working fluid thermodynamic properties. In view of these uncertainties, quantitative predictions will necessitate careful experimental measurements or the results can easily be rendered meaningless. Qualitatively greater liquid superheating will occur at the heated surface when the depth of the liquid layer or the heat flux is increased. As the liquid superheat increases, the thermal conditions necessary for incipient bubble formation are further enhanced.

Figure 1-21 presents the trend of the surface heat flux in the evaporator section as a function of saturation temperature which is necessary for incipient boiling of sodium. These curves are obtained for arbitrarily selected values of cavity size r_c from the experimental data for incipient pool boiling shown in Figure 1-22, in conjunction with the sodium vapor pressure curve and Equation 2. The general conclusion to be noted from this figure is that as saturation temperature is increased, the evaporator heat flux required for incipient bubble formation decreases.

To design a heat pipe which is capable of transferring nearly the maximum heat flow, precise information for predicting heat pipe limits is needed. If the two-component wick is properly constructed, the limits to heat pipe operation can be either vapor velocity effects at the exit of the evaporator or nucleate bubble formation in the evaporator. By comparing Figures 1-20 and 1-21, the maximum heat flow for a given working fluid and heat pipe design is seen to occur at the point where the vapor velocity and liquid superheat limits intersect. If the operating temperature is lower than the temperature corresponding to this intersection, vapor velocity is the limiting factor. On the other hand, if the operating temperature is higher than the intersection temperature, the liquid superheat becomes the limiting temperature. If the operating temperature is higher than the intersection temperature, the liquid superheat becomes the limiting factor.

In summary, for a given heat pipe working fluid, it can be concluded that:

- 1) At low values of saturation temperature, which may be encountered during startup or steady-state operation, high vapor velocities can "choke" ($M = 1$) the vapor flow or cause severe liquid-vapor interaction which may limit heat pipe performance.

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Figure 1-21. Incipient Boiling Limitations on Sodium Heat Pipe Capability

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Figure 1-22. Boiling Inception Superheat Data for Sodium

2) At high values of saturation temperature the conditions for incipient bubble formation are enhanced and, therefore, bubble formation may limit heat pipe performance.

A small portion of the analytical work has been directed toward a study of the vapor chamber fin as a heat rejection system for tubular thermoelectric modules. The heat leaving the module could be rejected to space by a vapor chamber fin, which is a highly effective space radiator incorporating the capillary liquid flow principle used in the heat pipe to maintain a nearly uniform radiator surface temperature. A vapor chamber fin space radiator can achieve high effectivity, be lightweight, and have extremely good protection from the adverse effects of meteoroid penetration.

The high effectiveness results from the nearly uniform evaporating condensing temperature of the working fluid. Fin effectiveness, therefore, remains near unity regardless of the radiator configuration. Substantial weight reduction results from replacing the solid conducting fin material of the conventional radiator by a fin casing that forms a chamber. In turn, meteoroid protection of the radiator results from segmenting the chambers so that in the event of a failure of one chamber, surrounding chambers continue to function and redistribute the heat which was carried by the lost chamber. The more the radiator is segmented, the greater will be the reliability of the radiator. Design optimization is based upon operating fluid pressure, the degree of reliability and lifetime sought, and the configuration constraints of the integrated vehicle. Possible vapor chamber fin working fluids and radiator configurations suitable for use with tubular thermoelectric modules will be considered here.

Figure 1-23 presents the vapor pressure curves of some of the candidate working fluids suitable for use in vapor chamber fins. Although there are many other possible fluids, the ones shown have tabulated thermodynamic properties which readily permit comparison. As more property data are compiled, the list of candidate fluids will be increased. For the temperature range of 400°F to 600°F, promising vapor chamber fin working fluids are aluminum bromide, Dowtherm, mercury, and sulfur. In addition to favorable thermodynamic properties, two considerations must be made; these are the material compatibility of the working fluid and container, and vapor pressure limitations.

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Figure 1-23. Vapor Pressure Curves of Candidate Working Fluids Suitable for Use in Vapor Chamber Fins

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The slopes of the vapor pressure curves for fluids operating in this temperature range are quite steep when compared with the liquid metals (see Figure 1-23). In view of the previous discussion of vapor velocity and boiling limitations incurred by the working fluid, optimized vapor chamber fin working fluids will be limited to a narrow band of operating temperatures surrounding the design temperature of the radiator. In addition, if an over-temperature of the radiator occurs, containment becomes a problem as a result of the steep vapor pressure rise for a relatively small temperature increase.

The preliminary study of vapor chamber fins which are suitable as space radiators has suggested that a substantial weight reduction can be achieved by using the vapor chamber fin in place of a conventional conducting fin. At present, a study of suitable working fluids for radiating temperatures of 400 to 600°F has been initiated.

D. SUMMARY

Significant progress has been made on the module performance improvement program which is aimed at development of tubular modules with approximately 70 percent improved performance above that obtained from current modules. The degree of success of each of the design improvements is determined by analysis of test data from proof test modules.

Analysis of heatup data from TEM-9T S/N-1, a module containing thinner mica insulating washers (0.0015 inch versus 0.005 inch in the reference TEM-9I module), has been completed. Test data for this module indicate a slightly greater than anticipated reduction in shunt heat losses through the mica. As a result, this module had the highest beginning-of-life circuit efficiency of any module at standard operating conditions.

Evaluation of temperature data from TEM-9S S/N-1 indicated a reduction by nearly 50 percent in end closure heat losses. Excellent agreement was achieved between preliminary design calculations and final calculations using experimental temperature profiles from this module.

A new series of modules, TEM-10, was designed to provide a marked advance in tubular module technology. The new modules have an ID of approximately 1 inch and an OD of approximately 2-1/2 inches. This will be a high efficiency module design which is suitable for heat pipe application to supply module heating.

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Compaction test data from two modules with slightly modified low heat loss end closures were used to size Alsimag parts for the end closure of the TEM-10 module. Excellent agreement between calculated diametral reduction during processing was achieved for TEM-10 S/N-1 which is presently being prepared for test.

One heat pipe was tested for 1600 hours with 2300 watts heat transport. During this time, no significant change occurred in the axial temperature profile or power output. The test established the long-term performance capabilities of the Westinghouse-built heat pipe and provides support for the methods used in designing and fabricating heat pipe/thermoelectric systems.

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II. MATERIALS AND PROCESS DEVELOPMENT

The objectives of the Materials and Process Development effort in Phase II-B are to achieve an understanding of the materials and processes used during the fabrication of modules, to investigate new materials, and develop new processes as required for the solution of module fabrication problems to assure confidence in the behavior of modules fabricated for qualification in later phases of the program. The principal materials effort is directed toward the determination of the degradation model of the thermoelectric circuit materials.

During this period experimental work was devoted to evaluating the compatibility of various contact materials with lead telluride. This materials work was conducted using EXC capsules, high temperature die experiments, TEM experimental materials modules, and the necessary analytical tools.

Data obtained on TEM experimental materials modules show significant performance stability has been achieved over prior conventional modules.

A. MATERIALS DEVELOPMENT

P-Type Lead Telluride

Previous reports discussed the identification of iron contacts as detrimental to p-type lead telluride.* The results and conclusions discussed in this report resulted in the fabrication of a module which incorporated molybdenum as an alternate contact and four modules which utilized a tungsten diffusion barrier.

TEM-9AC S/N-1 has been on test at $\bar{T}_H = 538^\circ\text{C}$ and $\bar{T}_C = 200^\circ\text{C}$ for 2514 hours. The operating characteristics of this module are shown in Figure 2-1. This module shows considerable improvement and stability when compared with standard modules which use iron electrical contacts. However, on an absolute basis, there are still changes occurring in the electrical properties of this module. The reason for the changes may be due to the reaction zone that forms at the molybdenum/lead telluride interface. These changes will probably be accelerated in TEM-9ACS/N-2 which has recently been placed on test at 650°C (1200°F). It

* NYOO-3584-8, October 12, 1968.
NYOO-3584-9, January 12, 1968.

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Figure 2-1. Operating Characteristics of TEM-9AC S/N-1

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is tentatively concluded that although the use of molybdenum contacts is preferable to iron, the molybdenum is not the ideal passive contact for the achievement of absolute electrical stability.

Three modules were fabricated with tungsten as a diffusion barrier to prevent iron from contacting the p-type lead telluride. These modules were placed on test with average hot side temperatures of 538°C, 593°C, and 650°C, corresponding to 1000°F, 1100°F, and 1200°F, respectively. The operating characteristics of these modules are shown in Figures 2-2, 2-3, and 2-4. The electrical performance of these modules is quite similar in that the trends for open circuit voltage and internal resistance are all up and the rate of change increases with increasing temperature. The stability of TEM-9U S/N-1 shows a significant improvement over standard modules, and demonstrates the proof of principle that tungsten is a preferred electrical contact.

However, small but finite changes are observed for operation at 538°C and larger changes measured at elevated temperatures. The reason for the observed changes may be associated with the manner in which the foil diffusion barrier was positioned between the iron contact and the thermoelectric material. Both radial and axial gaps could have existed after assembly and, as a result, it was postulated that iron could diffuse through these gaps and contaminate the p-type lead telluride. However, because of the reduced contact area between the p-type lead telluride and the iron, the resulting changes were significantly reduced.

TEM-9U S/N-3 was removed from test after 980 hours for destructive examination to test the validity of the above conclusion regarding the cause of degradation. This module was chosen because the changes would be more pronounced and easier to detect than those in a module that had yielded fairly stable performance. It was also assumed that the three TEM-9U modules, since they were fabricated identically, would all be degrading by a common mechanism. Indeed, a plot of the log of resistance change with time versus $1/T$ produced a straight line whose slope was calculated as $\sim 40,000$ calories/mol, which may be considered an estimate of the activation energy for the processes occurring in these modules.

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Figure 2-2. Operating Parameters Versus Time for TEM-9U S/N-1,
Test Temperature = 538°C (1000°F)

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Figure 2-3. Operating Parameters Versus Time for TEM-9U S/N-2,
Test Temperature = 593°C (1100°F)

Figure 2-4. Operating Parameters Versus Time for TEM-9U S/N-3,
Test Temperatures = 650°C (1200°F)

The module was sectioned both parallel and perpendicular to the module axis. Figure 2-5 is a photomicrograph of a section normal to the module axis with the p-type washer exposed. This photograph clearly shows that the gap in the tungsten foil which existed at assembly was not closed up during subsequent processing. This 0.035-inch gap allowed the p-type lead telluride to contact the iron conductor ring. Further, this gap extended axially along the entire couple. Figure 2-6 shows an enlarged view of the area near the gap shown in Figure 2-5. A gray second phase, identified previously as Fe-Te, is observed at the interface region and in the lead telluride. This Fe-Te phase is not observed at any other points near the tungsten barrier but appears to be continued to an area which is illustrated schematically in Figure 2-7. It appears that the iron diffuses radially outward and then spreads circumferentially. It is anticipated that these iron diffusion problems will be resolved by the use of solid tungsten conductor rings which completely eliminate iron. These rings have been prepared and will be used in the fabrication of an additional TEM-9U series module.

TEM-9U S/N-4, another foil barrier module, has been fabricated so that the foil overlaps circumferentially. The module has been on test for 137 hours at 538°C without any changes in the electrical properties. It is not anticipated that this method will solve the problems associated with axial gaps but should show improved performance over modules that have a circumferential as well as axial gaps.

P-Type Lead-Tin Telluride

The lead-tin telluride has been found to be more electrically stable in contact with iron than the p-type lead telluride. Operation with iron produces an interface layer of Fe-Sn which gives the appearance that the thermoelectric material had been brazed to the iron. Destructive examination of capsules tested isothermally at temperatures as high as 750°C was performed and Seebeck probes show that the lead-tin telluride was not affected by the contacts. Microprobe measurements after high temperature operation at 750°C show large amounts of manganese present as a second phase.

The stability of this material despite reactions with contacts was demonstrated by compressing the PbSnTe in contact with Inconel X-750 for 2 hours at 750°C. Severe reactions

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50X

Figure 2-5. Photomicrograph Showing Circumferential Gap in Tungsten Foil Barrier. Radial Section from TEM-9U S/N-3. Tested for 980 Hours at $\bar{T}_H = 650^\circ\text{C}$ (1200°F).

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200X

Figure 2-6. Photomicrograph Showing Area Near Circumferential Gap in Tungsten Foil Barrier. Radial Section from TEM-9U S/N-3. Tested for 980 Hours at $\bar{T}_H = 650^\circ\text{C}$ (1200°F).

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Figure 2-7. Schematic Showing the Appearance of p-Type Washer from TEM-9U S/N-3. Tested for 980 Hours at $T_H = 650^\circ\text{C}$.

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in the form of second phases were noted after this test. The boundary region appeared to be composed of a thin layer (4-6 μ thick) of material, composed predominantly of tellurium and nickel with chromium and tin. A second barrier layer, about 18 μ thick, showed more tellurium than the first layer, as well as chromium, tin, nickel, and iron. An acicular-like second phase distributed through the lead-tin telluride near the junction region consisted primarily of nickel and tin with the occasional presence of chromium. Despite these by-products, the electrical properties of the lead-tin telluride were not affected in the junction region. It appears that the lead-tin telluride alloy contains sufficient material (tin and tellurium) which can be lost in reactions without changing the electrical properties.

The major objection to the use of PbSnTe for the p-type element in a thermoelectric module is that the power and efficiency are reduced from the level obtained by using lead telluride at the same temperature. The output power and efficiency for comparable modules and test conditions are shown in Table 2-1 for comparison.

TABLE 2-1
OUTPUT POWER AND EFFICIENCY FOR COMPARABLE MODULES

	Power Output (watts)	Efficiency Percent	$\bar{T}_H$ (°C)	$\bar{T}_C$ (°C)
PbTe	91.5	6.10	538	200
PbSnTe	79.5	5.67		
PbTe	111.5	6.69	593	200
PbSnTe	96.4	6.02		
PbTe	140.6	7.13	650	200
PbSnTe	119.1	6.56		

It is easily seen that the p-type lead telluride yields output powers that are about 16 percent higher than those produced by the use of PbSnTe as the p-type washer.

Four modules were fabricated with PbSnTe as the p-type washer in the thermoelectric couple and placed on test. These modules, TEM-9Q S/N-1, -2, -3, and -4, are being tested at average hot side temperatures of 538°C, 593°C, 621°C, and 650°C, respectively. Prior to testing at 650°C, TEM-9Q S/N-4 was on test for 1660 hours at 593°C. All modules are being tested with constant power output to the module heater. The operational parameters

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for these modules are plotted in Figures 2-8, 2-9, 2-10, and 2-11, which show the average hot-side temperature, internal circuit resistance, open circuit voltage, and electrical power output.

The internal resistance of TEM-9Q S/N-1 ($\bar{T}_H = 538^\circ\text{C}$) has remained very constant during the 6000 hours of testing. However, a 4 percent decrease in the open circuit voltage resulted in a decrease of the power output. The major portion of these changes occurred in the early stages of operation so that relatively stable operation has been achieved over the last 4000 test hours.

TEM-9Q S/N-2, on test at $\bar{T}_H = 593^\circ\text{C}$, while displaying small random fluctuations between data points, has demonstrated satisfactory performance. The power output at 6000 and 1100 hours was identical at 92.8 watts, down 3.7 percent from the power at time equals zero. TEM-9Q S/N-3, tested at $\bar{T}_H = 621^\circ\text{C}$, follows a trend similar to TEM-9Q S/N-1. The internal resistance is constant and the open circuit voltage has dropped. The net result is a reduction in power output of less than 4 percent in 3000 hours.

TEM-9Q S/N-4 was tested for 1650 hours at 538°C ; the temperature was then raised to 650°C . Prior to the test change, operation was comparable to that of TEM-9Q S/N-1. After the temperature increase, the hot-side temperature increased slightly at constant power input. As a result, the power output and efficiency increased.

One module containing all lead-tin telluride is on test to establish if there is an upper temperature limit at which this material can be operated in a tubular module without experiencing significant changes in the electrical properties. The initial hot side temperature of $\bar{T}_H = 650^\circ\text{C}$ was increased to $\bar{T}_H = 675^\circ\text{C}$ and presently to $\bar{T}_H = 700^\circ\text{C}$. The peak temperature at the present time is 750°C (1382°F). The internal resistance with time during the above test conditions is shown in Figure 2-12. Operation has been quite stable over the time tested and obviously the maximum operation temperature of the lead-tin telluride thermoelectric has not been reached.

The above results do not agree with the information presented by 3M representatives on the behavior of 3P material.* The manufacturer claims that a 25 percent decrease in

*"Lead Telluride Discussion Group Meeting Number One," Sandia Laboratories, April 25-26, 1967

Figure 2-8. Operating Parameters Versus Time for TEM-9Q S/N-1,
Test Temperature = 538°C (1000°F)

Figure 2-9. Operating Parameters Versus Time for TEM-9Q S/N-2,
Test Temperature = 593°C (1100°F)

Figure 2-10. Operating Parameters Versus Time for TEM-9Q S/N-3,
Test Temperature = 621°C (1150°F)

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Figure 2-11. Operating Parameters Versus Time for TEM-9Q S/N-4,
Test Temperature as Indicated

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Figure 2-12. Operating Parameters Versus Time for TEM-9X S/N-1,
Test Temperature as Indicated

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resistance, 10 percent decrease in voltage, and a 10 percent increase in power is observed in the first 300 hours of operation of TELPS non-bonded 3P elements. No information was given on any changes in thermal conductivity which would be expected to change as a result of the increased electronic contribution to the thermal conductivity. Obviously, the relevancy of these results to the present tubular testing is obscure at best. Certainly, WANL data indicate significantly less decrease in voltage and no decrease in resistance with operating time. These modules certainly offer better performance promise than previous modules using p-type lead telluride. However, a penalty in decreased initial power output and efficiency was exacted for the more stable performance. It should be borne in mind that the void-free, non-contaminating atmosphere of the tubular module permits the first evaluation of this material without the effect of extraneous factors. The choice of the operating atmosphere could be a significant factor in changing test results. The WANL test results demonstrate that lead-tin telluride can be operated satisfactorily at temperatures above the recommended 593°C (1100°F) limit. The attainment of successful results up to 750°C (1382°F) is attributed to the protected environment that the tubular module provides for the thermoelectric materials.

N-Type Lead Telluride

TEM-9M S/N-1, containing all GE n-type lead telluride, has been on test for 2738 hours at $\bar{T}_H = 702^\circ\text{C}$ after being tested at 595°C and 650°C for 1314 hours and 574 hours, respectively. The use of this n-type material, which does not contain excess lead as a second phase, effectively eliminates circuit to clad shorting problems which occur when free lead is present in the n-type lead telluride (see for example, TEM-9K S/N-1^{*}.) The circuit to clad resistance has remained stable at each operational level without any decrease in value. The module also shows stable performance with time at 702°C (Figure 2-13) which is a temperature considerably in excess of the usual maximum (593°C) at which lead telluride has been operated in conventional systems.

The feasibility of segmenting n-type lead telluride was investigated using capsule tests and washers. Seebeck probes were made along the axis of an EXC capsule containing

* NYOO-3584-9, Section II, January 12, 1968

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Figure 2-13. Operating Parameters Versus Time for TEM-9M S/N-1, Test Temperature as Indicated

alternate TEGS-2N and -3N pellets which had been tested for 1250 hours at 550°C. There was no apparent interaction between these materials, nor did there appear to be any tendency for the dopant to diffuse across the concentration gradient. Traces of the Seebeck coefficient across the interfaces showed sharp breaks with no smearing of values from one material to the next. Results obtained from fabricating and testing integral washers of TEGS-2N and -3N are discussed in the Process Development section of this report.

Mechanical testing of GE n-type material was conducted to aid in the mechanical design analysis of module reduction. Stress strain curves and Young's moduli were obtained during loading, unloading, and reloading over the temperature range of 23 to 750°C. The elastic modulus during unloading was increased substantially over the value obtained during the initial loading cycle. These results help to explain some of the anomalies which had arisen in predicting module reduction and subsequent behavior during the release of hydrostatic pressure after hot autoclaving.

Boron Nitride

Plots of circuit-to-clad resistance, R_c values versus temperature, show that the temperature dependency is not the same for all modules. At elevated temperatures R_c is limited by the resistivity of the inner BN sleeve. Because of the large increase in electrical resistivity of BN with decreasing temperature, the resistance of the outer BN sleeve is significantly greater than that of the inner BN sleeve during operation. Figure 2-14 shows the measured circuit-to-clad resistance values for various TEM-9 modules as well as the R_c value calculated for Carborundum data. While some modules follow the calculated curve quite well, others appear to trace out a different curve. While this latter curve shows lower values during heatup, short-term operation at high temperature (650°C) results in an increase in the R_c of the calculated curve. (Note that for TEM-9U S/N-3 the initial values of R_c increased from 1.8×10^4 ohms to 6×10^4 ohms.) In no case did the resistance decrease from the value at BOL. As a result of the above data, an investigation was begun to evaluate some of the BN in stock in regard to the electrical resistivity and any factors that would affect it.

The first measurements of electrical resistivity on boron nitride were performed on thin disks. The values obtained were significantly lower than values quoted by Carborundum.

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Figure 2-14. Circuit-to-Clad Resistance Values Versus Temperature
for TEM Modules

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Subsequent examination showed that the limiting resistance was probably in the measuring circuit and not in the boron nitride. A radial resistance technique was devised and implemented to evaluate whether this type of measurement would produce more reliable data and, at the same time, simulate more closely the conditions under which the boron nitride is used in the tubular module. Three concentric cylinders of Kovar, boron nitride, and stainless steel were assembled and the resulting resistance between the metal sleeves was measured in argon to a maximum temperature of 650°C. Figure 2-15 shows the calculated electrical resistivity of the boron nitride. The results are in good agreement with the anticipated values. Since as-fabricated ingots of boron nitride could vary in resistance, it is planned to measure a test sample from the master ingot before additional sleeves are machined for module use.

B. PROCESS DEVELOPMENT

Thermally Cascaded T/E Washer Development

A comprehensive topical report (WANL-TME-1767) was prepared covering the development and evaluation of cascaded TEGS-2N/TEGS-3N T/E washers for TEM module applications. This report includes some recent Seebeck probe measurements made on washers heat treated in argon at 500°C for up to 3000 hours, which indicate that some small changes may occur in the radial Seebeck coefficient (hence, dopant concentration) distribution.

Hydrogen Purge-Vacuum Degassing Cycle Studies

Relative moisture content measurements of purge cycle process hydrogen and of module internal atmosphere during vacuum degassing were made on TEM-9S S/N-4 and TEM-9U S/N-4. Analysis of the data has not yet been performed. Measurement system modifications are being planned to permit calculation of actual concentrations in preference to the relative measurements currently being made.

Module Degassing Tube Closure

After vacuum degassing a standard module, electron beam welding is used to seal the small degassing tube (3/16-inch OD, and 0.035-inch wall). In the past, during the EB welding, frequent excessive expulsion or flashing occurred and an occasional weld failure

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Figure 2-15. Electrical Resistivity of Boron Nitride Versus Temperature

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resulted. After a metallographic evaluation of these conditions it was concluded that if the tube could be more uniformly flattened prior to EB welding, predetermined optimum EB welding parameters could be established. After developing a procedure that resulted in a more uniformly flattened tube, an optimum EB welding cycle was achieved and satisfactory closure welds were made.

Additional experiments are now in progress to see whether or not inert-gas metal-arc welding or "cold-pinch-off" could be used as a substitute or alternate method for EB welding. Metallographic sectioning of samples after flattening show complete interface contact, and base metal yielding or slight end cracking at the interface extremities. All samples uniformly flattened and then subsequently "cold-pinch-off" failed to provide satisfactory hermetically sealed tubes.

Since repeated attempts by the "cold-pinch-off" method produced unsatisfactory results, the inert-gas metal-arc welding technique is now being pursued. Laboratory tests have been successful by following these steps:

- 1) Using a set of dies, the tube is preflattened longitudinally for approximately 1 inch.
- 2) Using a set of holding dies, a load is maintained transversely to the pre-flattened area.
- 3) The tube is welded by the inert-gas metal-arc process.

The criterion for a successful sealing of the tubes was that no backstreaming through the molten pool was permitted during the welding operation. This was measured by using a standard helium leak detector (mass spectrometer). Helium was used as the inert gas for welding, the open end of the tube was evacuated to less than 1×10^{-7} torr, and the leak detector was monitored during welding.

Reproducibility of this method has not yet been obtained. If the holding dies are not centrally aligned, the tube is accidentally sheared and the end of the tube is not successfully sealed. It is believed that with further development work, a reproducible method capable of successfully hermetically sealing degassing tubes by metal arc welding will be produced.

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C. SUMMARY

The use of tungsten foil as a barrier against iron diffusion has been applied to TEM modules which were tested over a range of temperatures, 538°C (1000°F) to 650°C (1200°F). Results indicate that the barrier results in modules whose electrical performance is far superior to those which use a conventional iron contact. Destructive examination of a module tested at $\bar{T}_H = 650^\circ\text{C}$ (1200°F) showed that the achievement of complete electrical stability was compromised by the lack of a complete mechanical separation of the iron and lead telluride. Iron diffused through a gap in the foil and resulted in contamination of the p-type lead telluride. This problem will be avoided in future experimental modules which use a solid tungsten conductor ring which eliminates the iron completely.

Modules of the series with lead-tin telluride in place of p-type lead telluride continue to show superior performance when compared to prior conventional modules. Stable output power has been achieved over 1600 hours at an average temperature of 650°C (1200°F) with a peak temperature of 695°C (1283°F). Data show that the lead-tin telluride can be operated in the protective, void-free environment of the tubular module at 695°C (1283°F) without the large changes experienced in other systems using this material at lower temperatures. These results are attributed to the lack of any contaminating atmosphere in the TEM module. Only the diffusion barrier or alternate electrical contact modules with their higher output power and efficiency offer more promise as high temperature modules.

Radial measurements of the electrical resistivity of BN sleeves have led to the recommendation that this technique be used for qualification of BN ingots prior to purchase.

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III. MODULE DEVELOPMENT

The objectives of the module development program are to provide a means of evaluating the combined results of the design, analysis, and materials and process development efforts through the study of modules subjected to pre-performance testing, destructive evaluation, and long-term life testing. During this quarter of Phase II-B eleven modules were completed, twenty-four modules were on test, and the fabrication and assembly of eight additional modules was in progress.

Continued tests of a variety of modules containing many thermoelectric circuit materials and utilizing various construction and fabrication processes have demonstrated their consistent and reproducible performance. All of the modules fabricated since mid-1966 have demonstrated that the module shorting problem encountered in earlier periods of the program has been solved. Excellent module performance at temperatures up to 1370°F (peak) has been obtained.

A. MODULE FABRICATION

The following items were accomplished during this Quarter.

- 1) Fabrication of TEM-9S S/N-3 (low thermal end loss and 0.050-inch wall 316 stainless steel outer clad design) was completed and fabrication of TEM-9S S/N-4 progressed through cold hydrostatic compaction at 50,000 psi.
- 2) Fabrication of TEM-9U S/N-4 and -5 (GE n-type PbTe + 3M TEGS-2P p-type PbTe + tungsten foil conductor contacts) was completed.
- 3) Fabrication of TEM-9AC S/N-2 (molybdenum hot side conductors) was completed.
- 4) A set of thermally cascaded TEGS-2N/TEGS-3N n-type PbTe washers with a nominal interface diameter of 0.99 inch was pressed, heat treated, evaluated, and released for TEM-9Z module use.
- 5) Tool and fixture design and fabrication and T/E washer fabrication development for the TEM-10 (large diameter) module series were completed. Fabrication of TEM-10 S/N-1 was completed, and fabrication of TEM-10 S/N-2 progressed through the hydrogen purge-vacuum degassing process.

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6) Gas-pressure-sintering cycles were run successfully in the WANL autoclave on the following modules:

TEM-9S S/N-3

TEM-9U S/N-4 and -5

TEM-9AC S/N-2

TEM-10 S/N-1

TEM-9Q S/N-5 and -6

TEM-9I S/N-5

All of these cycles were 650°C - 20,000 psi - 2 hour cycles. Temperature control and general cycle configuration were very satisfactory.

B. TEST RESULTS

Twenty-four modules were on test during this Quarter at hot clad temperatures ranging from 1000°F to 1380°F. Of this number, twelve were materials study modules: TEM-9X S/N-1 (all TEGS-3P material, non-power producing module), TEM-9M S/N-1 (all GE n-type non-power producing module), four TEM-9U series (tungsten foil barrier modules), two TEM-9AC series (molybdenum hot-side conductor ring modules), and four TEM-9Q series (single-piece TEGS-3P and -2N type washer modules). Results of these experiments are discussed in a separate section of this report, but efficiency data for all power producing modules are presented and discussed below.

Five new modules were placed on test during the past quarter. Heatup data for TEM-9U S/N-2, -3, and -4 are presented and discussed in Section I of this report. Heatup data from TEM-9T S/N-1 (thin mica insulating ring module for reducing shunt heat losses) are also discussed in detail in Section I. TEM-9AC S/N-2 (molybdenum hot-side conductor ring module) data were not available in time for inclusion in this report.

During the past quarter, the liquid metal loop was restarted with three modules (TEM-9C S/N-9, TEM-9E S/N-1, and TEM-9I S/N-1) previously tested in static test stands. The NaK temperatures of each leg of the loop have been adjusted so that each module is

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currently operating at the same average temperature level as before removal from static test. Data from the loop test modules were not available in time for inclusion in this report.

Table 3-1 presents the most recent data from all power modules on test.

Performance Data for TEM-1 S/N-1

The first TEM module built in the Compact Converter Program, TEM-1 S/N-1, is continuing in its third year of successful operation.

The circuit efficiency of this module, which has accumulated over 21,000 hours at life test conditions, is shown in Figure 3-1. Although many improvements have been incorporated in module design and processing since the fabrication of this module, TEM-1 S/N-1 continues to exhibit the long-term capabilities of the tubular thermoelectric module. This module has been and is currently being tested under matched load conditions.

Performance Data for TEM-9C S/N-2

Two TEM-9C series modules (with two-piece TEGS 3N-2N, 2P-2P lead telluride washers) were tested during this quarter. TEM-9C S/N-2, the first TEM-9 series model placed on life test, has accrued over 12,800 hours under open circuit test conditions with constant power input and constant cold clad temperature maintained.

A second two-piece washer module, TEM-9C S/N-9, was removed from static test after 8328 hours and has been placed in the liquid metal loop for further testing, along with two additional modules. Loop test data taken during this quarter have not yet been processed. Circuit efficiencies for TEM-9C modules on static test with constant power input are shown in Figure 3-2. Reproducibility of operation of TEM-9C series modules is discussed in a later section of this report.

Performance Data for TEM-9E and 9I Series Modules

Five TEM-9E and -9I non-barrier modules with single-piece (TEGS-2N and TEGS-2P) thermoelectric washers were on test during the past quarter. TEM-9I S/N-4 differs from the remaining four in that it was autoclaved three times for a compaction study. This module is discussed separately at the end of this section. The circuit efficiencies for the TEM-9E and

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TABLE 3-1

MODULE PERFORMANCE DATA

TEM Module	Test Method	Test Conditions	T_{OH} (°C)	T_C (°C)	Peak Temp (°C)	P_i (Watts)	V_{oc} (Volts)	V_L (Volts)	I_L (Amps)	R_g (Ohms)	R_c (Ohms)	P_o (Watts)	η (%)	Total Elapsed Time (Hours)
1 S/N-1*	Static	Constant T_H & T_C	540	196	564	1500	5.95	2.97	18.4	0.162	$R_c < 1\Omega$	54.8	3.96	21304.2
9AC S/N-1	Static	Constant P_i & T_C	536	197	567	1240	5.48	2.65	32.3	0.082	4.1×10^4	85.7	5.65	2635.5
9C S/N-2	Static	Constant P_i & T_C	562	199	581	1260	6.44	3.15	21.3	0.148	1.2×10^6	67.0	4.70	12858.6
9E S/N-2	Static	Constant P_i & T_C	567	198	583	1280	6.87	3.36	20.0	0.168	2.5×10^5	67.1	4.65	11726.9
9I S/N-2	Static	Constant P_i & T_C	549	199	572	1220	6.36	3.10	21.5	0.145	4.5×10^6	66.6	4.77	7384.7
9I S/N-4**	Static	Constant P_i & T_C	547	199	570	1220	6.18	3.01	22.98	0.131	3.5×10^6	71.2	4.91	2949.3
9N S/N-1**	Static	Constant P_i & T_C	650	200	671	1630	7.93	3.88	24.2	0.160	8.6×10^4	93.9	5.08	4179.9
9Q S/N-1	Static	Constant P_i & T_C	539	198	560	1160	5.03	2.45	30.6	0.080	3.1×10^6	74.8	5.42	6234.3
9Q S/N-2	Static	Constant P_i & T_C	596	199	614	1340	5.93	2.89	32.0	0.090	4.5×10^5	92.5	5.80	6238.7
9Q S/N-3	Static	Constant T_H & T_C	621	200	655	1400	6.42	3.12	33.4	0.094	3.9×10^5	104.2	6.20	3208.9
9Q S/N-4	Static	Constant P_i & T_C	655	200	702	1500	6.93	3.38	34.0	0.099	1.0×10^5	115.1	6.40	3504.4
9U S/N-1	Static	Constant P_i & T_C	540	198	588	1190	5.67	2.74	32.4	0.085	2.3×10^6	88.7	6.00	4032.1
9U S/N-2	Static	Constant P_i & T_C	590	198	640	1320	6.61	3.21	31.9	0.100	8.5×10^4	102.4	6.32	1889.4
9U S/N-4	Static	Constant P_i & T_C	539	198	574	1180	5.44	2.62	35.4	0.074	5.6×10^4	92.8	6.23	407.9
9Y S/N-1	Static	Constant P_i & T_C	634	199	682	1480	6.75	3.28	34.6	0.095	1.0×10^5	113.4	6.34	2971.9

* TEM-1 S/N-1 tested at matched load conditions with V_L and I_L measured. All other modules are tested under open circuit conditions with V_L and I_L calculated.

** Last point before module was removed from test.

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Figure 3-1. TEM-1 S/N-1: Circuit Efficiency Versus Time on Test

Figure 3-2. Circuit Efficiency of Two-Piece (TEGS 2N-3N, 2P-2P) Washer Modules

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-9I series are presented as functions of time at life test conditions in Figure 3-3. As in the TEM-9C series modules discussed above, the reproducibility of operation of these four modules with identical thermoelectric circuits is evident.

TEM-9E S/N-1 and TEM-9I S/N-1 were removed from static test in January and have been installed in the liquid metal loop along with TEM-9C S/N-9.

TEM-9I S/N-4, identical in construction to the other TEM-9I modules, was subjected to three autoclave cycles of successively increasing pressures (20,000, 25,000, and 30,000 psi, respectively). Because the autoclave cycles are performed at temperatures sufficiently high to cause reaction between the TEGS-2P lead telluride and iron conductor rings, TEM-9I S/N-4 incurred more pre-testing degradation than other modules. As a result, at the beginning-of-life testing the internal resistance of TEM-9I S/N-4 was about 5 milliohms higher than the average for the modules with the same electrical circuit (87 as compared to 82 milliohms). TEM-9I S/N-4 was removed from test after 2950 hours of successful operation.

Performance Data of Stoichiometric n-Type PbTe Module TEM-9N S/N-1

TEM-9N S/N-1 was the first power-producing module constructed incorporating GE stoichiometric n-type lead telluride. The GE n-type material is designed to eliminate lead migration through the boron nitride, which caused circuit-to-clad shorting in some early TEM modules subjected to high temperatures (1375°F) during the autoclave cycle.

Data presented and discussed in the last Quarterly Report^{*} showed performance of this module to be nearly identical to that of single-piece (TEGS-2N-2P) washer modules over the temperature range encountered during a normal heatup. After TEM-9N S/N-1 was on life test for 1263 hours at normal $\bar{T}_H = 1000^\circ\text{F}$ test conditions, a comparison of TEM-9N S/N-1 experimental parameters with those of TEM-9E and TEM-9I series modules showed performance to be unaffected by replacing TEGS-2N material with GE n-type material. At this time the average hot clad temperature of TEM-9N S/N-1 was raised to 1100°F to study high temperature capabilities of GE n-type material.

After accruing 1750 hours at $\bar{T}_H = 1100^\circ\text{F}$ with satisfactory performance (increased degradation rate but no signs of circuit-to-clad shorting), the average hot clad temperature

^{*}NYOO-3584-9, January 12, 1968, page 1-50

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Figure 3-3. Circuit Efficiency of Non-Barrier Single-Piece (TEGS 2N/2P) Washer Modules

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was again increased by 100°F to $\bar{T}_H = 1200^\circ\text{F}$ ($T_{\text{PEAK}} = 1290^\circ\text{F}$). Figure 3-4 presents efficiency data from TEM-9N S/N-1 at all three temperature levels. The module was removed from test after an unscheduled shutdown caused by a heater failure. TEM-9N S/N-1 was on test at open circuit conditions for a total time of 4180 hours, the last 1325 of which were at $\bar{T}_H = 1200^\circ\text{F}$.

A material study module, TEM-9M S/N-1, constructed with all GE n-type material, was tested for 1314 hours at $\bar{T}_H = 1000^\circ\text{F}$ and 574 hours at $\bar{T}_H = 1100^\circ\text{F}$. After successfully operating an additional 2738 hours at $\bar{T}_H = 1300^\circ\text{F}$ ($T_{\text{PEAK}} = 1335^\circ\text{F}$) with no signs of degradation or development of circuit-to-clad shorts, a heater failure caused an unscheduled shutdown. TEM-9M S/N-1 is being fitted with a new heater and will be replaced on test at $\bar{T}_H = 1300^\circ\text{F}$. Data from this non-power producing materials experiment module are discussed in detail in Section II of this report.

Performance of TEGS-3P Material Modules

The first approach studied for eliminating the diffusion reaction between TEGS-2P material and iron conductor rings employed the use of TEGS-3P material. Six modules fabricated with the latter material were tested at average hot clad temperatures ranging from 811°K (1000°F) to 976°K (1250°F). Peak temperatures up to 1340°F were encountered.

A plan has been initiated for testing modules containing TEGS-3P material at elevated temperatures to determine the limit of high temperature capability of this material in a tubular module environment. This plan uses TEM-9X S/N-1, an all TEGS-3P material non-power producing module, as a lead module to be tested at successively higher temperature for at least 2 weeks prior to raising any power module to that temperature.

TEM-9Q S/N-1, the first module of this series, has accrued 6100 hours at $\bar{T}_H = 811^\circ\text{K}$ (1000°F). TEM-9Q S/N-2 has been on test for the same amount of time at $\bar{T}_H = 867^\circ\text{K}$ (1100°F). Efficiency data from these modules are presented in Figure 3-5. Although there is some reduction in efficiency with time, both of these modules exhibit much reduced performance degradation over that of the TEM-9I series modules.

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Figure 3-4. TEM-9N S/N-1: Circuit Efficiency Versus Time on Test

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Figure 3-5. TEM-9Q S/N-1, -2, and -3: Circuit Efficiency Versus Time on Test

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In addition to the above mentioned modules, the circuit efficiency of TEM-9Q S/N-3, tested at $\bar{T}_H = 893^\circ\text{K}$ (1150°F), is presented in Figure 3-5. Although this module has been on test for only 3070 hours, the amount of degradation at this elevated temperature is much lower than that of non-barrier TEGS-2P material modules tested at 811°K (1000°F).

Two additional TEGS-3P material power modules, TEM-9Q S/N-4 and TEM-9Y S/N-1, were tested during this Quarter. Both of these modules were raised in temperature, causing step increases in circuit efficiency. Plots of circuit efficiency versus time on test are presented in Figure 3-6. The time at which each of the modules was raised in temperature is indicated in the figure.

TEM-9Q S/N-4 was initially tested for 1633 hours at $\bar{T}_H = 867^\circ\text{K}$ (1100°F) before being raised in temperature to 922°K (1200°F). At the higher temperature, the module has been tested for over 1700 hours at an efficiency level of 6.4 percent with negligible decrease in circuit-to-clad resistance.

The remaining TEGS-3P material module, TEM-9X S/N-1, is a non-power producing materials experiment module. This module was operated initially for 524 hours at $\bar{T}_H = 1200^\circ\text{F}$, and then for 1200 hours at 1250°F ($T_{\text{PEAK}} = 1340^\circ\text{F}$), with no significant decrease in circuit-to-clad resistance and a barely perceptible drop in internal resistance from the initial level of 84.5 to 82.6 milliohms. On the basis of this successful operation at $\bar{T}_H = 1250^\circ\text{F}$, the average hot clad temperature of TEM-9X S/N-1 was raised to 1300°F ($T_{\text{PEAK}} = 1382^\circ\text{F}$), where it has accrued 525 hours. The circuit-to-clad resistance and internal resistance have remained constant at 9000 ohms and 85.8 milliohms, respectively, since the module was taken to 1300°F . These data give no indication of circuit deterioration as a result of extremely high temperature operation. Data from this non-power producing materials experiment module are discussed in detail in Section II of this report.

Barrier Study Modules

Three methods of eliminating the diffusion reaction between TEGS-2P lead telluride and iron conductor rings are being tested. The first method eliminated the TEGS-2P material altogether by replacing it with TEGS-3P material. Experimental data from modules constructed

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Figure 3-6. Circuit Efficiency of High Temperature TEGS-3P Material Modules

with TEGS-3P material (TEM-9Q and -9Y series modules discussed above) indicate that the rate of degradation has been reduced by an order of magnitude.

The major drawback with the TEGS-3P material is that its figure-of-merit is lower than that of TEGS-2P material throughout the temperature range in which TEM modules are designed to operate. Therefore, a major effort during this phase of the program has been directed toward developing a method of eliminating module degradation without removing TEGS-2P material, through the use of barriers or alternate conductor ring materials.

The experimental capsule program uncovered two alternate conductor materials, tungsten and molybdenum, which are more compatible (less reactive) with lead telluride than iron. As a result, modules were constructed and are being tested to verify the findings of the experimental capsule program. These modules are referred to as "barrier study modules."

Performance Data of TEM-9U Series, Barrier Study Modules

TEM-9U S/N-1 is a single-piece (TEGS 2N-2P) washer module identical in every respect to TEM-9I series modules except for a 0.001 inch tungsten barrier placed between the lead telluride washer and the iron conductor ring at each module hot junction. This tungsten foil was designed as a diffusion barrier to combat the iron/TEGS-2P lead telluride reaction isolated in Phase II-B as the chief cause of module degradation.

The significant difference between the operation of TEM-9U S/N-1 and other single-piece (TEGS-2N/2P) washer modules is that the TEM-9U module evidenced no reduction in efficiency during the first 500 hours of operation, the time period in which other modules containing TEGS-2P material degrade most rapidly. Although there has been some measurable degradation in TEM-9U S/N-1 after 500 hours of operation brought about by a slight increase with time of internal resistance (discussed in Section II of this report), this module is by far the most stable operating module ever tested in the program. A more complete discussion of module parameters of TEM-9U S/N-1 is presented in Section II.

The operation of TEM-9U S/N-1 at normal operating conditions, $\bar{T}_H = 1000^\circ\text{F}$ and $\bar{T}_C = 392^\circ\text{F}$, prompted the fabrication and testing of additional TEM-9U series modules to study tungsten foil effectiveness at higher temperatures. The first two additional TEM-9U

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series modules, S/N-2 and S/N-3, on test for 1750 hours at $\bar{T}_H = 1100^\circ\text{F}$ and 979 hours at $\bar{T}_H = 1200^\circ\text{F}$, respectively, have indicated that degradation (increase of internal resistance with time) of the tungsten foil barrier modules is dependent on average hot clad temperatures. TEM-9U S/N-3 was removed from test in January for destructive examination, the results of which are discussed in Section II. Heat losses through the end closure regions of these modules being tested at high temperature have not yet been evaluated and circuit efficiencies, which are functions of end closure heat losses, are not presented in this report. The initial circuit efficiency level for TEM-9U S/N-1, at 6.10 percent, was at the top of the band of data formed by all TEM-9E and -9I series modules at the beginning-of-life test.

Heatup data from TEM-9U S/N-1, S/N-2, and S/N-3, presented in Section I of this report, revealed that the performance of the tungsten foil modules during heatup was nearly identical to that of all other single-piece (TEGS 2N-2P) washer modules except for a slight (2 milliohm) reduction in internal resistance. This reduction was attributed to the elimination of the hot conductor ring/lead telluride reaction during autoclaving.

Fabrication of TEM-9U S/N-4 was identical to that of the first three TEM-9U series modules except for the addition of tungsten foil barriers incorporated at the cold junction of the former. Also, the inner foil liners were designed to permit an overlapping to eliminate the gaps at the ends of the foil, through which iron diffused quite extensively. As a result, TEM-9U S/N-4 exhibited a beginning-of-life internal resistance 5 milliohms lower than the TEM-9U series modules with only hot junction tungsten barriers. After 262 hours of operation, TEM-9U S/N-4 has exhibited no measurable degradation. Degradation in TEM-9U S/N-1 was also unmeasurable after the same number of hours on test.

Figure 3-7 presents the efficiency data from TEM-9U S/N-1 and S/N-4, along with that of the first two TEM-9I series modules as a comparison. Also included in the figure are data from another type of barrier module, TEM-9AC S/N-1, explained below.

Performance Data of Molybdenum Barrier Module TEM-9AC S/N-1

The second barrier module constructed and placed on test was TEM-9AC S/N-1, a single-piece (TEGS 2N-2P) washer module identical to TEM-9I series modules with the exception that the hot iron conductor ring was replaced with molybdenum. As in the case of

TEM-9U S/N-1, discussed above, heatup data from TEM-9AC were identical to the data for other single-piece washer modules with the exception of a 2.0 milliohm reduction in internal resistance.

Efficiency data of TEM-9AC S/N-1, on test for 2635 hours at $\bar{T}_H = 1000^\circ\text{F}$ and $\bar{T}_C = 392^\circ\text{F}$, shown in Figure 3-7, reveals completely stable operation at a level somewhat lower than that of TEM-9U S/N-1, the other barrier module. However, aside from TEM-9U S/N-1, no other module tested at standard operating conditions exhibited as high an efficiency as TEM-9AC S/N-1 at the end of 500 hours of testing.

Recently, an additional TEM-9AC series module identical to TEM-9AC S/N-1 was placed on test. Heatup data were not available in time for inclusion in this report. This module is being tested at $\bar{T}_H = 1200^\circ\text{F}$ to determine the high temperature capability of molybdenum conductor ring modules.

Reproducibility

One of the major objectives of the Compact Converter Program during Phase II-B is to establish the reproducibility of operation of similarly constructed thermoelectric modules. The good reproducibility obtained with modules of similar design is evident from a direct comparison of module data.

Table 3-2 compares various operating parameters after 500, 3500, and 6000 hours on test (0, 3000, and 5500 hours after the 500-hour seasoning period) for various TEM-9 series power modules. The comparison is made for all similarly constructed modules, presented in two groups, being tested at the standard hot clad temperature level, $\bar{T}_H = 1000^\circ\text{F}$. Data from TEM-9C S/N-6, tested in the liquid metal loop, is presented first as-taken and then again as-corrected to the average temperature level of the other TEM-9C series modules. The nearly complete performance reproducibility exhibited by all TEM-9C series two-piece (TEGS 2N-3N, 2P-2P) washer modules on static test (i.e., TEM-9C S/N-2, -3, -4, and -9) is indicated clearly in Table 3-2. The circuit efficiencies of these modules vary by less than 4 percent when compared at the same test time.

Figure 3-7. A Comparison of Circuit Efficiency of Barrier Modules With That of Non-Barrier Modules

TABLE 3-2

OPERATING PARAMETERS OF TEM-9C, TEM-9I, AND TEM-9E SERIES MODULES

Two-Piece (2N-3N, 2P-2P) Washer Modules	Elapsed Time After 500-Hour Seasoning Period								
	0 Hours			3000 Hours			5500 Hours		
	V _{oc} , ML	R _g	η	V _{oc} , ML	R _g	η	V _{oc} , ML	R _g	
TEM-9C S/N-2	5.46	0.099	5.07	5.94	0.121	5.01	6.08	0.131	4.87
TEM-9C S/N-3	5.42	0.100	5.05	5.78	0.117	4.97	5.95	0.133	4.70
TEM-9C S/N-4	5.46	0.097	5.17	5.86	0.116	4.99	5.94	0.123	4.87
TEM-9C S/N-6	5.28	0.096	5.22	5.54	0.124	4.71		**	
TEM-9C S/N-6*	5.26	0.096	5.17	5.75	0.124	4.83		**	
TEM-9C S/N-9	5.50	0.101	5.06	5.98	0.121	5.02	6.12	0.130	4.92
Single-Piece (2N-2P) Washer Modules									
TEM-9E S/N-1	5.93	0.113	5.20	6.28	0.137	5.02	6.44	0.149	4.89
TEM-9E S/N-2	6.08	0.120	5.13	6.48	0.141	5.15	6.60	0.150	4.94
TEM-9I S/N-1	5.73	0.105	5.30	6.13	0.132	4.99	6.25	0.142	4.87
TEM-9I S/N-2	5.66	0.105	5.28	6.09	0.130	5.02	6.15	0.139	4.83

*Temperature level of TEM-9C S/N-6 corrected to average level of other TEM-9 series modules

**Insufficient number of hours on test

To further accentuate operation reproducibility, Figures 3-8, 3-9, and 3-10 present an up-to-date set of experimental parameters for all TEM-9C series modules on static test plotted as functions of time on test. Figure 3-2, discussed previously, exhibited the reproducibility of efficiency data from TEM-9C series modules.

Figure 3-8 presents internal resistance data for the TEM-9C series of statically tested modules and shows that the rapid initial increase of resistance with time is common to all modules. It is this phenomenon which causes the initial degradation of modules. In contrast, however, barrier module internal resistance has remained virtually constant.

Figures 3-9 and 3-10 present open circuit voltage and thermal impedance data, respectively, from all TEM-9C series modules on static test. Both of these parameters exhibit the reproducibility of operation of TEM modules.

Plots of similar data for barrier modules (TEM-9U S/N-1 and TEM-9AC S/N-1) show, within experimental accuracy (i. e., ± 3 percent), no variations in any of the above parameters.

Also shown in Table 3-2 are the operating parameters of the four single-piece (TEGS 2N/2P) washer modules (TEM-9E and TEM-9I series) compared at the same three time periods as for the TEM-9C modules during their testing. As in the case of the complete TEM-9C series, the performance of these four modules is identical within experimental accuracy. The single-piece Inconel 718 inner clad used in the TEM-9I series, as expected, had no effect on module performance. TEM-9N S/N-1, identical to TEM-9I series modules except for the use of GE n-type material in the n-leg, also points out the similarity of GE n-type and TEGS-2N type materials.

Plots of experimental parameters of single-piece (TEGS 2N-2P) washer modules, which are not presented here, exhibit the same extent of operation reproducibility for these modules as shown for two-piece washer modules.

C. SUMMARY

Twenty-four modules were on test during this quarter. Three of these modules, tested in conjunction with the liquid metal loop system recently restarted, had previously been tested in static test stands and will allow a direct comparison of module performance during liquid metal loop operation and operation in static test stands.

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Figure 3-8. Internal Resistance of Two-Piece (TEGS 2N-3N, 2P-2P) Washer Modules

Figure 3-9. Open Circuit Voltage of Two-Piece (TEGS 2N-3N, 2P-2P) Washer Modules

Figure 3-10. Thermal Impedance of Two-Piece (TEGS 2N-3N, 2P-2P) Washer Modules

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TEM-1 S/N-1 has accumulated over 21,000 hours of successful operation under matched load conditions. All modules on test at $\bar{T}_H = 1000^\circ\text{F}$ and reported in previous Quarterly Progress Reports continue to behave without deviation from prior trends of behavior. The reproducibility of operation exhibited by all modules with identical thermoelectric circuits has continued through this Quarter.

Data from TEM-9U series and TEM-9AC series barrier modules have continued to exhibit the effectiveness of two methods for operating modules employing TEGS-2P material with markedly reduced degradation at $\bar{T}_H = 1000^\circ\text{F}$. Although the degradation rate of the barrier modules has been found to be temperature dependent, this rate is greatly reduced over that of non-barrier modules operating at $\bar{T}_H = 1000^\circ\text{F}$.

High temperature data from modules employing TEGS-3P material indicate that within experimental accuracy there is no increase in degradation rate as hot clad temperatures are increased. These data include peak temperatures as high as 1370°F .

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IV. EQUIPMENT AND FACILITIES

The objectives of this task are to provide the equipment and facilities required to meet the needs of the Compact Thermoelectric Converter Program. Effort during Phase II-B has been concentrated on expanding the module testing capability, procuring additional equipment for processing modules and module components, procuring special equipment for the determination of thermoelectric materials properties, and planning equipment needs for the remainder of Phase II-B and the subsequent phases of the program.

A. FACILITIES

The Westinghouse autoclave facility is considered to be completed and fully capable of meeting the present requirements of the module fabrication program. Three cycles have been operated successfully, with eight modules and some experimental capsules, at 650°C/20,000 psi. Excellent temperature distribution has been achieved, as indicated by TEM-10 S/N-1 which had a range of 2°C over the thermoelectric length as measured by thermocouples welded directly to the outer clad surface. There will be no further reporting on this facility.

The modification and expansion of the Thermoelectric Laboratory has progressed slowly during this period, but the basic utilities rearrangement has been completed so that movement of the materials evaluation section can begin early in the next Quarter. This vacated space will then enable the construction of new module static test stands to begin. The Laboratory currently has nineteen static test stands and three liquid metal loop test positions in operation. The expansion will add twenty-one new static test stands, thus providing test facilities for forty-three modules.

B. SPECIAL EQUIPMENT

The status of the equipment releases initiated in June 1967 is as follows:

- 1) The thermal conductivity apparatus will be installed in April, following the completion of the above-mentioned laboratory rearrangement.
- 2) The chemical vapor deposition apparatus remains unchanged, awaiting delivery of the vacuum chamber which is now expected in April and which will enable completion of the apparatus at that time.

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3) The powder press load cells have been received.

The status of the equipment releases initiated for the Mod. 6 revision to AT(30-1)-3584 is as follows:

1) The details of the Hewlett Packard data acquisition system modification were not resolved completely until the end of this period. The final quotation, based on these details, is expected shortly so that a procurement recommendation can be made in April 1968.

2) The bulk of the miscellaneous hardware required for the new module test stands has been ordered and many components have been received. A procurement recommendation for three major components (for each of the thirteen stands to be built) has been transmitted to Sandia for approval, includes the thermocouple reference junctions, the main heater power supply and control, and the temperature recorder and limiter.

3) The electron microprobe procurement recommendation has been transmitted to Sandia for approval.

4) The materials characterization equipment has been delayed pending decisions on the correct course of action for equipping the Materials Laboratory. Quotations are currently being obtained for the principal items, including the inert processing chamber, the vacuum storage chamber, the hydrogen furnace, and the rocking furnace.

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APPENDIX A
NOMENCLATURE

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NOMENCLATURE

α	Seebeck Coefficient
BOL	"Beginning-of-Life" in reference to the first data point taken at life test conditions
$^{\circ}\text{C}$	Degrees Centigrade
η	Circuit Efficiency, defined as $\frac{100 P_e}{Q_{ML}}$ (in percent)
η_T	Overall Efficiency, defined as $100 P_e / (Q_H + 2Q_G)$ (in percent)
η_c	Carnot Efficiency, defined as $100 (1 - \frac{\bar{T}_C}{\bar{T}_H})$ (in percent); temp. in $^{\circ}\text{K}$
η_d	Device Efficiency, defined as $\frac{100 \eta}{\eta_c}$ (in percent)
$^{\circ}\text{F}$	Degrees Fahrenheit
HEP	High Efficiency Prototype: a code selected by WANL to identify one of the thermoelectric module designs which was designed and tested by WANL prior to beginning the Compact Thermoelectric Converter Program.
ID	Inside Diameter
OD	Outside Diameter
$^{\circ}\text{K}$	Degrees Kelvin
k	Thermal Conductivity, watts/cm/ $^{\circ}\text{K}$
k_n	Thermal Conductivity of n-type Thermoelectric Material, watts/cm/ $^{\circ}\text{K}$
k_p	Thermal Conductivity of p-type Thermoelectric Material, watts/cm/ $^{\circ}\text{K}$
P_e	Electrical Power Output, watts
P_o	Electric Power Output, corrected for constant clad temperature tests

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NOMENCLATURE (CONTINUED)

Q_G	Guard Heater Power (watts)
Q_H	Main Heater Power (watts)
Q_E	Power Loss to End Closure (watts)
Q_T	Power Throughput to Module Thermoelectric Circuit ($Q_T = Q_H - Q_E$) (watts)
Q_{ML}	Power Throughput to Module Thermoelectric Circuit Required at Matched Load (watts)
ρ	Electrical Resistivity, ohms-cm
ρ_n	Electrical Resistivity of the n-type Thermoelectric Material, ohms-cm
ρ_p	Electrical Resistivity of the p-type Thermoelectric Material, ohms-cm
ρ_{intf}	Electrical Interface Contact Resistivity between the Thermoelectric Material and the Electrical Conductor, ohms-cm ²
TEGS-2P	3M Company Code Name for Sodium Doped Lead-Telluride
TEGS-3P	3M Company Code Name for Lead-Tin-Telluride Containing Manganese and Sodium
TEGS-2N	3M Company Code Name for Lead Iodide Doped Lead-Telluride
TEGS-3N	3M Company Code Name for Lead-Telluride with a Higher Lead Iodide Dopant Concentration than Used in the 2N Material
n-Type	Designation given to a material with an excess of negative charge carriers (electrons)
p-Type	Designation given to a material with an excess of positive charge carriers (holes)
R	Radius (in)
R_c	Resistance Measured from Electrical Circuit-to-Clad (ohms)

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NOMENCLATURE (CONTINUED)

R_i	Inside Radius (in)
R_o	Outside Radius (in)
$^{\circ}R$	Degrees Rankine
R_g	Internal Resistance of a Module (ohms)
R_L	Load Resistance Applied to Module (ohms)
T	Temperature
$\bar{T}$	Average Temperature defined as $\frac{T_H + T_C}{2}$
$\bar{T}_C$	Mean Cold Side Temperature
$\bar{T}_H$	Mean Hot Side Temperature
$\Delta\bar{T}$	Mean Hot Side to Cold Side Radial Temperature Drop Across Module
ΔT_H	Axial Temperature Drop on the Hot Side of the Module
ΔT_C	Axial Temperature Drop on the Cold Side of the Module
T/E	Thermoelectric
TEM	Thermoelectric Module: a code selected by WANL to identify all tubular modules to be fabricated under the Compact Thermoelectric Converter Program
V_{oc}	Open-Circuit Voltage (volts)
V_L	Voltage Mesured at Module Terminals with Load Resistor R_L Applied (volts)
V_{ML}	Voltage Measured at Module Terminals with Load Resistance $R_L = R_G$ (Matched Load) Applied (volts)
$V_{oc, ML}$	Open Circuit Voltage at Matched Load Heat Throughput Conditions $V_{oc, ML} = 2 V_{ML}$
I_L	Current Drawn Through Load Resistor R_L

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APPENDIX B

SUMMARY OF MODULE DESIGN DEVELOPMENT

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APPENDIX B

SUMMARY OF MODULE DESIGN DEVELOPMENT

TEM Series	Series Number	Design Features	Processing Conditions	Program Objectives	Status and/or Results
1	1, 2, 4	2-piece washers of standard n- and p-type PbTe, Inconel X-750 inner clad	Rotary swage, GPS at 750°C/10,000 psi with bore open	Demonstrate state-of-the-art of modules in Phase I, using parts remaining from another program.	Testing initiated in Phase I continuing into Phase II-B. S/N-1 continuing at 21302 hours, S/N-2 terminated after 10,000 hours for destructive examination, S/N-4 terminated at 5735 hours for destructive examination.
2*	1, 2	Same as TEM-1	Rotary swage, GPS at 750°C/10,000 psi with bore plugged	Investigate influence of plugged bore during hot autoclave processing (TEM-1 modules processed with bores open to hot autoclave pressure).	Non-destructive examination indicated no measurable effect. Modules removed from program.
3*	1, 2, 3, 4	Same as TEM-1	Same as TEM-1	Investigate effect of hydrogen heat treatment of PbTe powder prior to washer fabrication.	S/N-1 tested for 2100 hours, then sent to JPL for test system development and module evaluation. After 2400 test hours at JPL, module returned to WNL, 1600 additional test hours accumulated. Module held in bond room for program developments. S/N-2, -3, -4 destructively examined in Phase I to evaluate effects of processing.
4*	1	Same as TEM-1	40,000 psi, room temperature hydraulic compaction followed by rotary swage, GPS at 650°C/7500 psi with bore open	Evaluate compaction and performance of modules processed as noted.	Dimensional, electrical, and performance characteristics verified lack of full compaction, indicating that substantially higher pressures would be required for modules hot autoclaved at 650°C. Module destructively examined after short test period to evaluate initial performance.
4A	1, 2	Same as TEM-1 except ends slightly redesigned to reduce stiffness.	45,000 psi, hydraulic compaction, GPS at 750°C/7500 psi with bore open	Evaluate effects of more flexible end design and eliminate swaging on BN cracking and module performance.	S/N-1 was removed from test at 8581 hours to create test stand availability for a new module design. S/N-2 was destructively examined after processing.
5	1	Essentially a TEM-1 thermo-electric circuit with module ends completely redesigned to reduce stiffness, and several seal experiments incorporated between the circuit and inner clad.	45,000 psi, hydraulic compaction, GPS at 750°C/10,000 psi with bore open	Module experiment designed to evaluate the effectiveness of seals for retarding lead movement. Evaluate more flexible ends with new electrical conductor rings.	Destructive examination used to select design features in TEM-6, -7, and -8 modules.
6	1, 2	Essentially a TEM-4A module with ends slightly redesigned to reduce stiffness and a metal barrier to prevent circuit-to-clad shorting inserted between dual inner BN insulating sleeves.	45,000 psi, hydraulic compaction, GPS at 750°C/10,000 psi with bore open	Module experiment designed to evaluate more flexible ends, effectiveness of metal barrier in preventing system shorts and performance loss due to extra interface.	Tooling problems caused metal barrier to be ineffective; however, initial performance was established. Barrier used as basis for TEM-7 and -8 designs.
7	1, 2	Redesigned TEM-5 type design except TEM-6 metal barrier used in place of sealing experiments.	50,000 psi, hydraulic compaction, GPS at 750°C/10,000 psi with bore open	Module experiment designed for further evaluation of flexible end design with new style electrical end conductor rings.	S/N-1 was removed from test at 8321 hours to create test stand availability for a new module design. S/N-2 was performance tested for 382 hours after which the module was destructively examined.
7A	1	Same as TEM-7 modules without the metal barrier inserted between the inner BN insulating sleeves.	Same as TEM-7	Initial experiment using dual inner sleeves of BN to minimize shorting through lead-filled cracks.	Non-destructive examination indicated no improvement in resistance-to-cladding. Module removed from program.

*From another program

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APPENDIX B (Continued)

TEM Series	Serial Number	Design Features	Processing Conditions	Program Objectives	Status and/or Results
8*	1, 2	Essentially a TEM-6 design	50,000 psi, hydraulic compaction, GPS at 650°C/15,000 psi followed by GPS at 750°C/10,000 psi with bore open	Initial experiment to achieve modules suitable for life testing without evidence of system shorting.	Dimensional and electrical conditions indicated lack of full compaction after being autoclaved at 650°C. Accordingly, the TEM-8 modules were reautoclaved at 750°C. S/N-1 performance testing terminated at 2470 hours and the module was used for successful shock and vibration testing. Module being held in bond room for possible further use. S/N-2 was performance tested for 982 hours on a static test stand after which it was inserted into a NaK loop for additional testing. After having accumulated 8,588 hours of loop testing, and successfully withstanding severe thermal cycling tests, the module testing was terminated. The module is in storage.
8A*	1, 2	TEM-8 modules, without the metal barrier inserted between the inner BN insulating sleeves.	45,000 psi, hydraulic compaction, GPS at 650°C/15,000 psi with bore open	Initial experiment to achieve modules suitable for life testing without evidence of shorting by autoclaving at reduced temperature	Although dimensional and electrical measurements indicated lack of full compaction, the operational characteristics of such modules were not well defined. Accordingly, both modules were placed on test. S/N-1 removed from test at 4190 hours and destructively examined. S/N-2 removed from test and delivered to JPL for test and evaluation.
TEM-9 series. Sets of modules essentially identical in design to investigate the effects of materials and processing changes on dimensional and performance characteristics. The baseline module within the TEM-9 series is the TEM-9C.					
9	1, 2, 3	Same as TEM-9C	50,000 psi hydraulic compaction, processed at 750°C/10,000 psi with bore open	Demonstrate that the TEM-9C design, processed at 750°C/10,000 psi, will exhibit same dimensional and shorting characteristics as prior designs similarly processed	Destructive examination showed reduced BN cracking but some massive lead penetration of BN experienced in previous module experiments.
9A	1	Same as TEM-9C except one-piece washers all of 2P material	50,000 psi hydraulic compaction, GPS at 750°C/10,000 psi with bore open	Confirmation that p-type material does not cause shorting even when processed at 750°C. Investigation of performance characteristics of module with p-type material	Materials experiment module was tested at $T_H = 1000^\circ\text{F}$ for 5538 hours for evaluation of p-type material performance. Module is being stored in bond room.
9A	2	Same as TEM-9C except one-piece washers all of 2P material	50,000 psi hydraulic compaction, GPS at 650°C/20,000 psi with bore plugged	Investigate performance characteristics of a module with 2P material processed same as TEM-9C	Materials experiment module was tested 1600 hours at $T_H = 1000^\circ\text{F}$ followed by 2088 hours at $T_H = 1100^\circ\text{F}$. The module testing was terminated by 200 hours testing at $T_H = 1200^\circ\text{F}$.
9B	1, 2	Same as TEM-9C except n-type washers have reduced lead content.	Same as TEM-9C	Investigate performance and shorting characteristics of modules made with reduced lead content material processed to "preferred" cycle parameters.	Destructive examination of S/N-1 revealed NaK penetration into module through a cladding defect. S/N-2 held in bond room.
9B	3, 4	Same as TEM-9C except n-type washers have reduced lead content	Same as TEM-9C except GPS at 650°C/15,000 psi, S/N-3 bore open, S/N-4 bore plugged	Investigate reduced lead content material processed at 15,000 psi to determine if acceptable modules could be achieved, thereby relieving dependency on the single high-pressure autoclave at BNL	Processing completed; held in bond room for Phase II-b program.
9C	1, 2	Essentially a TEM-1 module incorporating the more flexible ends developed in TEM-8, increased thickness of BN insulating sleeves, and processed under the preferred conditions developed in Phase II-A.	50,000 psi hydraulic compaction, GPS at 650°C/20,000 psi, bore open	Baseline for comparison of modules in TEM-9 series and for evaluation of performance improvements due to the preferred process developed in Phase II-A, since thermoelectric circuits are essentially the same in all TEM modules.	S/N-1 destructively examined. S/N-2 open circuit life test continuing after 12860 hours.

* From another program

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APPENDIX B (Continued)

TEM Series	Serial Number	Design Features	Processing Conditions	Program Objectives	Status and/or Results
9C	3, 4	Same as above	50,000 psi hydraulic compaction; GPS at 650°C/15,000 psi; S/N-3 bore open; S/N-4 bore plugged	Same as 9B S/N-3 and -4.	S/N-3 and S/N-4 tests have been terminated at 5,807 hours and 6,237 hours respectively to provide testing space for more recently fabricated modules.
9C	5, 6, 8, 9, 10	Same as 9C S/N-1, -2	50,000 psi hydraulic compaction; GPS at 650°C/20,000 psi bore plugged	Some objectives as TEM-9C S/N-1 and -2 except these and all subsequent modules have bores plugged during GPS cycles.	TEM-9C S/N-6 testing was terminated after 6,212 hours of testing, which included three severe thermal shocks which did not change performance. TEM-9C S/N-9 on static test for 8328 hours, presently on test in liquid metal loop system.
9C	7	Same as above	50,000 psi, hydraulic compaction only, no GPS	Investigate performance characteristics of a module known to be less than fully compacted	Performance test of this module, which was not gas-pressure-sintered, was terminated at 1,484 hours. The module is being held in the bond room for program developments.
9D	1, 2	Same as TEM-9C except one-piece 2N and 2P washers	Same as TEM-9C S/N-5	Investigate processing and performance characteristics of modules made with one-piece PbTe washers.	S/N-1 was destructively examined after processing. S/N-2 was subjected to elevated isothermal testing for evaluation of materials properties.
9E	1, 2	Same as TEM-9C except one-piece 2N and 2P washers of reduced lead content	Same as TEM-9C S/N-5	Same as TEM-9D	TEM-9E S/N-1, on static test for 8103 hours, presently on test in liquid metal loop system. S/N-2 test continuing at 11730 hours.
9F	1, 2	Same as TEM-9C except outer clad thickness reduced to 0.051 inch from 0.147 inch.	Same as TEM-9C except S/N-1 first GPS at 650°C 15,000 psi prior to standard GPS 650°C/20,000 psi	Evaluate difference in compaction behavior of S/N-1 as a result of two GPS cycles; compare S/N-1 and S/N-2 after 20,000 psi cycle; compare thin clad compaction against standard clad compaction.	After 20,000 psi GPS both modules showed similar compaction. S/N-1 showed significant additional compaction between 15,000 and 20,000 psi GPS cycles. Thin clad equivalent to 3,000 psi additional pressure relative to standard thickness clad. S/N-1 testing was terminated after 3,452 hours at a performance level indicating that reduced operating interface pressures do not adversely affect initial module operation.
9I	1, 2, 3, 4, 5	Same as TEM-9C except one-piece 2N and 2P washers and Inconel 718 inner clad.	Same as TEM-9C S/N-5 except S/N-3, -4 were GPS successively at 650°C/20,000 psi and 30,000 psi.	Investigate processing and performance characteristics of modules having Inconel 718 inner clad.	TEM-9I S/N-1 on static test for 6034 hours, is presently on test in liquid metal loop system. S/N-2 test continuing at 7385. S/N-4 removed from static test after 2950 hours.
9K	1	Same as TEM-9C except one-piece washers of all 2N material	Same as TEM-9C S/N-5	Investigate performance characteristics of a module with 2N material processed same as TEM-9C.	Materials experiment module tested at $T_H = 1000^\circ\text{F}$ for 2,272 hours, following which the average hot side temperature, T_{HT} , was raised to 1100°F for evaluation of n-type material performance in the higher temperature environment. After 2,416 hours of very stable operation at 1100°F, the temperature was again raised to 1200°F. Total testing time was 5,624 hours after which the module was destructively examined.
9L	1, 2	Same as TEM-9I except 0.147-inch S S outer clad replaced with 0.020-inch thick Inconel 718 outer clad.	Same as TEM-9I	Evaluate compaction of module with thin Inconel 718 outer clad; provide elastic behavior of outer clad; minimize effect of additional compaction due to long-term operation; improve overtemperature behavior of cladding; minimize end heat loss.	TEM-9L S/N-1 is being prepared for static testing. TEM-9L S/N-2 was tested for 2,100 hours during which time it was subjected to thermal cycling tests. The module was destructively examined.

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APPENDIX B (Continued)

TEM Series	Series Number	Design Features	Processing Conditions	Program Objectives	Status and/or Results
9M	1	Same as TEM-9I except all washers are GE n-type material	Same as TEM-9I	Materials experiment to evaluate the properties of GE n-type material	Tested for 1314 hours at $T_H = 1100^\circ\text{F}$, 572 hours at $T_H = 1200^\circ\text{F}$ and 2738 hours at $T_H = 1300^\circ\text{F}$. No increase of internal resistance due to module degradation or signs of circuit-to-clad shorting noted at any of above temperature levels.
9N	1	Same as TEM-9I except n-type washers of GE material (2P washers of 3M material)	Same as TEM-9I	Evaluate GE n-type material effect on module performance.	Tested for 1263 hours at $T_H = 1000^\circ\text{F}$. Operation of module identical to that of TEM-9I series. Tested for 1589 hours at $T_H = 1100^\circ\text{F}$ and 1325 hours at $T_H = 1200^\circ\text{F}$. No circuit-to-clad shorting problems encountered and module was removed from test.
9Q	1, 2, 3, 4, 5, 6	Same as TEM-9I except 3P material used in place of 2P material	Same as TEM-9I	Determine effect of 3P material on module degradation. Study high temperature capability of TEGS-3P material.	S/N-1 heated to 1000°F and S/N-2 to 1100°F . After 3,900 hours of operation, degradation of both modules is greatly reduced. S/N-3 and S/N-4 have accrued 3069 and 3358 hours at hot clad temperature levels up to $T_H = 1200^\circ\text{F}$. Module degradation is not adversely affected by increasing temperature.
9S	1, 2, 3, 4	Same as TEM-9I except thin outer clad of Inconel 718 and redesigned end structure.	Same as TEM-9C S/N-5	Reduce end heat loss	S/N-1 tested at $T_H = 1000^\circ\text{F}$. Data revealed a 50% reduction in end closure heat losses. S/N-3 being prepared for test and S/N-4 being processed.
9T	1	Same as TEM-9I except 1.5 mil mica washers used replacing 5-mil washers.	Same as TEM-9C S/N-5	Reduce mica shunt heat loss.	Highest efficiency for any module previously tested at $T_H = 1000^\circ\text{F}$. Tested for 812 hours at $T_H = 1200^\circ\text{F}$ and removed for destructive examination of mica washers.
9U	1	Same as TEM-9I except thin foil of tungsten barrier material inserted between 2P washer and inner iron conductor ring	Same as TEM-9C S/N-5	Reduce 2P washers - iron conductor ring interaction, thus reducing degradation.	Module is on static test and has 3936 hours accumulated at $T_H = 1000^\circ\text{F}$. Module degradation reduced by an order of magnitude over non-barrier (TEM-9I) modules.
9U	2, 3, 4, 5, 6, 7, 8	Same as TEM-9U S/N-1 except n-leg washers of GE n-type material	Same as TEM-9C S/N-5	Determine effectiveness of tungsten foil barrier for high temperature operation.	S/N-2 has accumulated 1749 hours at $T_H = 1100^\circ\text{F}$. S/N-3 removed from test for destructive examination after 978 hours at $T_H = 1200^\circ\text{F}$. S/N-4 and -5 being tested at $T_H = 1000^\circ\text{F}$. S/N-6, -7, -8 being fabricated.
9X	1	Same as TEM-9Q except all 3P material washers used.	Same as TEM-9C S/N-5	Examine heat transfer and electrical resistance properties in a module of all 3P material.	Module has been placed on static test and test is continuing at 150 hours.

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APPENDIX B (Continued)

TEM Series	Serial Number	Design Features	Processing Conditions	Program Objectives	Status and/or Results
9Y	1	Same as TEM-9Q except n-leg washers have reduced lead content, and inner clad thickness reduced to 0.049 inch from 0.075 inch.	Same as TEM-9C S/N-5	Obtain performance and clad creep and relaxation data at various temperatures.	Tested for 1051 hours at $T_H = 1000^\circ\text{F}$ with performance nearly identical to that of 9Q S N-1. Has accumulated 1319 hours at $T_H = 1250^\circ\text{F}$. No signs of performance degradation.
9Z	1	Same as TEM-9U except n-leg cascaded optionally with 2N and 3N material.	Same as TEM-9C S/N-5	Obtain improved high temperature performance over a non-cascaded 9U-type module.	Released for fabrication
9AC	1, 2	Same as TEM-9I except molybdenum hot side	Same as TEM-9C S/N-5	Study degradation in a module using molybdenum hot side	S N-1 has accumulated 2636 hours at $T_H = 1000^\circ\text{F}$ with degradation reduced by an order of magnitude over non-barrier (TEM-9I) modules. S N-2 on test for 120 hours at $T_H = 1200^\circ\text{F}$.

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