WANL-TME-1438
July 15, 1966

Westinghouse Astronuclear Laboratory

DESIGN ANALYSIS OF JPL TUBULAR THERMOELECTRIC MODULE (909E686G01)

Contract CU-388002

Westinghouse Astronuclear Laboratory
P.O. Box 10864
Pittsburgh, Pa. 15236

WANL-TME-1438
July 15, 1966

Westinghouse Astronuclear Laboratory

DESIGN ANALYSIS OF JPL TUBULAR THERMOELECTRIC MODULE (909E686G01)

Contract CU-388002

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration under Contract NAS7-100.

Westinghouse Astronuclear Laboratory
P.O. Box 10864
Pittsburgh, Pa. 15236

TABLE OF CONTENTS

Section No.	Title	Page No.
I.	INTRODUCTION	1-1
II.	MODULE DESIGN	2-1
	A. Concept	2-1
	B. Description	2-3
III.	MODULE ANALYSIS	3-1
	A. Structural Analysis	3-1
	1. Stress Analysis	3-2
	2. Volumetric Analysis	3-2
	B. Thermoelectric and Thermal Analysis	3-5
	1. Thermoelectric Analysis	3-7
	2. Thermal Analysis	3-10
IV.	MODULE ASSEMBLY AND PROCESSING	4-1
	A. Thermoelectric Couple Assembly	4-1
	B. Module Assembly	4-1
	C. Degassing	4-3
	D. Cold Hydrostatic Compaction	4-4
	E. Gas Pressure Sintering	4-4
V.	WEIGHT TABULATION	5-1
VI.	RECOMMENDED OPERATION	6-1
	A. Start-up	6-1
	B. Shutdown	6-1
	C. Matched Load Operation	6-1
	D. Open Circuit Operation	6-2
	E. Nominal Operating Conditions	6-2
VII.	SHOCK AND VIBRATION CAPABILITY	7-1
VIII.	REFERENCES	8-1

LIST OF ILLUSTRATIONS

Figure No.	Title	Page No.
1	JPL Thermoelectric Module	2-4
2	JPL Module Installation	2-5
3a	JPL Test Assembly	2-6
3b	JPL Test Assembly	2-7
4	Radial Interface Pressure Tubular Module Operating Temperature, $T_H = 1025^oF$, $T_C = 395^oF$	3-3
5	Module Temperature Distribution (Determined from CPBTE-2 Code)	3-9
6	Module Temperature and Heat Flow Pattern	3-10
7	Compaction Data Summary	4-5
8	Shock Test of Tubular Thermoelectric Module	7-1

LIST OF TABLES

Table No.	Title	Page No.
1	Module Dimensions After Processing	2-8
2	Results of Volumetric Analysis	3-5
3	Module Materials	3-5
4	Matched Load Performance Predictions	3-8
5	Calculated Module Interface Temperature	3-8
6	Weight Tabulation	5-1
7	Table of Limits	6-4

I. INTRODUCTION

This report, submitted in partial fulfillment of the contractural commitments specified in contract CU-388002, presents a design description and analysis of the Jet Propulsion Laboratory (JPL) tubular thermoelectric module.

Development work on the tubular thermoelectric module concept is being performed by the Westinghouse Astronuclear Laboratory under Atomic Energy Commission contract AT-(30-1)-3584. The tubular thermoelectric module designed and manufactured for JPL is a "state-of-the-art" device in the sense that it is the same basic module as that being developed under the AEC program.

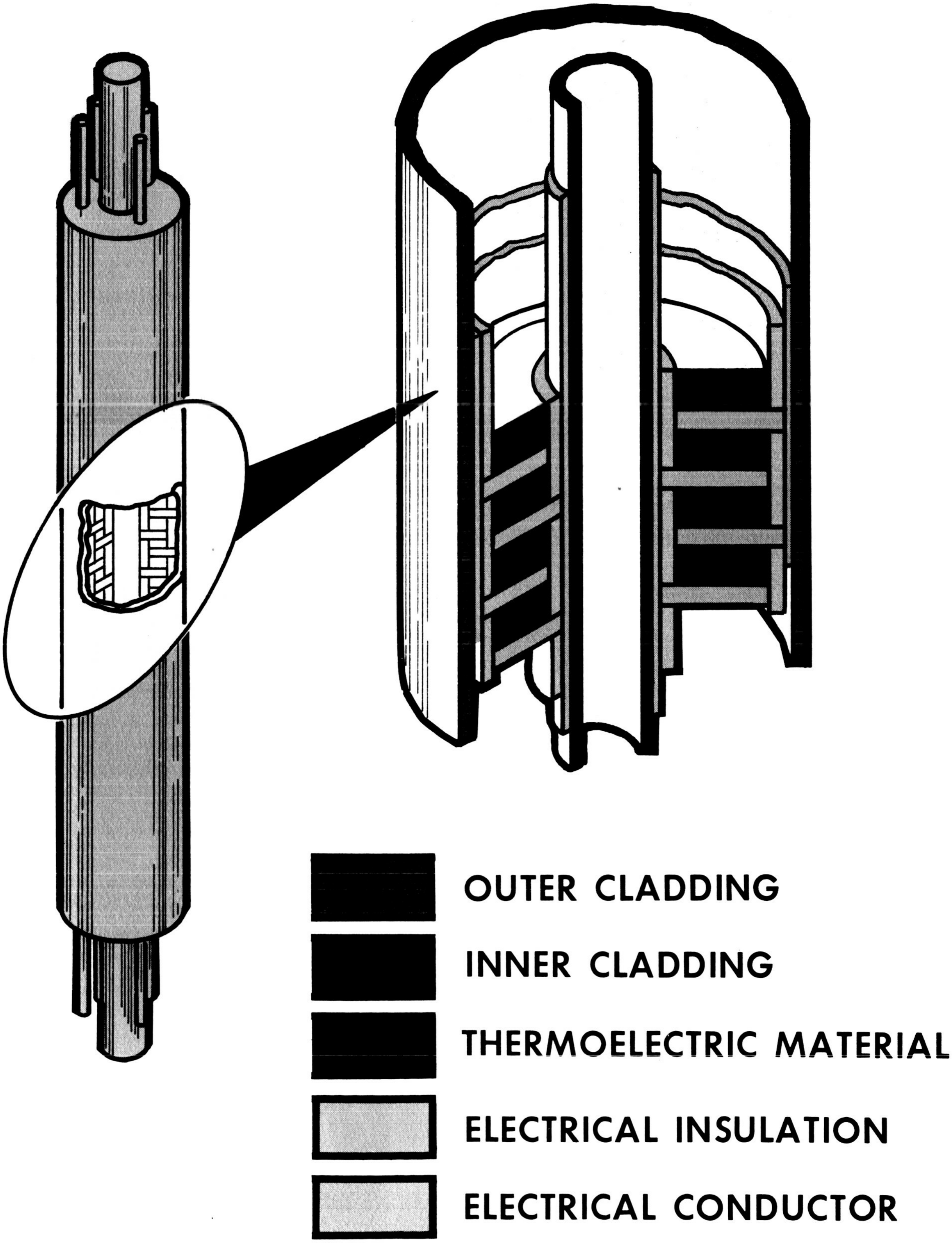
II. MODULE DESIGN

A. CONCEPT

The representation of the tubular module shown on the next page is well adapted for use in a two-loop liquid metal system. The inner cladding forms the flow channel and heat transfer surface for hot fluid, and the outer cladding forms a channel boundary and heat transfer surface for cold fluid. The thermoelectric material is lead telluride doped with sodium or lead iodide for p- and n-material, respectively, and pressed into washers. The washers are stacked alternately, p- and n-, with thin mica washers providing electrical insulation between them. The hot and cold junctions between adjacent washers are provided by rings of Armco iron which span two adjacent rings. Armco iron was selected because of its good electrical conductance and its compatibility with lead telluride. The configuration which results provides a serpentine electrical path through the module. Iron pins connected to the iron rings at each end of the thermoelectric stack project through the end retainers to complete the electrical path.

The thermoelectric stack is electrically isolated radially from the structural cladding by thin sleeves of boron nitride and axially from the end retainers by washers of Alsimag 222 and boron nitride. The boron nitride was selected because of its good electrical insulation properties (combined with a thermal conductivity close to that of stainless steel) to minimize the thermal impedance of the device. The Alsimag 222 was selected because its high thermal impedance reduces heat loss through the ends of the module.

The structural components of the module include the 316 stainless steel outer clad, which was chosen because of its relatively high strength at operation temperature, its low strength at sintering temperature, and its high coefficient of thermal expansion. The inner clad of Inconel X-750 was chosen because of its high short-time strength and its good creep and relaxation properties at operating temperatures. The end retainers, which are made of 304 stainless steel, serve to provide axial restraint to the thermoelectric stack to prevent axial


OUTER CLADDING
INNER CLADDING
THERMOELECTRIC MATERIAL
ELECTRICAL INSULATION
ELECTRICAL CONDUCTOR

DESIGN

displacement of thermoelectric components under high radial interface pressures. The retainers are welded to the inner and outer clad to provide gas tight seals at those joints.

The tubular thermoelectric module possesses a number of general characteristics which are worthy of note.

1. The total encapsulation and void-free nature of the design permits lead telluride thermoelectric material (with its high figure of merit) to be utilized at sufficiently high temperatures to provide an inherently high performance design.
2. The high interface pressure which can be generated by an axially symmetric tubular design insures good electrical and thermal conductance between internal parts without the need for metallurgical bonds and with minimal problems from differential thermal expansion.
3. The device is inherently rugged structurally and has already proven capable of withstanding high shock and vibration loads.
4. The tubular design lends itself to compact arrangements since it is capable of operating at high heat fluxes and has continuous heat transfer surfaces.
5. The device has low thermal losses since the heat source is essentially surrounded by thermoelectric material.
6. The unit possesses flexibility in design. For example, a given thermoelectric module can be utilized in many arrangements and the module length itself can be increased or decreased without any major effect on design.

B. DESCRIPTION

The JPL module defined in Figures 1, 2 and 3 has 40 thermoelectric couples. The detailed dimensions of the thermoelectric stack after processing are given in Table 1. Each couple is formed by a pair of n- and p-type lead-telluride thermoelectric washers which are separated by thin mica insulating rings. The couple is pre-assembled by positioning an iron conductor ring around the O.D. of the thermoelectric washers and the smaller of the two sizes of mica

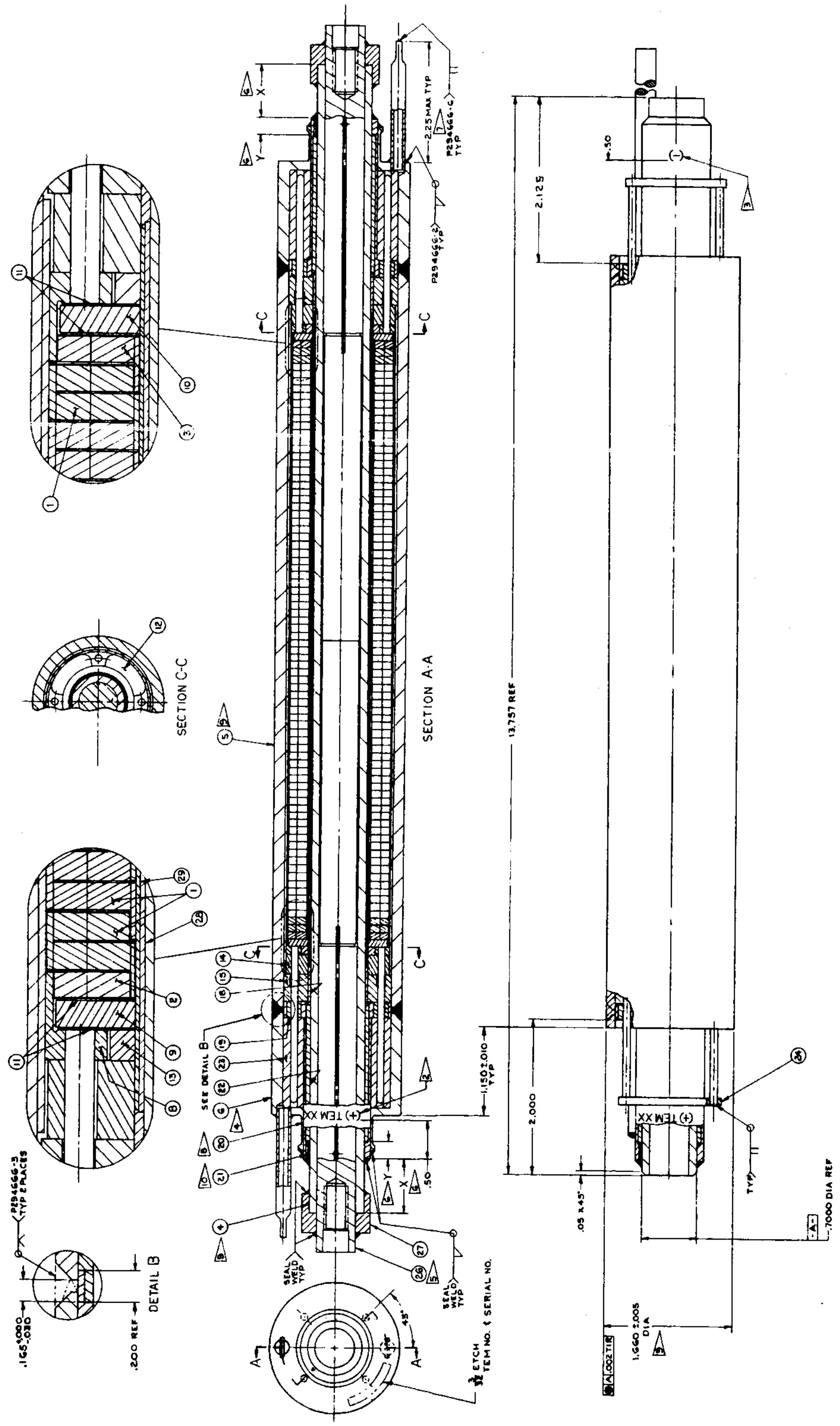


Figure 1. JPL Thermoelectric Module

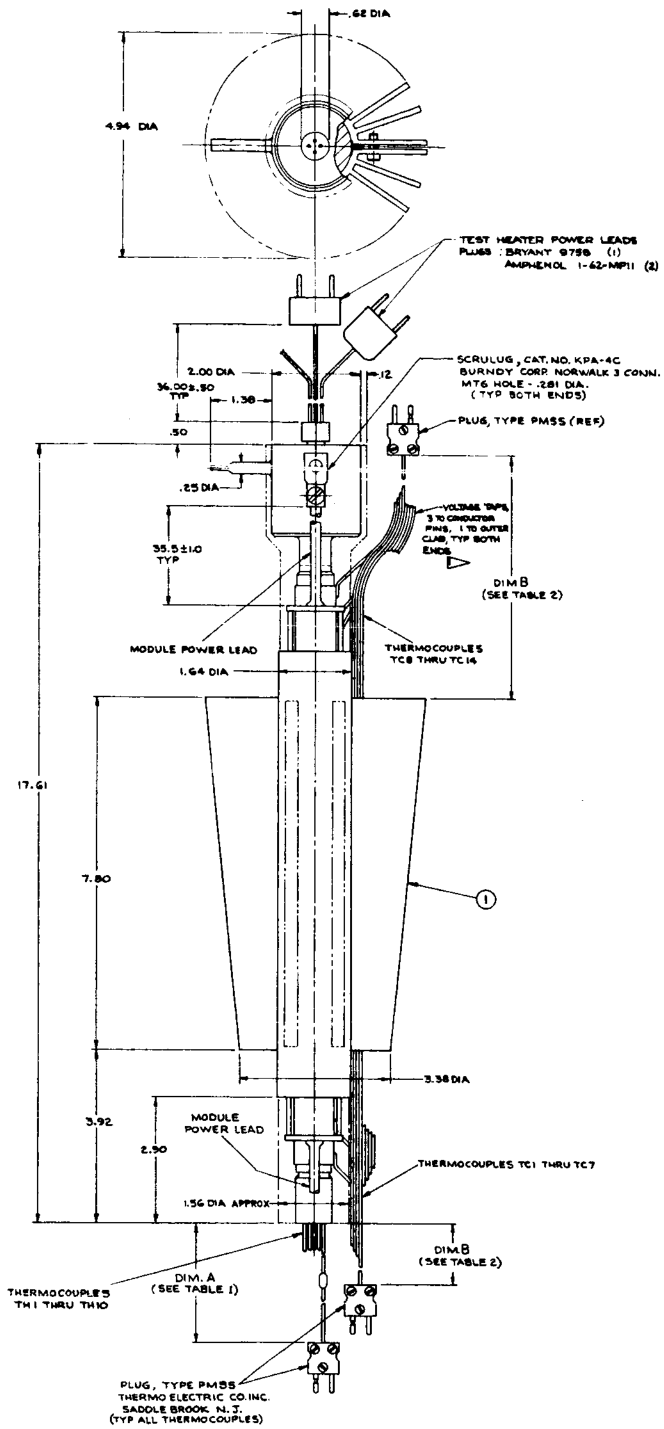


Figure 2. JPL Module Installation

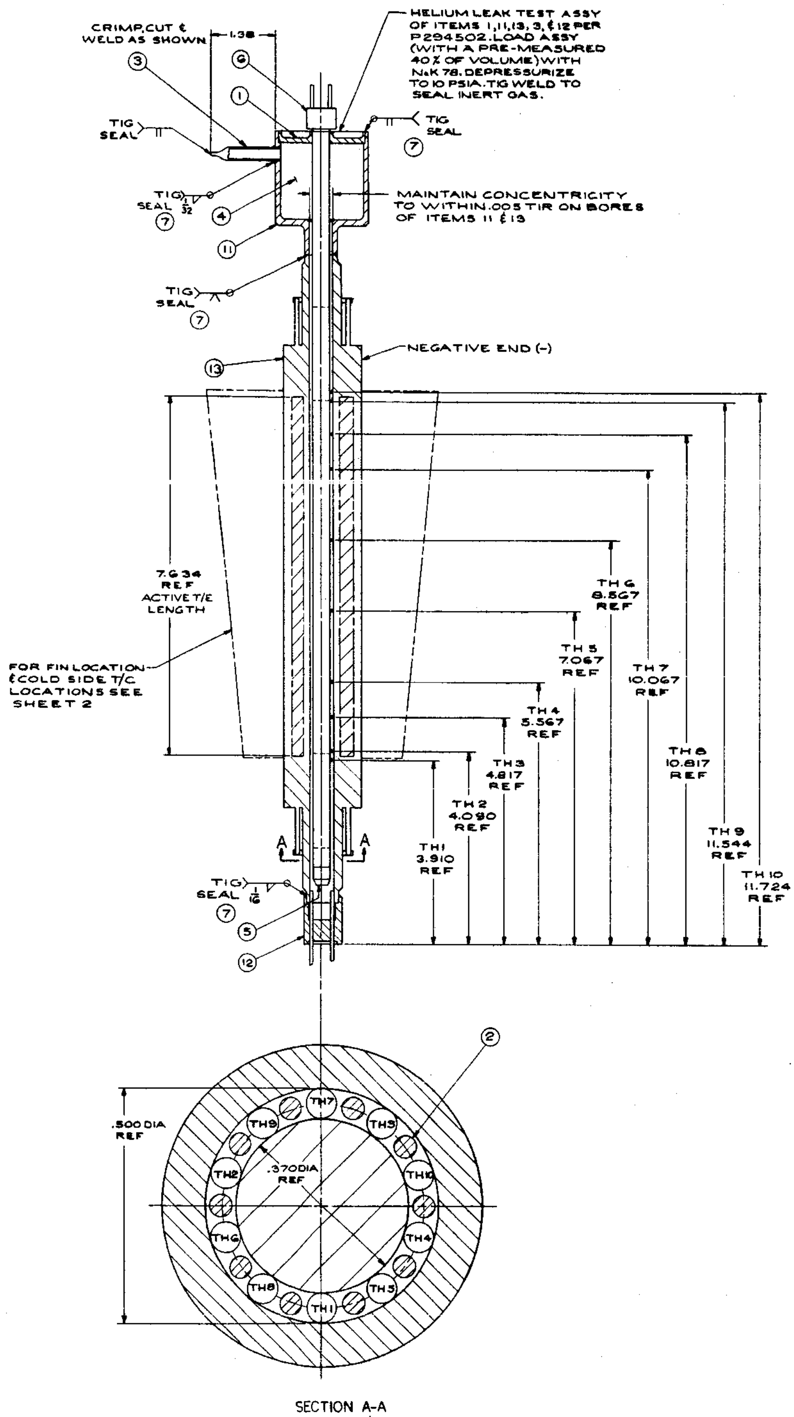


Figure 3a. JPL Test Assembly

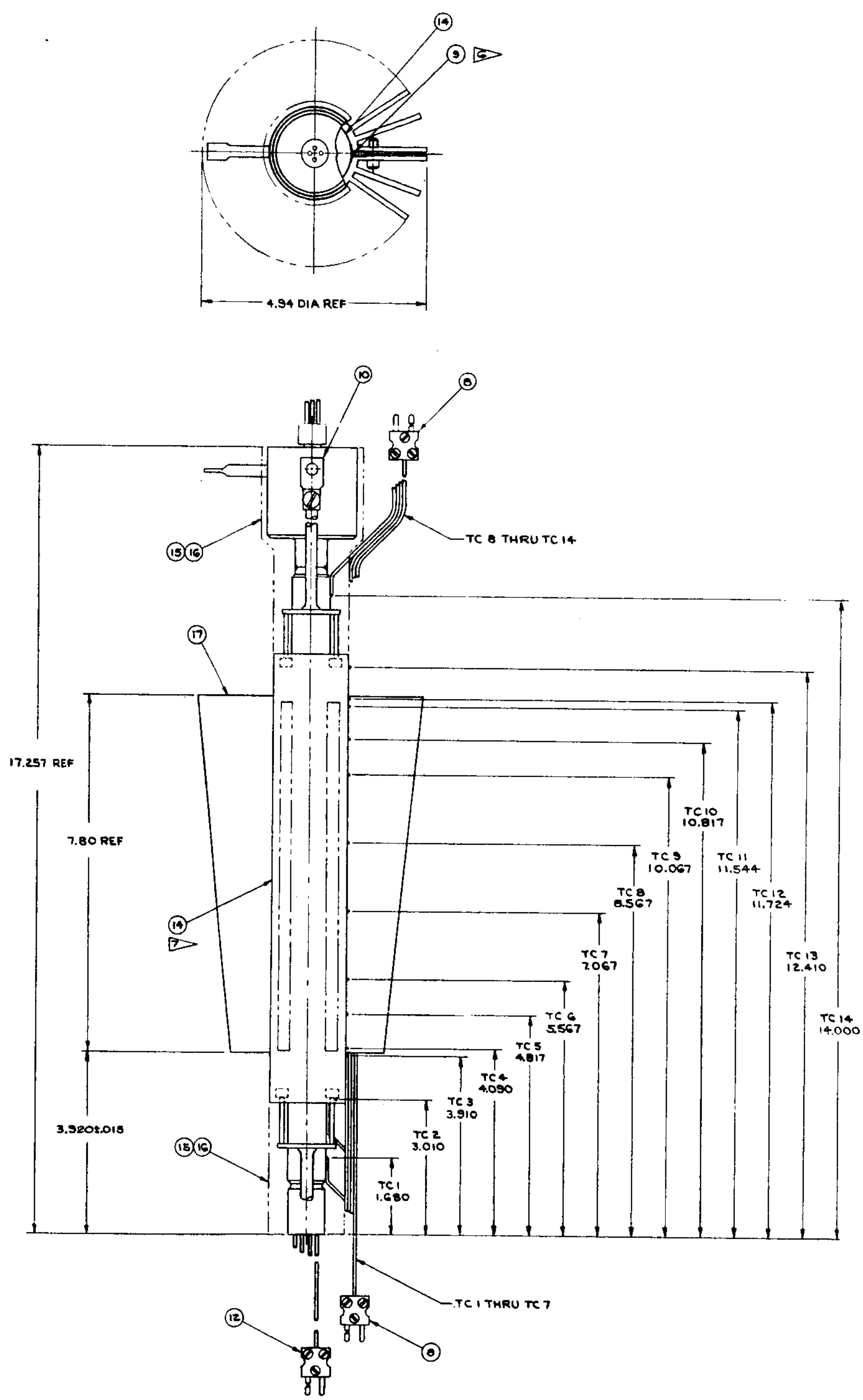


Figure 3b. JPL Test Assembly

TABLE 1

Module Dimensions After Processing

Radial Dimensions Item	I.D. (In.)	O.D. (In.)	Thickness (In.)
Inner Clad	0.250	0.350	0.100
Insulating Sleeve (Inner)	0.350	0.381	0.031
Conductor Ring	0.381	0.396	0.015
Inner PbTe Washer	0.396	0.527	0.131
Outer PbTe Washer	0.527	0.622	0.095
Conductor Ring	0.622	0.643	0.021
Insulating Sleeve (Outer)	0.643	0.665	0.022
Outer Clad	0.665	0.792	0.127

Axial Dimensions Item	Axial Length (In.)
"n"-type PbTe Washer	0.098
"P"-type PbTe Washer	0.091
Mica Insulating Washer	0.005
40-Couple Active Length	7.205
Total Module Length	13.757

insulating rings. The mica insulating rings protrude beyond the thermoelectric washers to separate and electrically isolate the iron conductor rings of adjacent couples. The inner iron conductor ring is axially offset one thermoelectric washer when compared with the outer conductor ring.

When couples are stacked together, forming a heavy walled composite cylinder, the electrical path through the module is of a serpentine nature; i.e., through an n-type washer into an iron conductor ring, out of the iron conductor ring into an adjacent p-type washer, and through this washer into an iron conductor ring, etc.

The thermoelectric couples are insulated from the inner and outer clad by concentric sleeves of boron nitride. The outer sleeve has a wall thickness of 0.022 inch, and the inner sleeve is formed in two concentric pieces having a combined wall thickness of 0.032 inch.

The outer clad is a type-316 stainless steel cylinder with a 0.145 inch wall. The inner clad is a 0.100 inch wall cylinder made from Inconel X-750. Because Inconel X-750 is apt to crack if welded in the solution treated and aged condition in which it is used, transition pieces of type-316 stainless steel are welded onto the end of the inner clad prior to heat treatment. This arrangement permits the end closure welds to be composed of stainless steel-to-stainless steel joints. The electrical connections from the thermoelectric stack are brought out at each end of the module through the retaining rings by use of collector pins. End caps are welded over the entire end-structure of the device to provide gas tight seals during the processing operations. The end caps are subsequently removed after the last processing operation.

III. MODULE ANALYSIS

The major objectives in the analysis of the module are as follows:

1. To determine contact pressures, strains, and changes in volume of the module components during the various stages of fabrication and at initial operating conditions.
2. To provide guidelines for module material selection and component geometries.
3. To assist in the development of the fabrication processes.
4. To specify the thermal and thermoelectric characteristics required to produce the necessary power output and performance.

Because the analytical techniques employed in the analysis of the tubular module are still in the process of development, the analysis described below represents the current state-of-the-art understanding of module behavior.

The analyses which were performed to determine the design parameters for the JPL module can be conveniently grouped under two categories: structural analysis and thermal and thermoelectric analysis.

A. STRUCTURAL ANALYSIS

The determination of contact pressures during the processing and operating cycles is of primary concern during the initial design stages. In order to assure good electrical and thermal performance, it is necessary that high radial contact pressure be maintained. Two types of analysis were performed to gain better understanding of the relationship of contact pressure to module assembly gaps, material properties, dimensions, and process variables: stress analyses, which were used to determine contact pressures between the various material interfaces in the module; and volumetric analyses, which were used in a parallel investigation to determine whether the volume expansions due to the change in temperature distributions from room temperature to operating conditions would cause an increase in contact pressure.

1. Stress Analysis

Two analytical models were used to represent the module. The first model considered that all material between the inner and outer clads was homogeneous, and had lumped properties equivalent to those represented by the actual materials. From this three-layer model, calculations were developed for the overall average interface pressure. The horizontal dotted line on Figure 4 shows the contact pressure calculated for the three-cylinder simplified model when the effects of outer clad yielding and residual stress from the sintering process are included.

The second analytical model was more detailed in that it consisted of seven layers and, therefore, represented the actual construction more accurately. From this model, the contact pressures at each interface across the radius was calculated. The initial calculations with a seven-layer model were made to evaluate the initial interface pressure distribution across the radius during operation at 1025° and 395°F at the inner and outer clad, respectively. The results are shown in Figure 4. Since the calculations were based on the condition that the residual interface pressures resulting from the sintering process can be neglected, the results may be considered as the lower bound initial stress pattern in the module during operation. The figure shows that the contact pressure peaks at the iron-lead telluride hot interface and decreases to the lowest value at the boron nitride-outer clad interface.

On the basis of the analysis of these two models, it was believed that sufficient interface pressure exists during operation to assure adequate thermal and electrical contact.

2. Volumetric Analysis

Volumetric analysis is the calculation of the change in the volume enclosed by the cladding with respect to the volume of the component materials contained within the cladding during processing and operation of the module. This analysis considered the closing of assembly clearances and accounted for the densification that occurred in the boron nitride and lead telluride. The significant items determined by this analysis were:

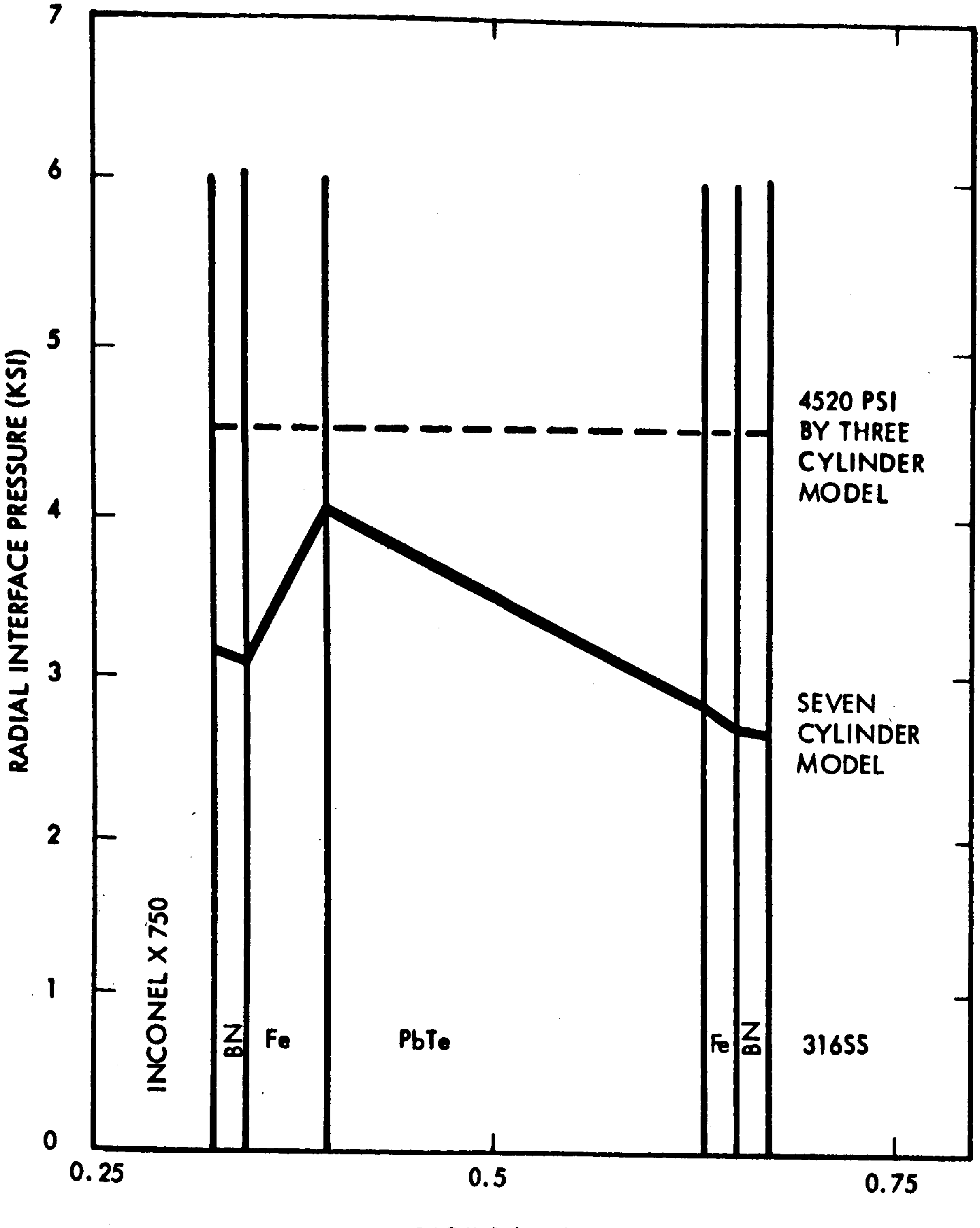


Figure 4. Radial Interface Pressure of Tubular Module at Operating Temperature, T_H=1025°F, T_C=395°F

1. The percentage void volume in the module at assembly, which was obtained by comparing the volume of the materials contained within the clad to the volume between the inner and outer clad, based on nominal drawing dimensions.
2. The percentage interference volume in the module at room temperature after the module was processed, which was obtained by considering the compaction of the lead telluride and boron nitride during processing. The module was assumed to contain no void volume at the top of the gas pressure sintering cycle, and the materials were assumed to be fully compacted. Since it was assumed that the materials remained compacted during the cooldown to room temperature, it was concluded that the interference volume was caused by the thermal change in volume of the materials enclosed within the clad and the volume outlined by the cladding.
3. The percentage interference volume in the module at operating temperature. This value was determined by superimposing the differential thermal expansion in going from room temperature to operating temperature upon the percentage interference volume at room temperature after processing.
4. The percentage of volume of each material within the module.

The results of this volumetric analysis are given in Tables 2 and 3.

Based on the volumetric analysis, it can be concluded that there is positive contact pressures between module components after processing and during operation.

An analysis was also made to evaluate lead telluride compacted during module processing. The analysis, which was based on a unit couple length, considered the void volume in the module at assembly, the percentage by volume of lead telluride in the module, and the measured changes in outside diameter of the module during processing. The JPL module sustained a compaction of 7.74% volume change in the PbTe. Since the starting density of the PbTe is approximately 92%, the analysis shows that the final density of the PbTe is essentially 100%.

TABLE 2

Results of Volumetric Analysis

	Void Volume at Assembly (%)	Interference Volume at Room Temperature After Processing (%)	Interference Volume at Operating Temperature (%)
JPL Module	2.0122	0.6191	1.4506

TABLE 3

Module Materials

	Material (in %)
Boron Nitride	13.4117
Alsimag	14.4207
Iron	9.8873
Mica	3.3573
Lead Telluride	58.9227

B. THERMOELECTRIC AND THERMAL ANALYSIS

The thermal analysis performed on the module provides temperatures for stress, volumetric, and thermoelectric analyses. As part of this analysis, temperature distribution was calculated in the cladding, electrical insulation, conductors and thermoelectric materials. The calculated temperature distribution also included the end closure region of the module.

As an indication of expected performance, the thermoelectric characteristics of the module, including electrical power output, output voltage, and overall efficiency, were calculated for matched load conditions.

The CPBTE-2 and the TOSS computer codes, which were used in the thermal and thermoelectric analyses, are described briefly in the two following subsections.

CPBTE-2. This code used computer integrated values for the Seebeck coefficient, electrical resistivity, and thermal conductivity of each thermoelectric material to calculate the operating conditions of a single couple. The module output was then taken as N times the output obtained from the single couple calculation, where N was the total number of couples in the module (40). The thermal impedance of cladding and electrical insulation, in addition to the electrical resistance of the conductors, were accounted for in the code.

The limitations of the CPBTE-2 code are as follows:

1. The use of average thermoelectric properties in a large radial region with high radial temperature gradients causes uncertainty in the analytical results (a reasonable approximation is that uncertainties of plus or minus 10% are introduced by utilization of average temperatures).
2. The effects of axial temperature variations or of axial variations in the radial temperature drop are not included.
3. End effects are neglected.

TOSS. The TOSS code was used to determine the steady-state temperature distribution and conductive heat losses through the module end closure. It was also used to determine the transient and/or steady-state temperature distribution of a three dimensional irregular body. The heat transfer mechanisms of conduction, radiation, forced and free convection were considered in the code. If applicable, the inclusion of internal heat generation, which is a function of time and space, may be achieved. Boundary temperatures and forced convection film coefficients may be varied with time. A modification of the TOSS code was made to permit material properties of specific heat and thermal conductivity to vary with temperature[1]. The TOSS code, which was developed at Oak Ridge National Laboratory, was reported in the AEC Research and Development Report K-1494[2].

1. Thermoelectric Analysis

Thermoelectric Analysis has been performed on the JPL module design in order to produce a basis for predicting operating characteristics. A revised version of the TOSS code was used in this analysis.

In order to predict the operation of a thermoelectric module based on a single-couple calculation performed with this code, it was assumed that the entire module was running at the temperatures used in the calculations. Accordingly, the following assumptions and approximations were made:

1. Predicted values for the post-processing dimensions of the various components in a couple were used.
2. End losses due to thermal conduction were not included in the efficiency or power output.
3. Open circuit voltage and total electrical power output were obtained by multiplying the calculated values per couple by 40, the number of couples in the JPL module.
4. Thermal conductivity of mica (parallel to baseplane) was assumed to be 0.08 watts/cm K^o.
5. Electrical resistivity of the conductor ring-thermoelectric material interface was assumed to be 10^{-4} ohm-cm^2.
6. Thermal conductance of the boron nitride layers (including interfaces) was assumed to be 1.95 watts/cm^2 K^o at the inner cladding and 2.50 watts/cm^2 K^o at the outer cladding.

---

1. Pierce, B. L., TOSS Program Transient of Steady-State Temperature Distributions, WANL-TME-1108, November 1963.

2. Bagwell, D., TOSS, An IBM-7090 Code for Computing Transient or Steady-State Temperature Distributions, Union Carbide Nuclear Co. K-1494, December 1961.

The results of the thermoelectric analysis are shown in Table 4 for hot clad temperatures of 1000° and 1100°F. For the 1000°F condition, cold clad temperatures of 285° and 400°F were examined. The internal temperature distribution obtained from Case 1 is shown in Figure 5 and Table 5.

TABLE 4

Matched Load Performance Predictions

Characteristics	Case 1	Case 2	Case 3
Cold Clad Temperature (°F)	400	400	284
Hot Clad Temperature (°F)	1000	1100	1000
Open Circuit Voltage (Volts)	5.44	6.50	6.20
Load Current (Amps)	32.1	34.8	41.8
Power Output (Watts)	87.3	113.0	129.4
Power Input (Watts)	1693	1943	2184
Efficiency (%)	5.16	5.82	5.92

TABLE 5

Calculated Module Interface Temperatures

Temperature (°F)	Radial Location (In)	Interface
1000	0.250	I.D. of Inner Clad
956	0.350	Inner Clad/Insulating Sleeve
947	0.381	Insulating Sleeve/Conductor Ring
944	0.396	Conductor Ring/Inner PbTe Washer
611	0.527	Inner/Outer PbTe Washers

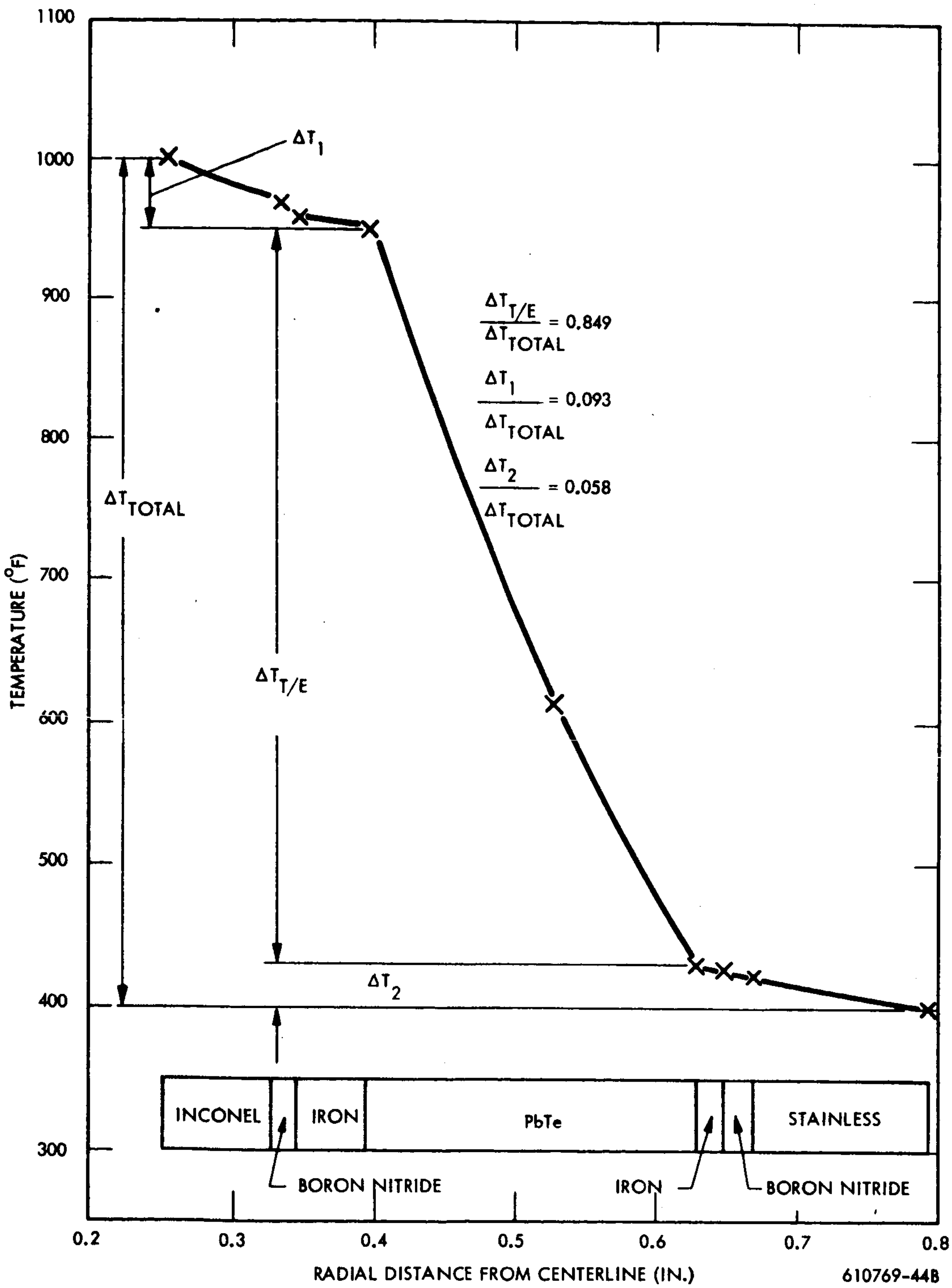


Figure 5. Module Temperature Distribution
(Determined From CPBTE-2 Code)

TABLE 5 (Continued)

435	0.622	Outer PbTe Washer/Conductor Ring
433	0.643	Conductor Ring/Insulating Sleeve
426	0.665	Insulating Sleeve/Outer Clad
400	0.792	O.D. of Outer Clad

2. Thermal Analysis

The temperature distributions and heat fluxes computed in the vicinity of the end closure utilized a TOSS model which was set up for the end closure dimensions and boundary conditions which represented the test conditions. The temperature and heat flow distribution obtained from this calculation are shown in Figure 6.

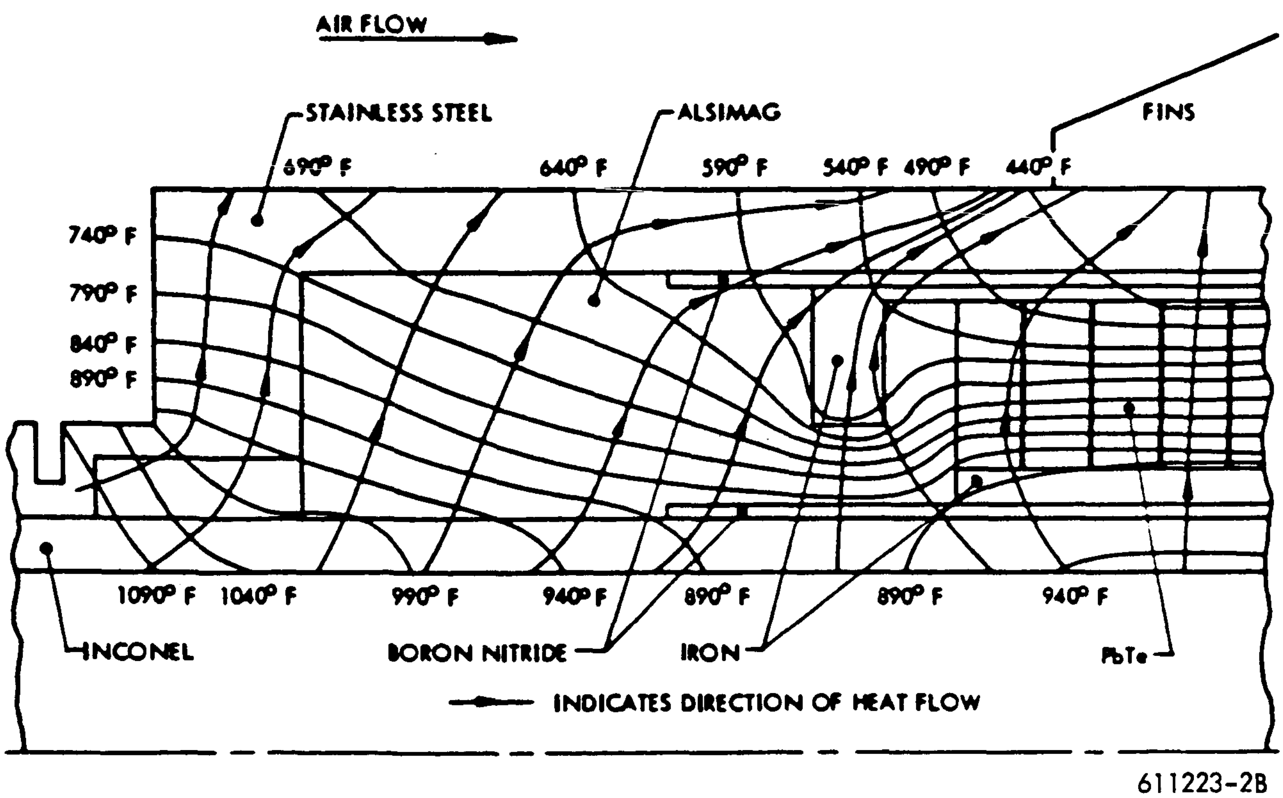


Figure 6. Module Temperature and Heat Flow Pattern

Two effects readily observable from this figure are the low radial impedance path through the outer iron collector ring and the axial heat transfer in the outer clad toward the finned region.

The boundary conditions imposed on the TOSS model are not identical to those which are indicated by the JPL module test results. However, the total amount of heat which passes through the end closure is approximately proportional to the temperature difference between the inner and outer surfaces at the end of the module; therefore, an estimate of end heat bypass can be obtained from the TOSS results. Surface heat flux was integrated over the inner surface of the clad and compared to the source heat which would be supplied to the thermoelectric module under the same conditions, but with no end heat bypass. This comparison showed that the end heat bypass was 230 watts for a module operating with a 600°F temperature differential. The approximate 230 watts is equivalent to the heat required by a 1-inch length of module with the same temperature difference operating at matched load conditions. Because the TOSS model uses a continuous iron collector ring, whereas the JPL module conductor ring is scalloped, the calculated end closure heat loss is conservatively high.

The calculated performance results given for the JPL module in the proceeding table were based on the assumption that there was no end closure heat bypass. Guard heaters were provided for the test module in an attempt to provide the bypass heat and confine the main heat supply to the active length of the thermoelectric generator.

IV. MODULE ASSEMBLY AND PROCESSING

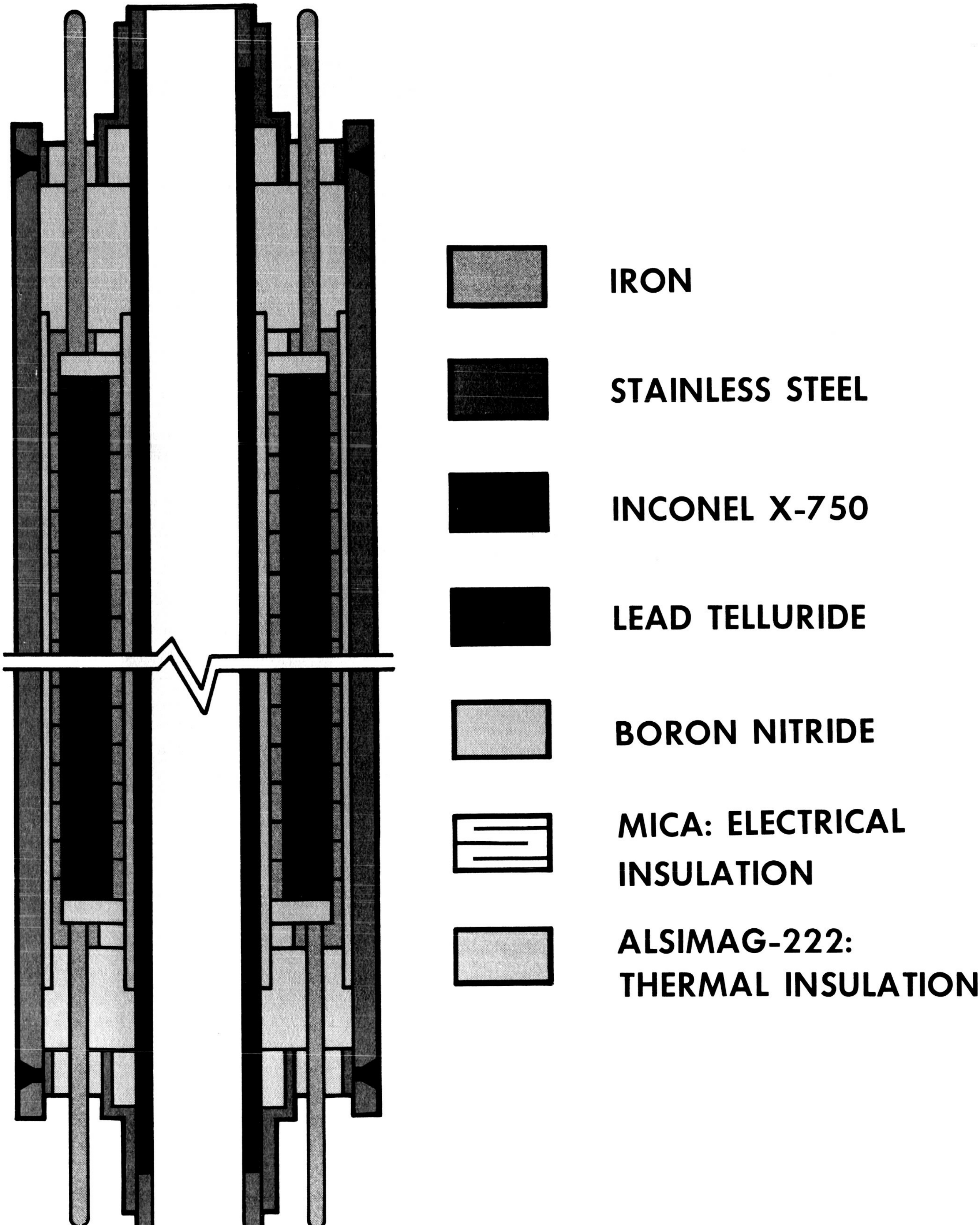
A. THERMOELECTRIC COUPLE ASSEMBLY

Prior to actually assembling the module, the couples required for the module were pre-assembled in an argon-filled glove box. Each couple consisted of inner-outer pairs of p- and n-type PbTe washers, inner and outer conductor rings, and two sizes of mica washers. A small stainless steel tray was used as an assembly base and for subsequent handling of each couple. The couples were assigned serial numbers as they were assembled, and these numbers, or other identification of each component used in each couple, were recorded. The p-n polarity of each PbTe washer was checked before the washer was added to a couple subassembly, and the trays containing the assembled couples were stacked in vented plastic boxes and stored in an argon glove box until needed for module assembly.

B. MODULE ASSEMBLY

As a first step in module assembly, all components, subassemblies, tools and fixtures required for the module were removed from storage and placed in an argon glove box. The inner clad was placed on a stainless steel assembly fixture, and the end components, inner boron nitride sleeve, couples, outer boron nitride sleeve and outer clad were then assembled. At this point, the partially assembled module was removed from the assembly fixture and placed in a hydraulic compression fixture, and the internal components were compressed axially with a load of 1000 pounds. With the module thus loaded, the retaining rings were welded to the inner clad, fixing the internal components in the axially compressed condition. The module was then removed from the compression fixture, and the outer clad was welded to the flanges of the two retaining rings. After end insulators and end cap-degassing tube subassemblies were installed, the end caps were welded to the inner and outer clads. A schemiatic of the axial cross-section of an assembled module is shown in the following illustration.

During the entire assembly process, the only times that the interior of the module was potentially exposed to air were during transfer between glove boxes, and during the final axial



FABRICATION

compression and welding operations. This procedure was followed to minimize the possibility of surface oxidation of interior components and to guard against the presence of entrapped atmospheric gases. In addition, the use of glove boxes ensures a clean module assembly.

C. DEGASSING

After assembly, the module was processed through a hydrogen-vacuum heat treatment cycle to reduce surface oxides which might have formed on the internal components.

The nominal configuration of the degassing process was as follows: The degassing tube at each end of a module was joined to a high vacuum valve by soldering. The module was then placed in a split tube furnace and the valves were connected to the manifold of a hydrogen-inert gas-vacuum system. The module interior was evacuated to approximately 5×10^{-5} torr, and the pumping was continued while the module was slowly heated to 150°C. This procedure allowed outgassing to occur. After that part of the cycle was completed, a flow of dry hydrogen was introduced through the module interior and the heating continued until the module temperature reached 400°C. During that part of the cycle, lead oxide on the surfaces of the PbTe washers can be reduced according to

$$PbO + H_2\,(g) \longrightarrow Pb + H_2O\,(g),$$

with the gaseous reaction product being swept out of the module in the hydrogen stream. With the module temperature maintained at 400°C, the hydrogen flow was sustained for 15 minutes. The module was then evacuated from both ends for 15 minutes; at which time it reached a pressure of 10^{-4} to 10^{-5} torr. The module interior was then flushed with hydrogen for 15 minutes after which it was re-evacuated, the furnace was shut off, and the module was slowly cooled to room temperature while the pumping continued. When the module reached room temperature and an internal pressure of approximately 2×10^{-4} torr, the valves at the ends of the degassing tube extensions were closed and the module was removed from the furnace. The degassing tubes were then flattened by hot-hammering near the module ends and seal welded and cut off across the flats by an electron beam welder.

D. COLD HYDROSTATIC COMPACTION

After the degassing tubes were seal-welded and the module leak tested, the bore was fitted with a mandrel which was welded to each end of the inner clad. The mandrel was designed to prevent axial distortion of the inner clad and to seal the bore to prevent pressurizing the I.D. of the inner clad during hydrostatic compaction. The module was hydrostatically pressurized to 45,000 psi in a cold fluid autoclave, which reduced the O.D. about 0.030 inch. This step closed the assembly gaps and initiated densification of the lead telluride.

E. GAS PRESSURE SINTERING

After cold compaction, the end seals of the inner clad mandrel were opened and the module was sent to Battelle Memorial Institute at Columbus, Ohio, for gas pressure sintering in a hot helium autoclave. The purpose of this process was twofold: first, to reduce the module diameter further until PbTe densification was complete and internal voids were eliminated; and second, to develop high contact pressures at the interfaces. The nominal configuration of the final autoclave cycle was as follows:

1. The module was pressurized with helium to 7500 psi at room temperature.
2. It was simultaneously heated and pressurized to 650°C and 15,000 psi in about 3 hours.
3. It was then held at those conditions for 2 hours.
4. It was furnace-cooled to room temperature, permitting pressure to reduce by gas-contraction to about 7500 psi, and venting at room temperature.

The module was reduced approximately another 0.010-inch diametrically during the hot helium autoclave cycle. A history of the diameter changes occurring during the module processing can be seen in Figure 7. After they were gas pressure sintered, the protective end caps were removed to expose the ends of the collector pins. Prior to putting the module on test, various non-destructive examinations and measurements were made such as, internal resistance and resistance to clad. The results of these examinations can be found in WANL-TME- 1467, "Performance of JPL Tubular Thermoelectric Module (Test Ass'y. 909E687).

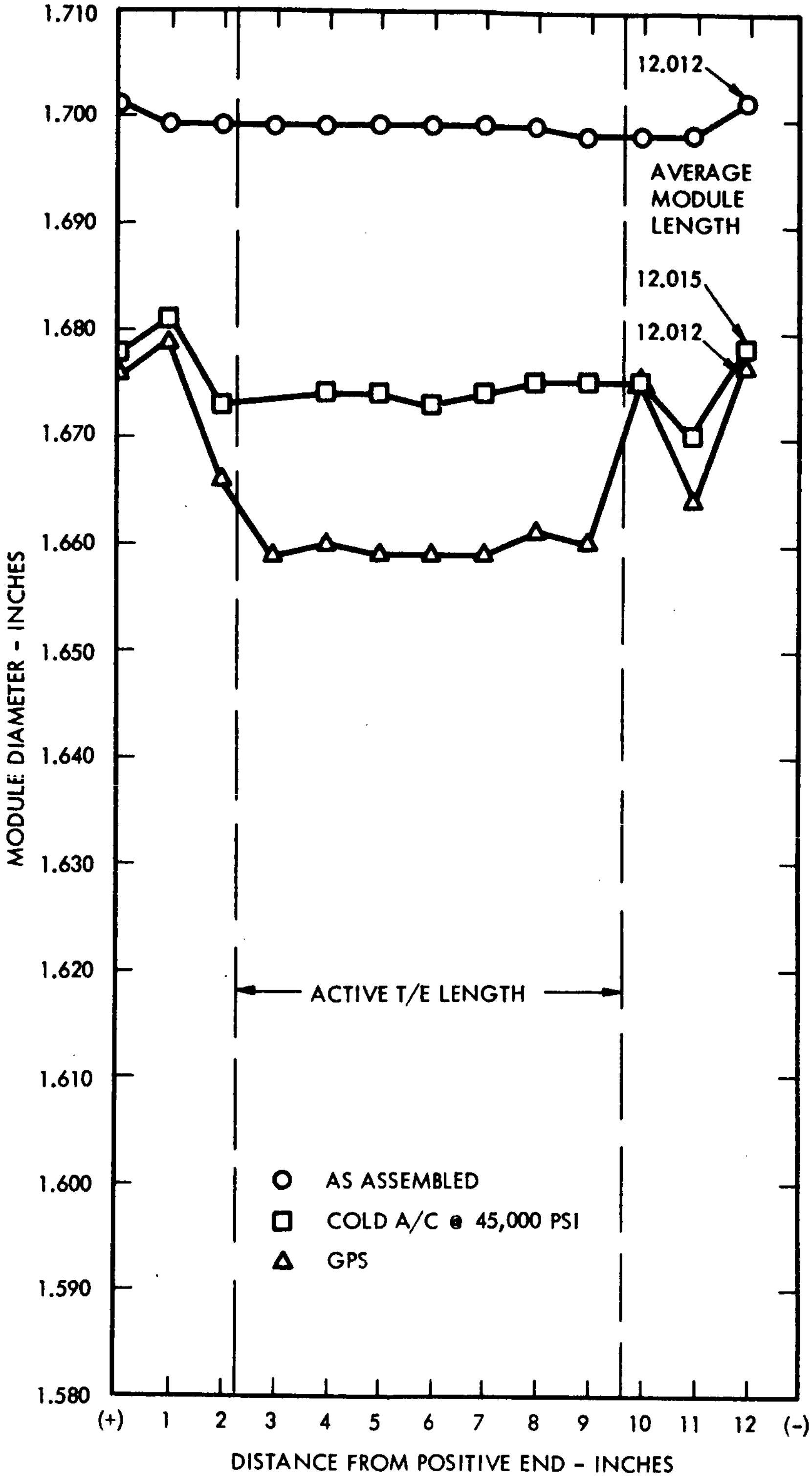


Figure 7. Compaction Data Summary

V. WEIGHT TABULATION

The component and total weight of the JPL tubular thermoelectric module test assembly are listed in Table 6.

TABLE 6

Weight Tabulation

Item	Pounds
JPL Module	5.2
Heater, Expansion Bulb and NaK	1.1
Instrumentation (Hot and Cold T/C's, etc.)	1.6
Cooling Fin	2.2
Miscellaneous (Cable Shields, Insulation, etc.)	4.7
Total weight of module in test configuration	14.8

VI. MODULE OPERATION

This section presents recommended procedures to be followed for the start-up, shutdown, matched load, and open circuit operating modes.

A. START-UP

Start-up is achieved by increasing the input power to the main heater in 50-watt increments until the selected outer clad average temperature is obtained. From that point, the outer clad temperature* is maintained at this value by increasing blower speed while the main heater power increase is continued in 50-watt increments. The upper and lower guard heaters, which are in-depently controllable, are used to help attain a flat temperature profile. Experience shows that temperatures can be readily attained that are uniform within 100°F. About 10 minutes is required between successive steps to allow equilibrium to be reached.

B. SHUTDOWN

The start-up procuedure is simply reversed to achieve shutdown. Cooldown is made by decreasing power to the main heater in 50-watt steps, guard heater adjustments are made to maintain the inner clad temperature profile uniform within 100°F, and blower adjustments are made to maintain the desired cold side temperature. This procedure should be continued while the outer clad temperature can no longer be maintained, guard heaters and blowers are shut down and main heater power reduction is resumed in 50-watt increments until shutdown is complete.

C. MATCHED LOAD OPERATION

Increases in electrical power output under matched load operation should be accomplished by lowering the outer clad temperature in the desired increment (not to exceed 50°F per

---

* The average temperature referred to throughout this section is the "mean" determined by applying the trapezoidal rule to the eight thermocouple readings from either the inner or the outer clad.

increment), by increasing blower speed, or lowering coolant temperature and then adjusting main and guard heater power to return the inner clad temperature to an average value of 1000°F and uniformity within 100°F. Several iterative adjustments of outer clad temperature and input power will be necessary to achieve the desired conditions. Nominal temperature conditions required to obtain 100-watt power output are 1000°F at the inner clad and 284°F at the outer clad. This reflects a total main heater power of 1930 watts. It is particularly important that the precautions given in the following paragraphs be observed in changing from matched-load to open-circuit operation.

D. OPEN CIRCUIT OPERATION

Changes in input power and in clad temperatures under open circuit conditions should be accomplished by the techniques discussed above.

A change from matched load to open circuit operation <u>must be preceded by a reduction in input power</u> to a maximum of 1600 watts if the outer clad temperature is held at 284°F; and 1280 watts if the outer clad temperature is held at 392°F. If this is not done, the loss in Peltier pumping effect will cause the inner clad temperature to exceed 1000°F.

E. NOMINAL OPERATING CONDITIONS

The nominal outer clad temperature and heater input power required to obtain a 100-watt power output with average inner clad temperature maintained at 1000°F are 284°F and 1930 watts, respectively, at matched load conditions.

During open circuit or matched load testing, optimum performance will be achieved when the arithmetic mean temperature $\frac{(\bar{T}_H + \bar{T}_C)}{2}$ of the module is maintained at approximately 644°F. For open circuit testing, the heat flux which would achieve near-optimum performance can be obtained with the main heater power set at 1600 watts and the upper and lower guard heater power set at 120 and 150 watts, respectively. For matched load testing, the heat flux required to achieve near-optimum performance can be obtained with the main heater power set at 1930 watts and the upper and lower guard heater power set at 120 and 150 watts, respectively.

Table 7 presents the recommended operating limits for the JPL module.

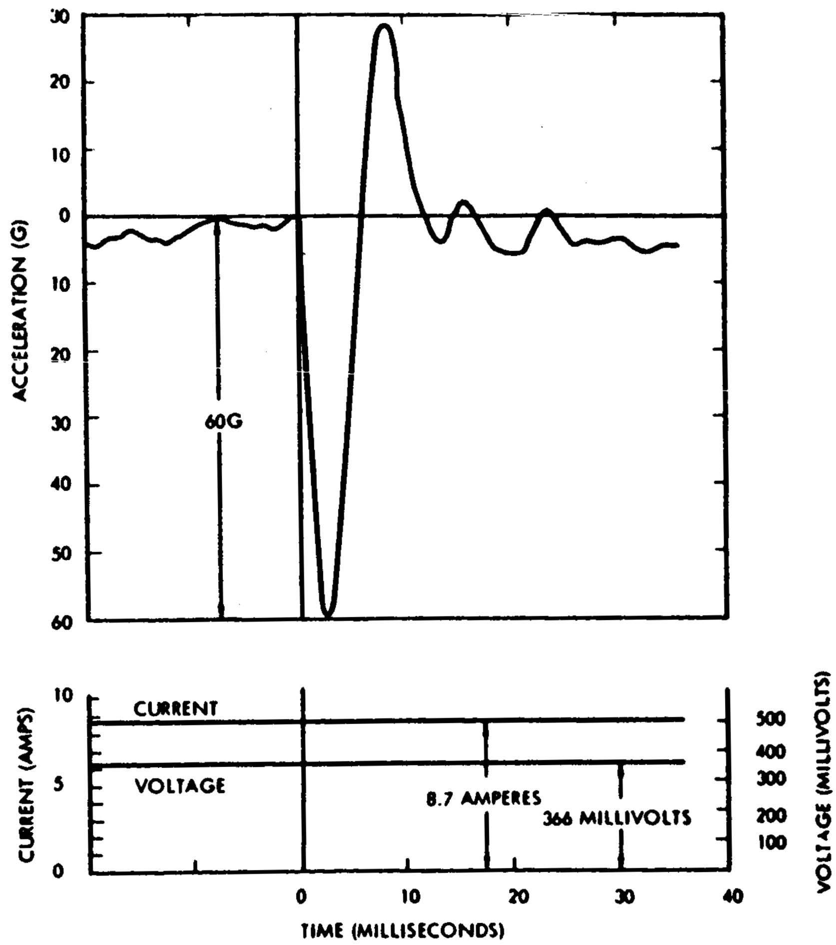
TABLE 7

Table of Limits

Characteristics	
Main Heater Power (Watts)	2300
Upper Guard Heater Power (Watts)	230
Lower Guard Heater Power (Watts)	230
Average Inner Clad Temperature (°F)	
Life Testing	1000
Short Time Testing	1100
Average Radial Temperature Drop (°F)	
Life Testing	720
Short Time Testing	750
Maximum Inner Clad Temperature (°F) (Individual Thermocouple)	
Life Testing	1050
Short Time Testing	1150

VII. SHOCK AND VIBRATION CAPABILITY

Some time ago, a test was performed to determine the integrity of the tubular type thermoelectric module under shock and vibration conditions. The module tested was a type PM unit, similar in concept (though smaller in size) than the JPL module. The device had been under continuous operation for 10,000 hours prior to dynamic testing. The maximum shock load applied was 60 g's in the lateral direction. No damage or performance loss occurred as a result of the test series (Figure 8).



611223-3B

Figure 8. Shock Test of Tubular Thermoelectric Module

Lateral and longitudinal shock and vibration loading was applied directly to the outer case of the module, and a resistance heater was used to make the module operational. Power output was monitored continuously before, during and after the test series. The test inputs were:

Longitudinal

Shock (half-sine) Magnitude (g) -3, 5, 15, 30, 44.

Vibration: Test 1

Magnitude	Frequency (cps)
1/8 in. peak-to-peak	5 to 20
2.5 g	20 to 400
4 g	400 to 3000

Test 2

Magnitude	Frequency (cps)
1/4 in. peak-to-peak	5 to 20
5.0 g	20 to 400
7 g	400 to 3000

Lateral

Shock (half-sine) Magnitude (g) - 10, 25, 47, 60.

Vibration: Test 1

Magnitude	Frequency (cps)
1/8 in. peak-to-peak	5 to 20
2.5 g	20 to 400
4 g	400 to 3000

Test 2

Magnitude	Frequency (cps)
1/4 in. peak-to-peak	5 to 20
5.0 g	20 to 400
7.5 g	400 to 3000

Test 3

Magnitude	Frequency (cps)
0.9 in. peak-to-peak	5 to 17
10 g	17 to 3000

The power output remained constant throughout the entire test series. During and after a 60 g, six millisecond lateral shock input, there was no change in the voltage and current output of the module.

VIII. REFERENCES

A further discussion of the basic tubular module design can be found by referring to the Compact Converter Phase I Final Report, NYOO-3584-1; Compact Converter Phase II-A Quarterly Progress Report (January 1 - March 31, 1966), NYOO-3584-2; and Compact Converter Phase II-A Quarterly Progress Report (April 1 - June 30, 1966) NYOO-3584-3. These reports cover work being performed by the Astronuclear Laboratory under AEC Contract AT(30-1)-3584.