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FABRICATION OF ONE SILICON-GERMANIUM THERMOELECTRIC TEST UNIT

FINAL REPORT

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DIRECT ENERGY CONVERSION

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PREPARED FOR:

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PASADENA, CALIFORNIA - 91103

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FABRICATION OF ONE SILICON-GERMANIUM THERMOELECTRIC TEST UNIT

FINAL REPORT

AUGUST 31, 1965

ORDER NO. 951136

OBJECTIVE The objective is the fabrication of a thermoelectric test unit which can be used to evaluate the performance of silicon-germanium thermocouples and modules.

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.

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FINAL REPORT

FABRICATION OF ONE SI-GE THERMOELECTRIC TEST UNIT

I. SUMMARY

RCA has fabricated one thermoelectric test unit to aid the Jet Propulsion Laboratory in assessing the applicability of silicon-germanium thermoelectric power conversion to their space power needs.

The unit was designed to feature versatility in adaptation to a sufficient variety of test conditions within the device process and materials limitations to illustrate the application of silicon-germanium thermoelectric couples and modules to practical power conversion devices.

The normal variations associated with engineering fabrication of a one-of-a-kind device will result in a unit which may exhibit the usual degree of variability to be expected from a laboratory product.

It consists of four, six-couple modules intended for high temperature radiative coupling to a heat source. These modules are arranged in two pairs on opposite sides of each of two planar, graphite ribbon heaters operating at power inputs up to 300 watts at E_H = 20 volts and I_H = 15 amperes, approximately. The graphite heater has long life when operated in vacuum at pressures of 1 x 10^{-5} Torr or less. A variety of cold junction temperatures may be secured through thermal coupling adjustments between module radiators and a fluid cooled heat exchanger. Process and materials requirements permit operation over a range of hot junction temperatures to 900°C and cold junction temperatures to 371°C.

Provision is included for monitoring temperatures of cold and hot junctions, radiator, heat exchanger outlet, frame and base mount through use of chromel-alumel thermocouples. An inconel sheathed couple design is used at the hot junction to extend its life and accuracy while operating in the immediate vicinity of the high temperature and metallurgically active constituents of the silicon-molybdenum alloy hot shoe.

The completed unit was subjected to a life test through six thermal cycles spanning 330 hours of operation. The conditions selected permitted operation at maximum hot junction temperature, maximum Δ T capability and near maximum heater input. The performance observed reached the levels expected with average power output of 1.05 watts per couple. The test duration of 330 hours brought the unit through approximately 75% of the expected initial characteristic adjustment toward ultimate stability under the conditions used.

II. INTRODUCTION

Under Contract No. NAS7-100, Order No. 951136 RCA was to fabricate a silicon-germanium thermoelectric test unit for the Jet Propulsion Laboratory. The unit was intended as an aid in determining the applicability of silicon-germanium power modules to the requirements of space power systems. To best achieve this purpose a design was selected which would enable operation over a range of conditions encompassing those most likely to occur in practical power conversion applications. Provision for determining major performance characteristics resulting from selected operating conditions was included. The results obtained could then be extended to aid in predicting performance of silicon-germanium thermoelectric devices when included as a power source in an overall space system.

A. General Features

The SiGe thermoelectric test unit was designed for laboratory determination of the thermoelectric characteristics of silicon-germanium alloys in practical thermocouple and modular configurations. Provisions were made for maximum test plan variety through test point access to each power thermocouple and temperature measurement thermocouple, and through a wide range of heater inputs and methods of securing a wide variety of cold junction temperatures. The unit size was selected to fit into the usually available sizes of laboratory vacuum test chambers. General design features may be seen from reference to Figures 1 and 2.

Major physical characteristics are:

Weight - 3000 gms (6.6 lbs) - approx.
Height - 13-3/4 inches - approx.
Width - 7 inches - approx.
Depth - 8 inches - approx.

Test Points for which access will be provided are:

Individual couple	32
Heater input	4
Module temp. measurement couples	24
Frame & Exchanger temp. couples	6
Total	66

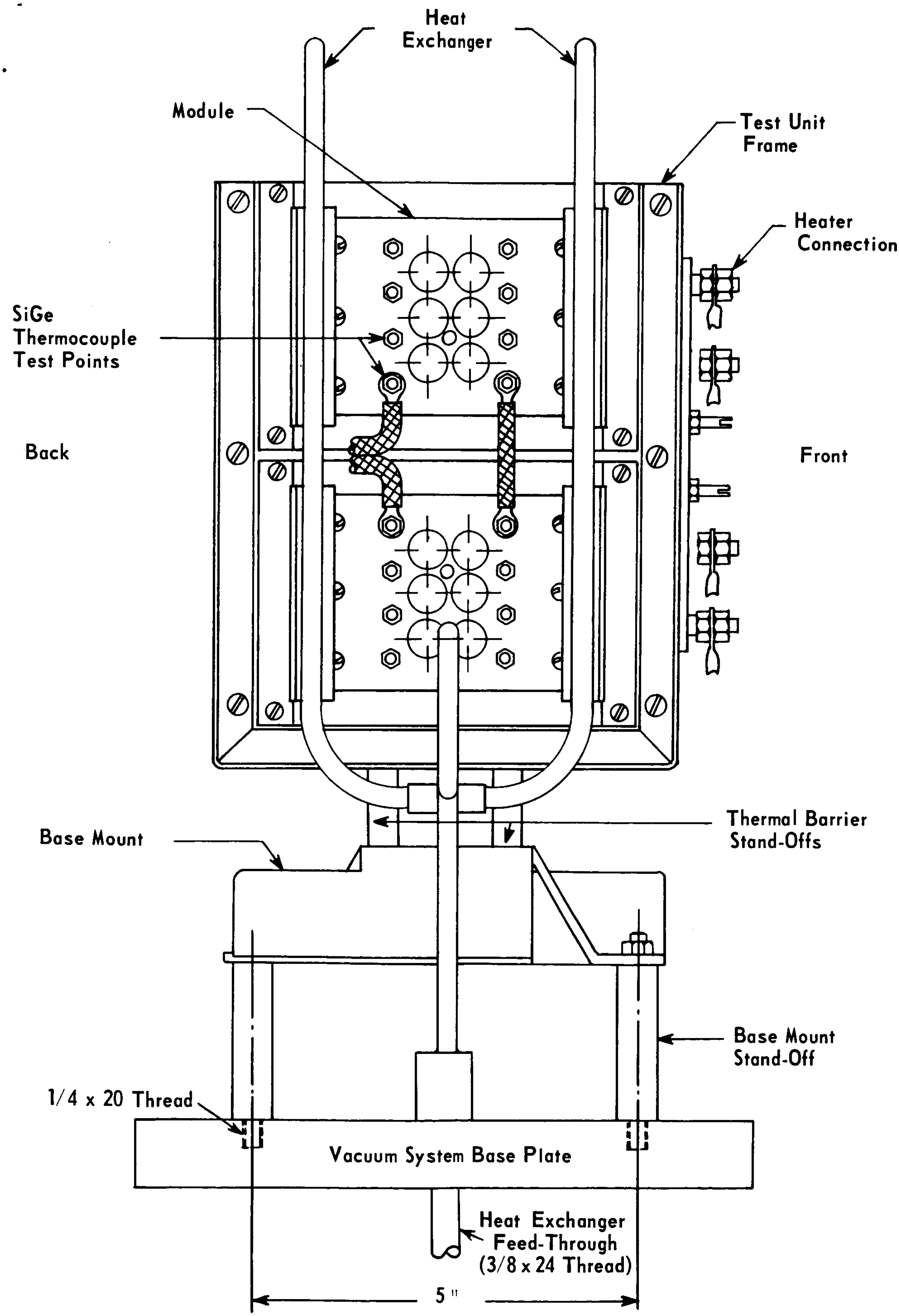

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FIGURE 1 - TEST UNIT ASSEMBLY - LEFT SIDE VIEW

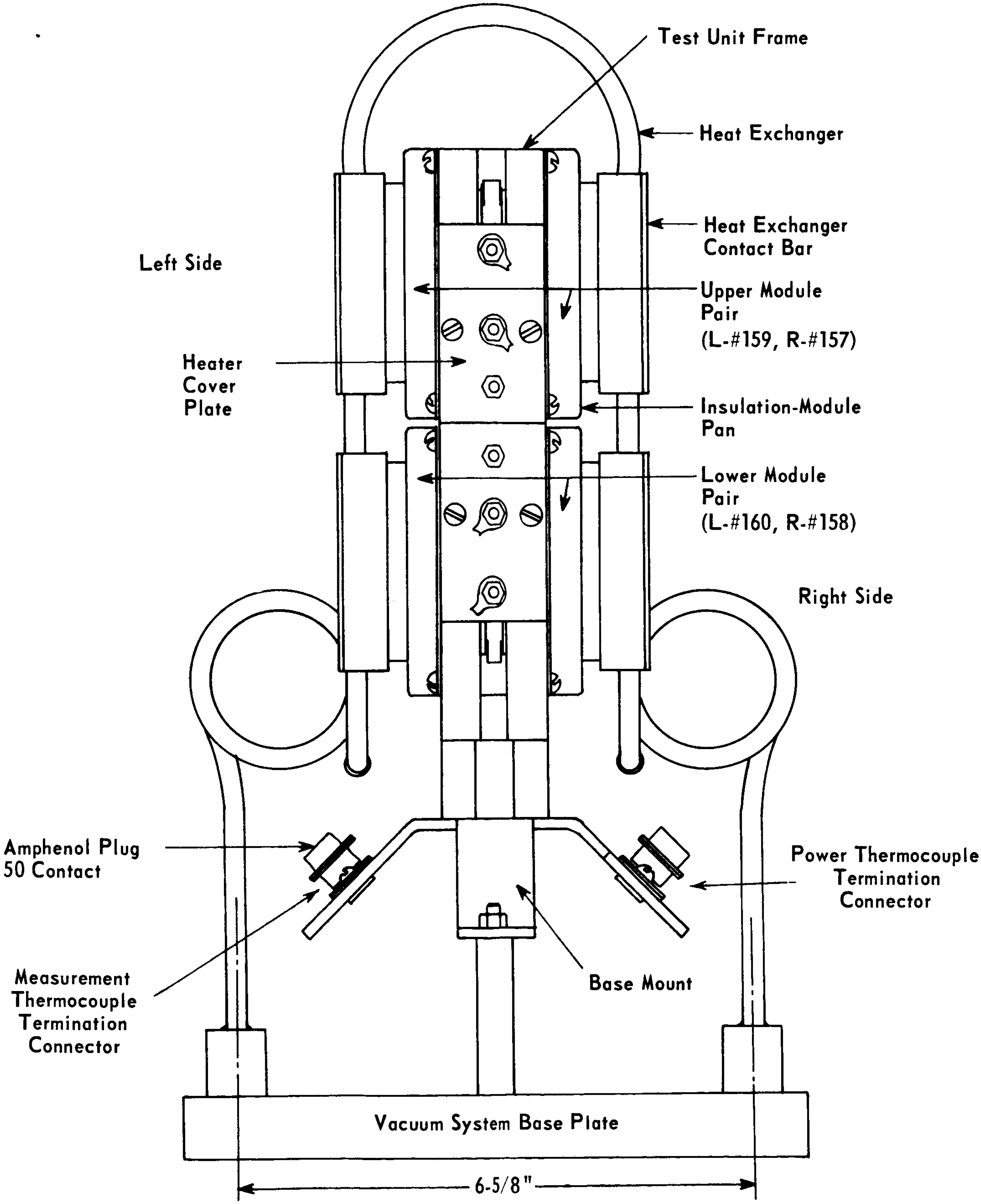


FIGURE 2 - TEST UNIT ASSEMBLY - FRONT VIEW

The base mount was designed to support the unit structure through 2 inch copper standoff spacers to be fastened directly to the vacuum chamber base plate or base-plate adaptor. Figure 3 indicates the position and size of the mounting holes required to give proper registry between the heat exchanger and the test unit base mount. If the unit is to be mounted directly upon the test chamber base plate, allowance should be made for the vacuum seal dimensions associated with the heat exchanger feed-throughs so that proper assembly registry may be maintained. The heat exchanger feed-throughs are $2\frac{1}{2}$ inches long at the 3/8" outside diameter and are threaded at 24 threads per inch for 2 inches. All wiring with the exception of the heater leads and power module output leads are terminated in two (2), Amphenol, 50 contact, quick disconnect, miniature, diallyl phthalate body (glass filled per MIL-M-19833, type GD1-30) connectors located on wings provided at the base mount. Facing the front of the test unit (front defined as that face containing the heater connections) all power module terminations appear at the connector on the right side and all measurement thermocouple terminations appear at the connector on the left side. Also on the left side are the heater terminations. The heat exchanger outlet is on the right and to this side is located the outlet temperature thermocouple.

Figure 4 identifies the power couple and module test points in terms of the right-hand connector pin numbers. Figure 5 is a schematic representation of the power couple, module and test point locations for the complete test unit just as they appear on the test unit. Couple test points are given the connector pin numbers at which they terminate. Couple interconnecting straps are shown in dashed outline very much as they would appear could the inside of the radiator plate be observed. Each element of each power thermocouple is identified by an "N" or "P". Both couple numbers and module numbers are scribed on the radiator plate of each module. Figure 6 shows the power module interconnection arrangement used in wiring the test unit. This wiring is terminated at two ceramic stand-off insulators located on the right-hand base mount apron.

Figure 7 identifies all measurement thermocouples with indicated polarity in terms of the left hand connector pin numbers.

In total there are twenty-six terminations associated directly with the thermoelectric power couples and modules, thirty terminations for the measurement thermocouples and two terminals for the heater. For complete instrumentation a minimum of fifty-eight (58) separate wires must be carried through the vacuum chamber base plate. In addition, water inlet and outlet feed-throughs must be provided. The module test frame is isolated thermally from the base mount by four (4) one inch ceramic stand-off insulators. This reduces heat losses from the units under test and permits the base mount and connectors to operate at near room temperatures. The test frame is designed to accommodate two heater and module pair assemblies in fixed registry, one above the other. Provision is made for

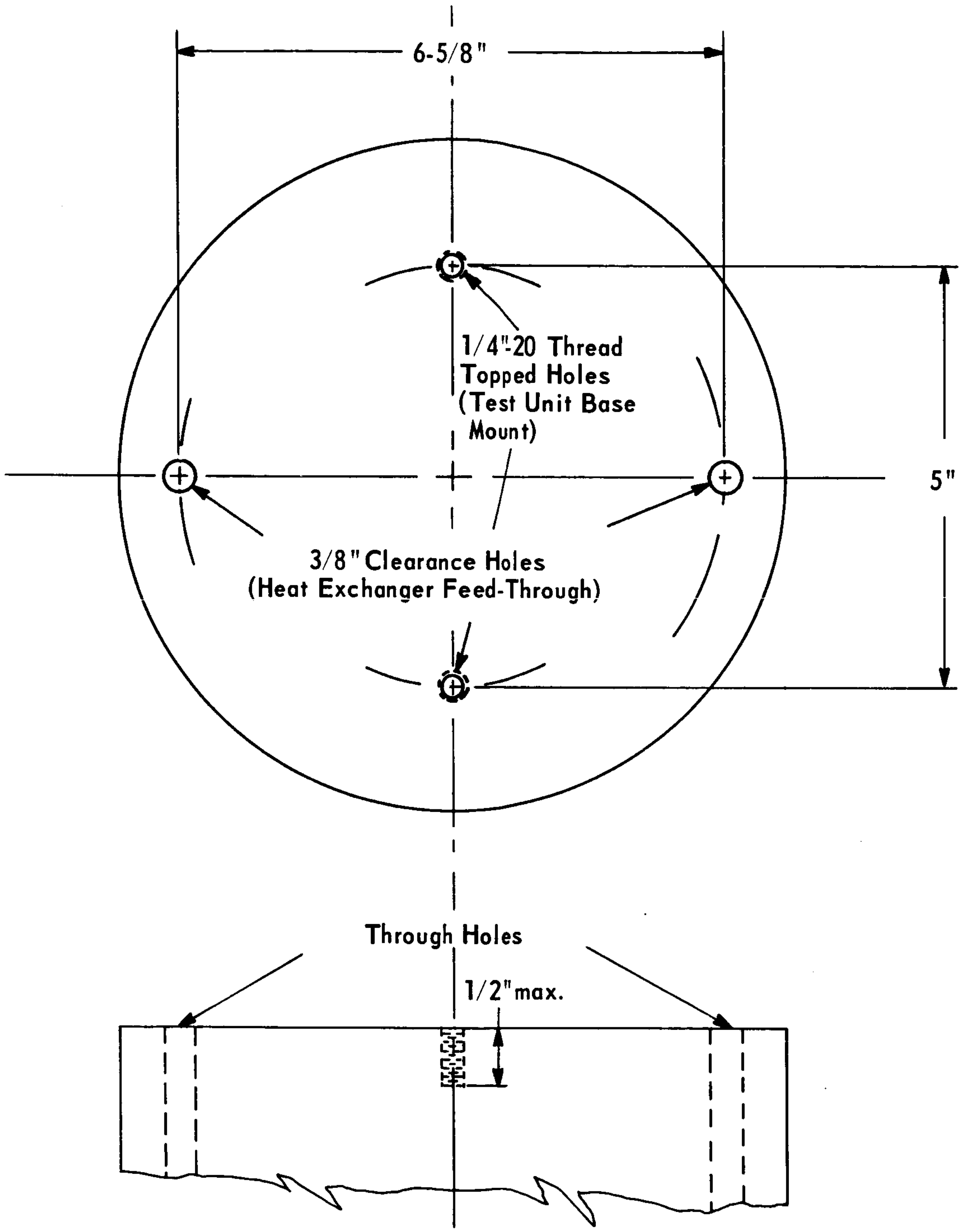
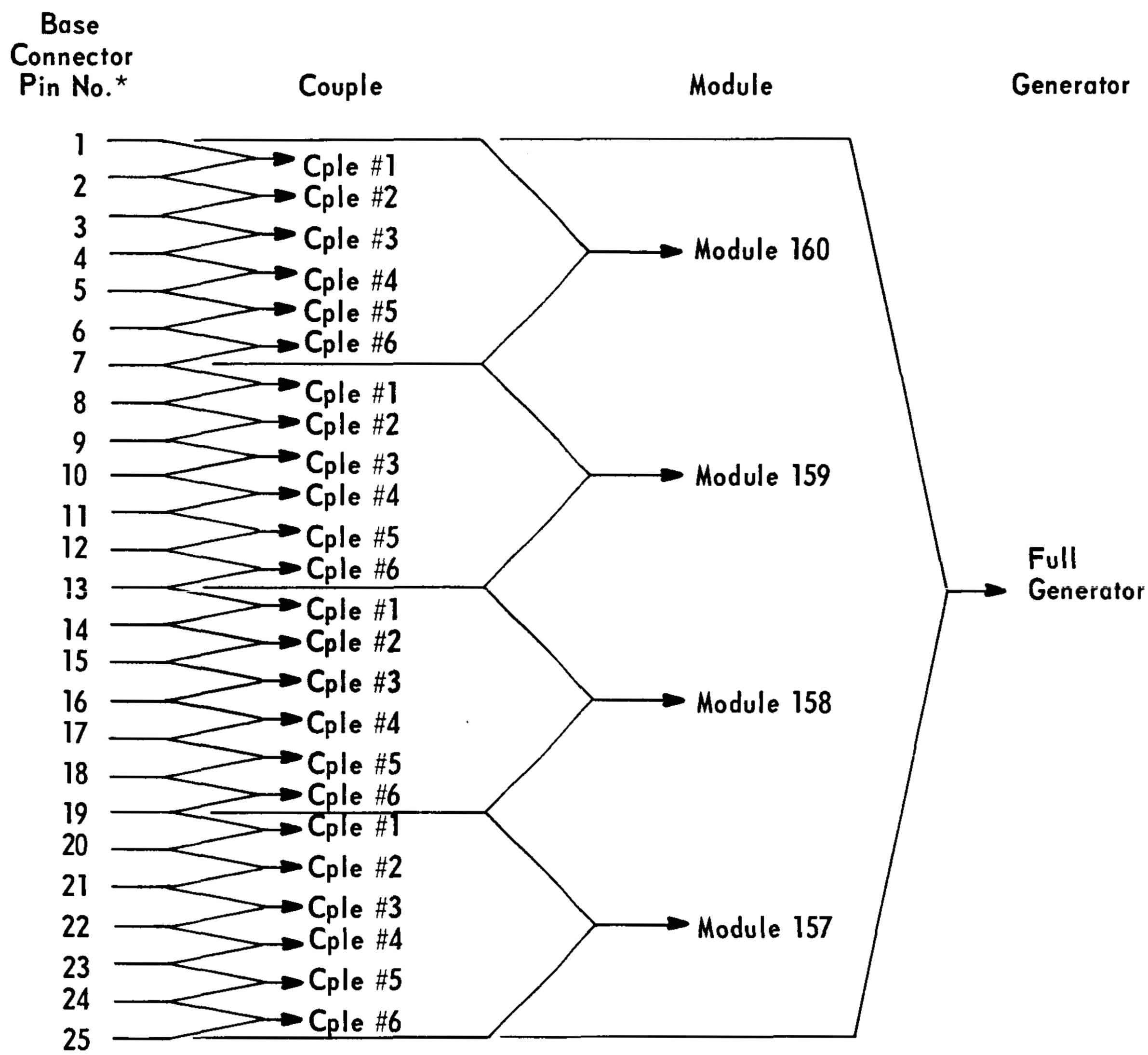


FIGURE 3 VACUUM BASE PLATE MOUNTING HOLE LOCATIONS



* Note: When facing heater leads the connector containing the Power Thermocouple terminations appears on the right hand apron of the base mount. The generator power take-off terminations are located on this same apron.

FIGURE 4 POWER THERMOCOUPLE MEASUREMENT CONNECTIONS JPL-MODEL-T.D.-65-201

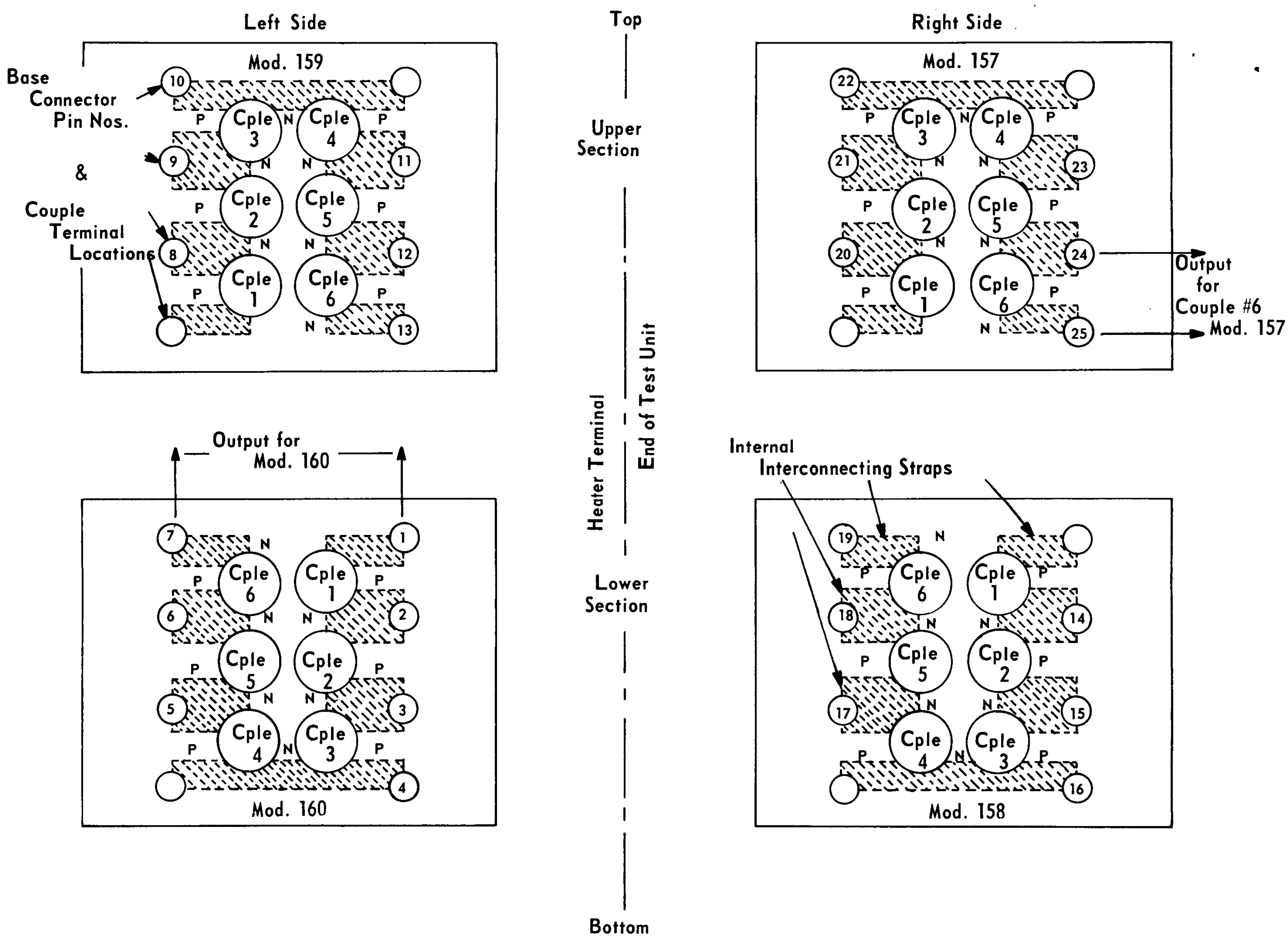


FIGURE 5 MODULE INTERNAL INTERCONNECTION DIAGRAM.

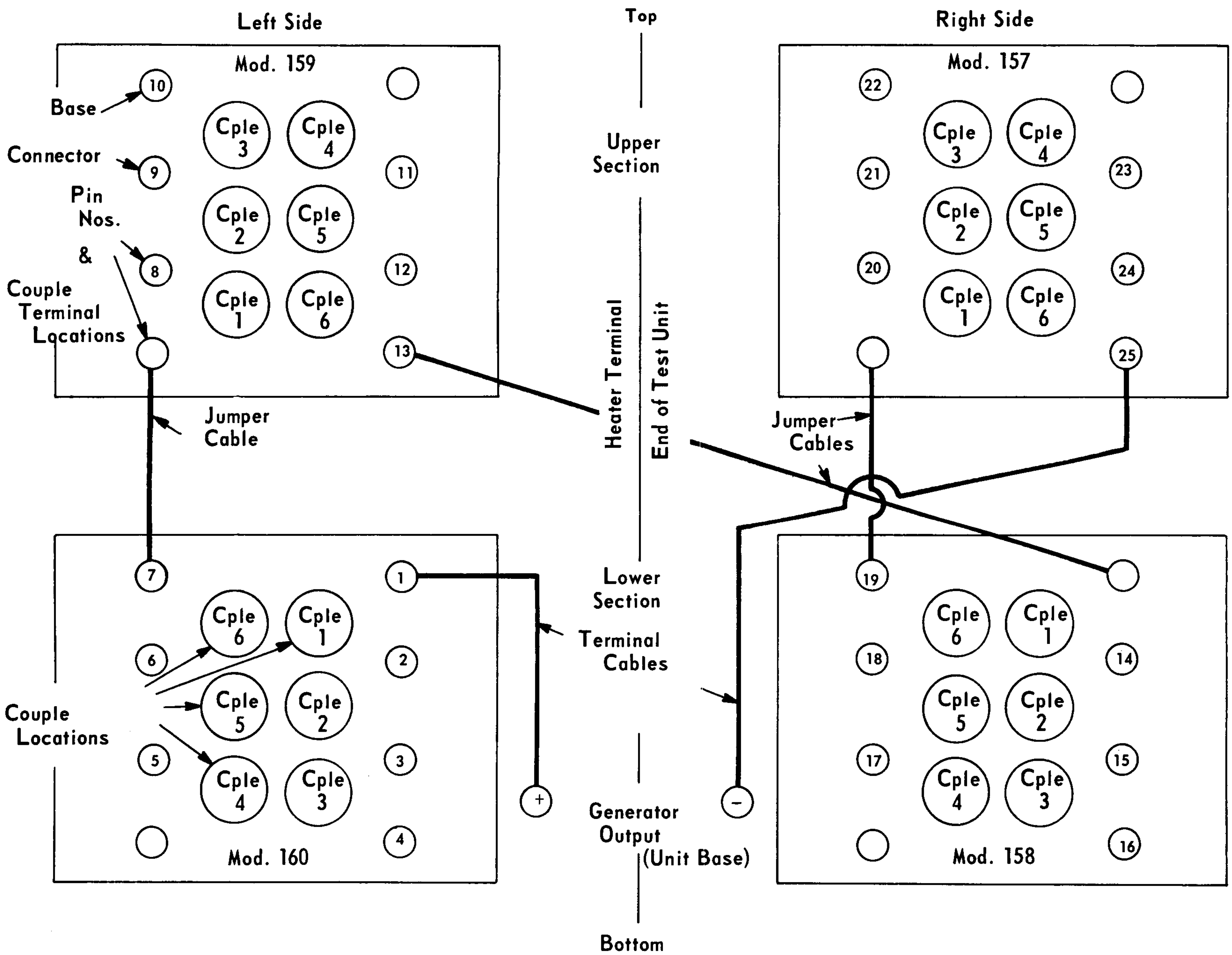


FIGURE 6 TEST GENERATOR MODULE INTERCONNECTION DIAGRAM.

Base Connector Pin* No.	Polarity	Position
1	P	Hot Shoe - Module 159 (Couple #2)
2	N	
3	P	Hot Shoe - Module 160 (Couple #5)
4	N	
5	P	Hot Shoe - Module 157 (Couple #5)
6	N	
7	P	Hot Shoe - Module 158 (Couple #2)
8	N	
9	P	Cold Shoe - Module 159 (Couple #2)
10	N	
11	P	Cold Shoe - Module 160 (Couple #2)
12	N	
13	P	Cold Shoe - Module 157 (Couple #2)
14	N	
15	P	Cold Shoe - Module 158 (Couple #2)
16	N	
17		Open
18	P	Radiator - Module 159
19	N	
20	P	Radiator - Module 160
21	N	
22	P	Radiator - Module 157
23	N	
24	P	Radiator - Module 158
25	N	
26	P	Test Unit Mid-Frame
27	N	
28	P	Base Mount (at Measurement TC Connector)
29	N	
30	P	Heat Exchanger Outlet
31	N	

* Note: When facing the heater leads the connector containing the Measurement Thermocouple terminations appears on the left hand apron of the base mount. The heater input terminations are located on this same apron.

FIGURE 7 MEASUREMENT THERMOCOUPLE CONNECTIONS JPL-MODEL-T.D.-65-201 removal, replacement or adjustment of modules or heaters without disturbance to any other portion of the test unit assembly.

The heat exchanger is a separate assembly which may be fastened directly to the module radiator wings or removed entirely, depending upon the cold junction temperatures desired.

Both the heat exchanger and test frame and base mount assembly were designed for proper registry when mounted upon the same base plane.

III. TEST UNIT DESCRIPTION

A. Test Unit Frame

The module test frame is made of aluminum angle and bar stock. Channels are milled in the heater support bars which are also fitted with stops for positive and precise location of each heater. Connections to each heater are made outside the heater cover plates which may be removed separately for individual heater replacement or adjustment.

The insulated module pan assemblies are fastened to the frame on opposite sides of each heater and consist of an aluminum pan to which the module radiator is fastened in such a manner as to form the bottom of the pan. The couples then appear surrounded by the walls of the pan and separated from them by Dyna Quartz insulation to the level of the hot shoe.

B. Base Mount

The base mount is made of aluminum formed to support the Amphenol connector bodies and to fasten to the vacuum chamber base stand-offs. The mounting holes are set on 5-inch centers. Copper stand-offs are provided of proper height to maintain registry with the heat exchanger when both assemblies are direct mounted to the same vacuum system base plate. Thermal isolation between the module test frame and the base mount is maintained through the use of four, 1-inch ceramic stand-offs. This reduces conduction heat losses from the modules under test.

C. Heat Exchanger

The heat exchanger is made of Monel tubing terminated in copper feed-through fittings located on 6-5/8 inch centers. Copper contact bars are brazed to the tubing in the proper positions for fastening to the module radiator wings. Adjustment of the radiator temperature is achieved through changes in conduction coupling between the radiator wings and the heat exchanger contact bars. This can be accomplished through the interposition of thermal resistance between radiator wings and heat exchanger in the form of shims or washers of varied material, number, conducting area, and thickness while maintaining a constant fluid flow and temperature. This method provides the condition of greatest cold junction temperature uniformity amongst the test modules regardless of their location between inlet and outlet terminations of the heat exchanger. The test unit as designed will give temperature adjustment capability, by this method, from the 371°C maximum permitted by the module structure, down to approximately 150°C with 20°C water at approximately ten gallons per hour. Reference to Figures 1 and 2 will clarify details of the heat exchanger design.

D. Heater

The heater is designed to provide a uniform, planar heat source having extended life up to temperatures of 1500°K while operating in pressures of 10^{-5} Torr or less. The heating element is made of ½ inch woven graphite ribbon. For the six-couple module, source temperature uniformity is secured through use of a heater design utilizing two graphite ribbon legs mounted in one plane and connected, electrically, in series. Within the generator and module rating limitations, the full range of thermal test conditions will require individual heater inputs of from 200 to 300 watts approximately. Typical current-voltage requirements for each heater will range from approximately 12.5 amperes and 16 volts to 15 amperes and 20 volts. With the two heaters connected in series, this range would appear as 12.5 amperes and 32 volts to 15 amperes and 40 volts, approximately. Major features of the heater structure can be seen in Figure 8. In the event of heater replacement, the heater-to-module frame orientation instruction must be followed.

E. Silicon-Germanium Thermoelectric Module

The average couple weight for this test unit design is 8.3 grams. This includes a completely bonded assembly of an N-type and a P-type silicon-germanium alloy thermoelement, a silicon alloy hot shoe and two tungsten cold shoes. Constructional and dimensional details are presented in Figure 9.

Each module, without thermal shunt insulation, but otherwise completely assembled, including six couples, thermal stress compensation, electrical interconnecting straps and test terminals, electrical insulators, and a radiator base plate weighs approximately 226 grams.

Reference to Figure 10 will disclose the major structural and dimensional features of the test module design.

The recommended maximum operating values for hot and cold junction temperatures are 900°C and 371°C respectively. These values arise from considerations of structure, thermal stress compensation, and electrical heater design rather than from silicon-germanium limitations. Utilizing water at approximately 20°C the practical minimum cold junction temperature will run about 150°C. Thus the maximum practically obtainable couple temperature differential is 750°C for this test unit. However, a maximum temperature differential for this thermocouple design is set at 900°C.

The principal thermoelectric properties of the silicon-germanium alloy used in this test unit design are shown in Figures 11 and 12 (Seebeck Coefficient), Figures 13 and 14 (Electrical Resistivity), and Figures 15 and 16 (Thermal Resistivity). Physical properties appear from the following

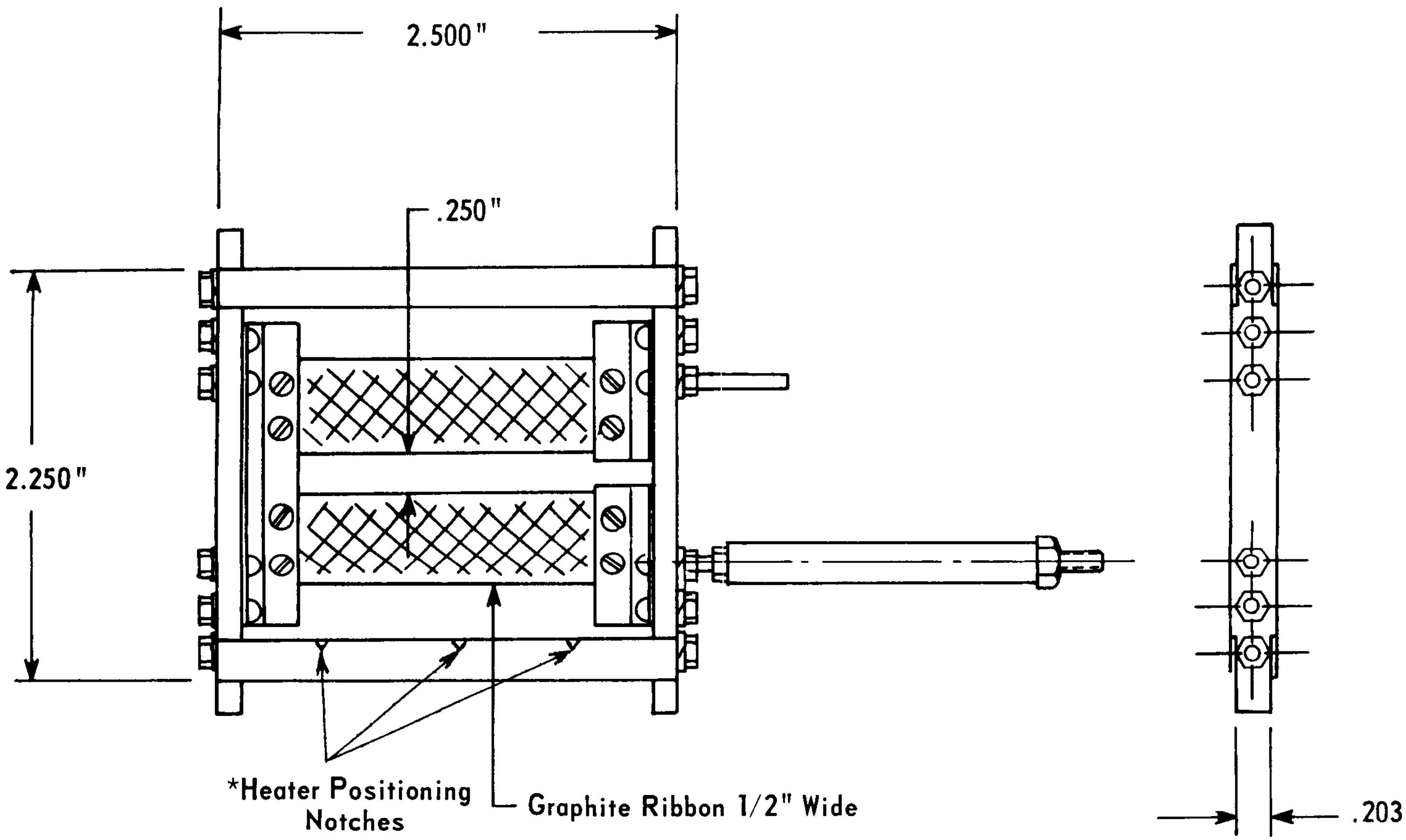


FIGURE 8 - GRAPHITE RIBBON HEATER

* Notched Frame Member always placed nearest frame center bar when inserted into test module frame.

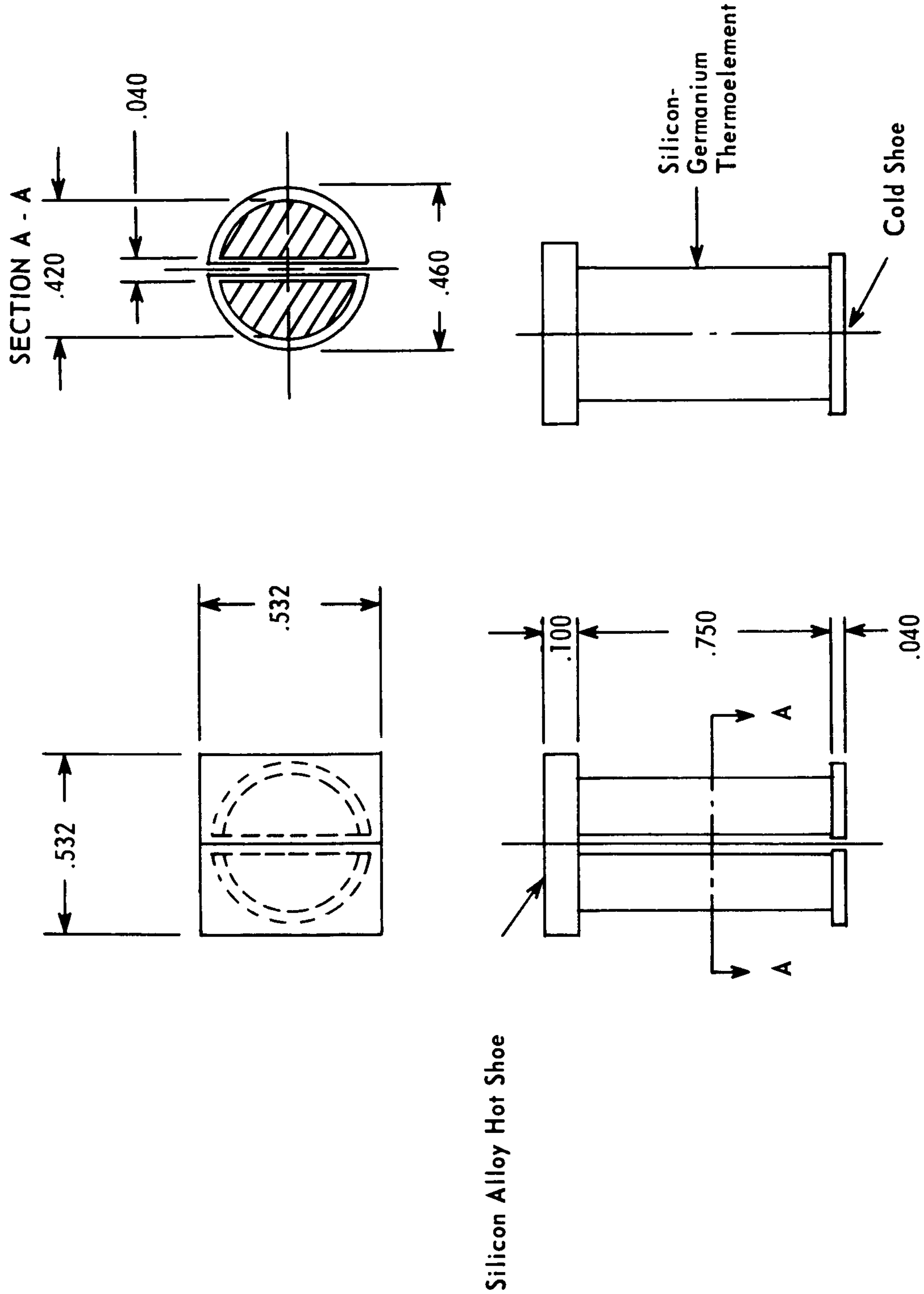


FIGURE 9 - SILICON GERMANIUM THERMOCOUPLE

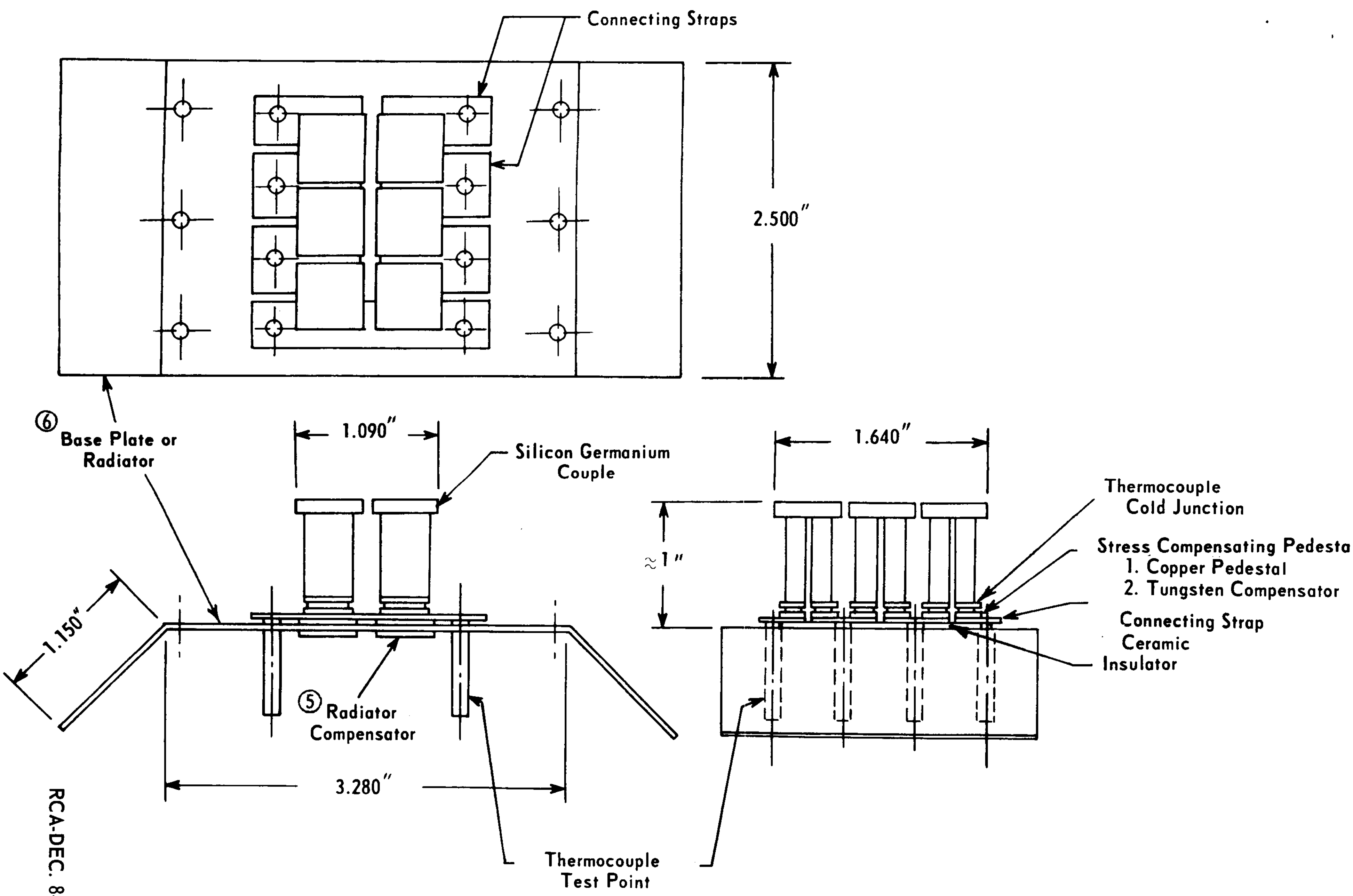


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FIGURE 10 - MODIFIED 6 COUPLE T/E POWER MODULE STRUCTURE

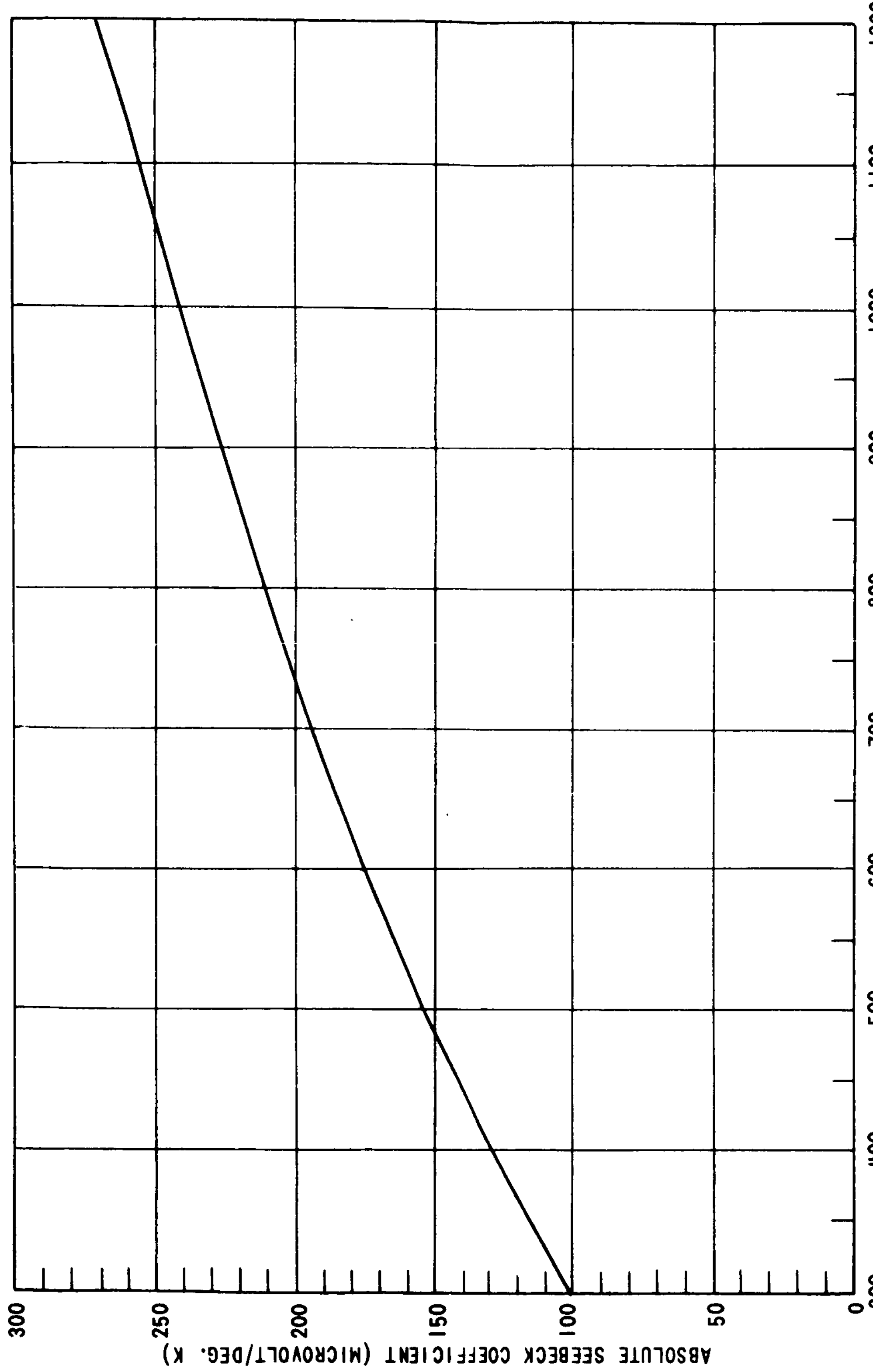


Figure 11 SEEBECK COEFFICIENT P - TYPE SILICON GERMANIUM ALLOY

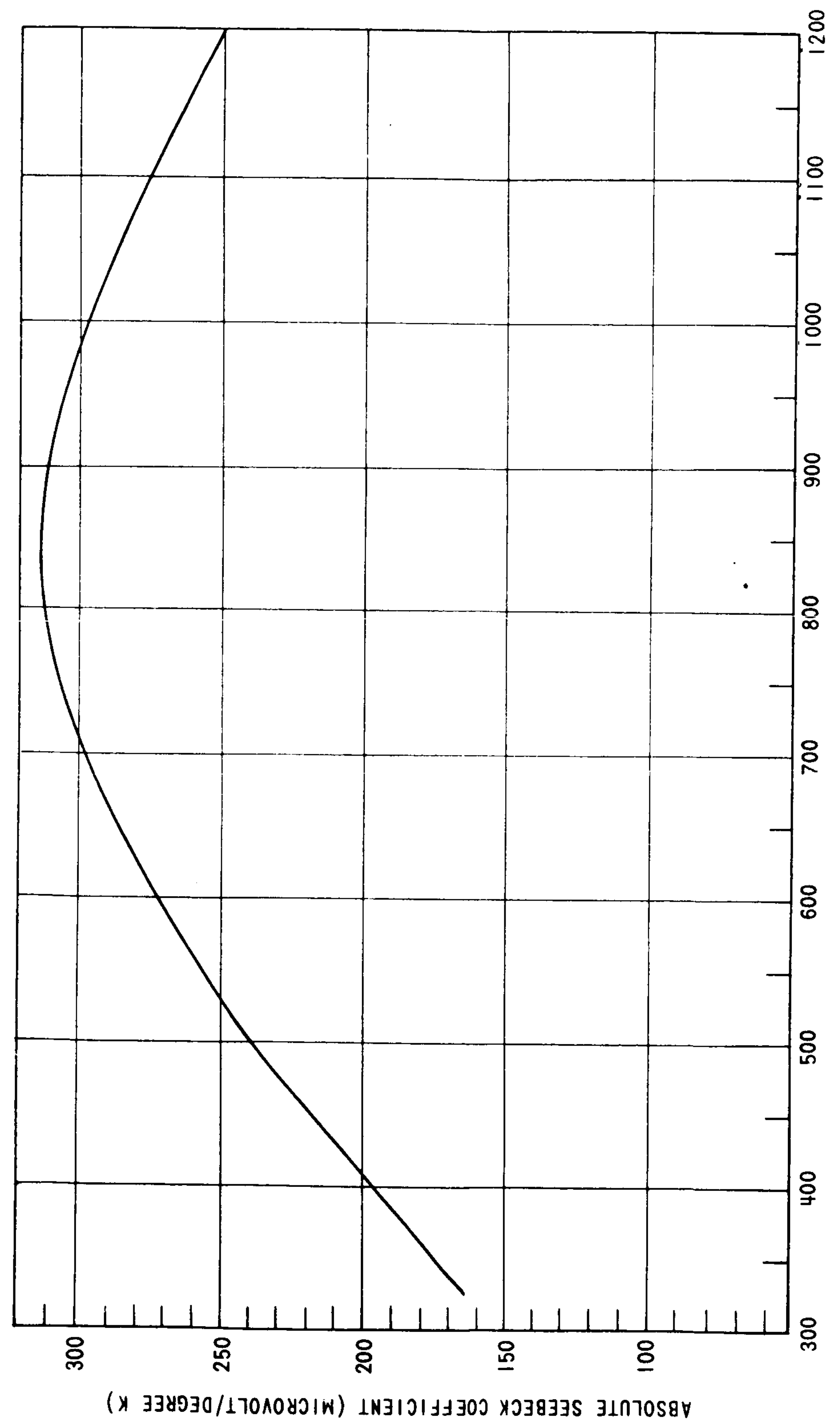


Figure 12 SEEBECK COEFFICIENT N-TYPE SILICON GERMANIUM ALLOY

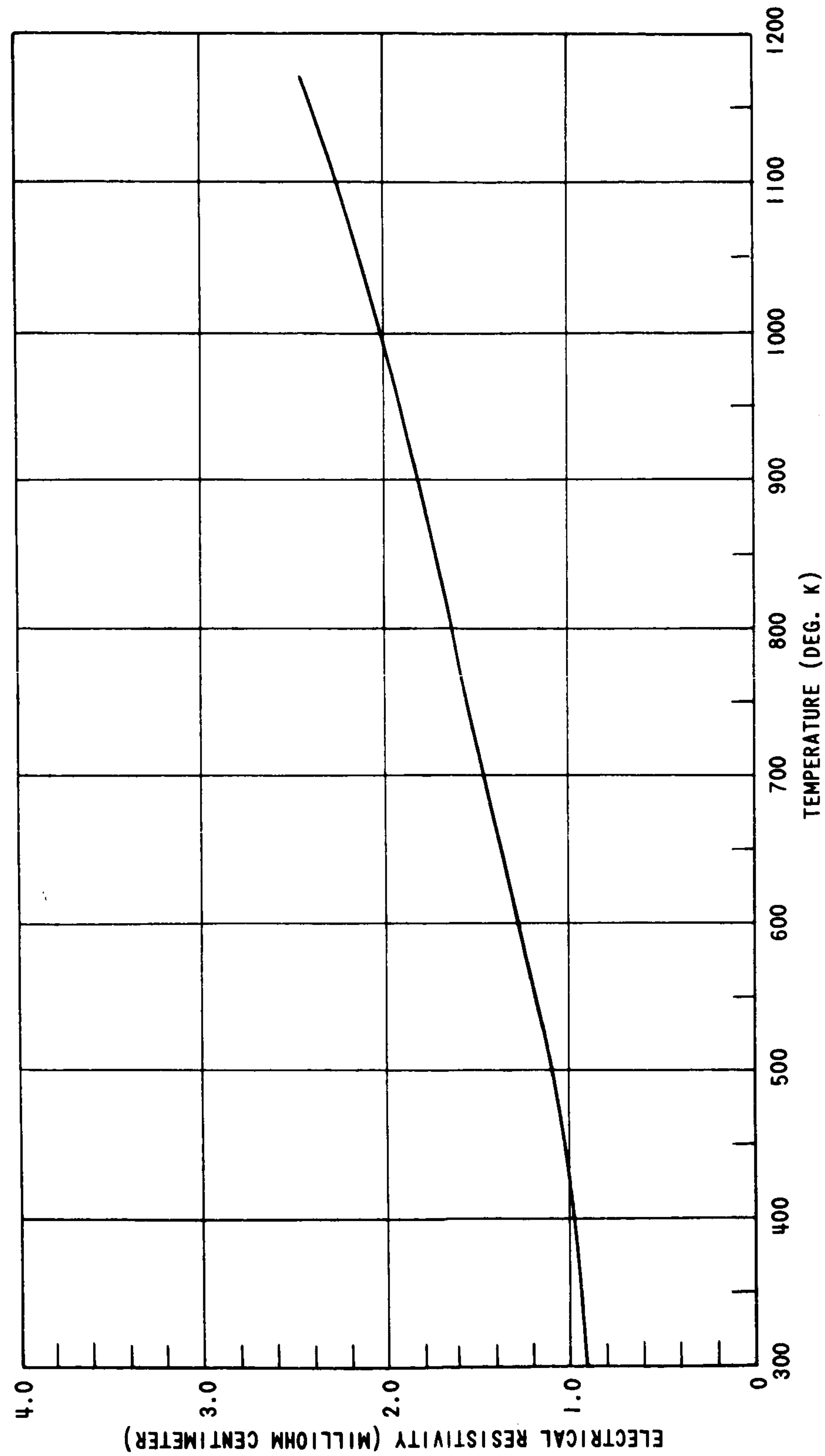


Figure 13 Electrical Resistivity P - Type Silicon Germanium Alloy

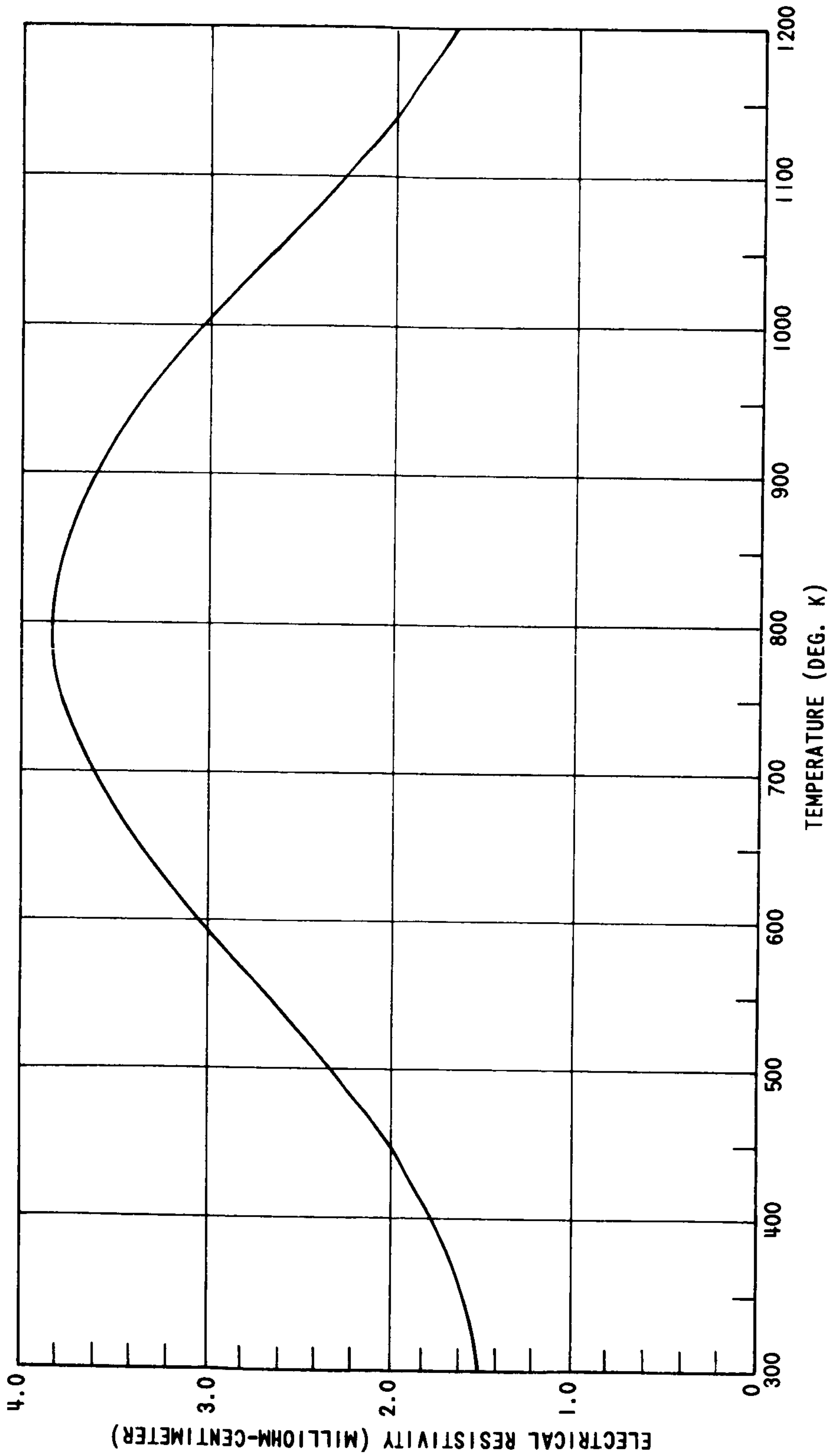


Figure 14 Electrical Resistivity N-Type Silicon Germanium Alloy

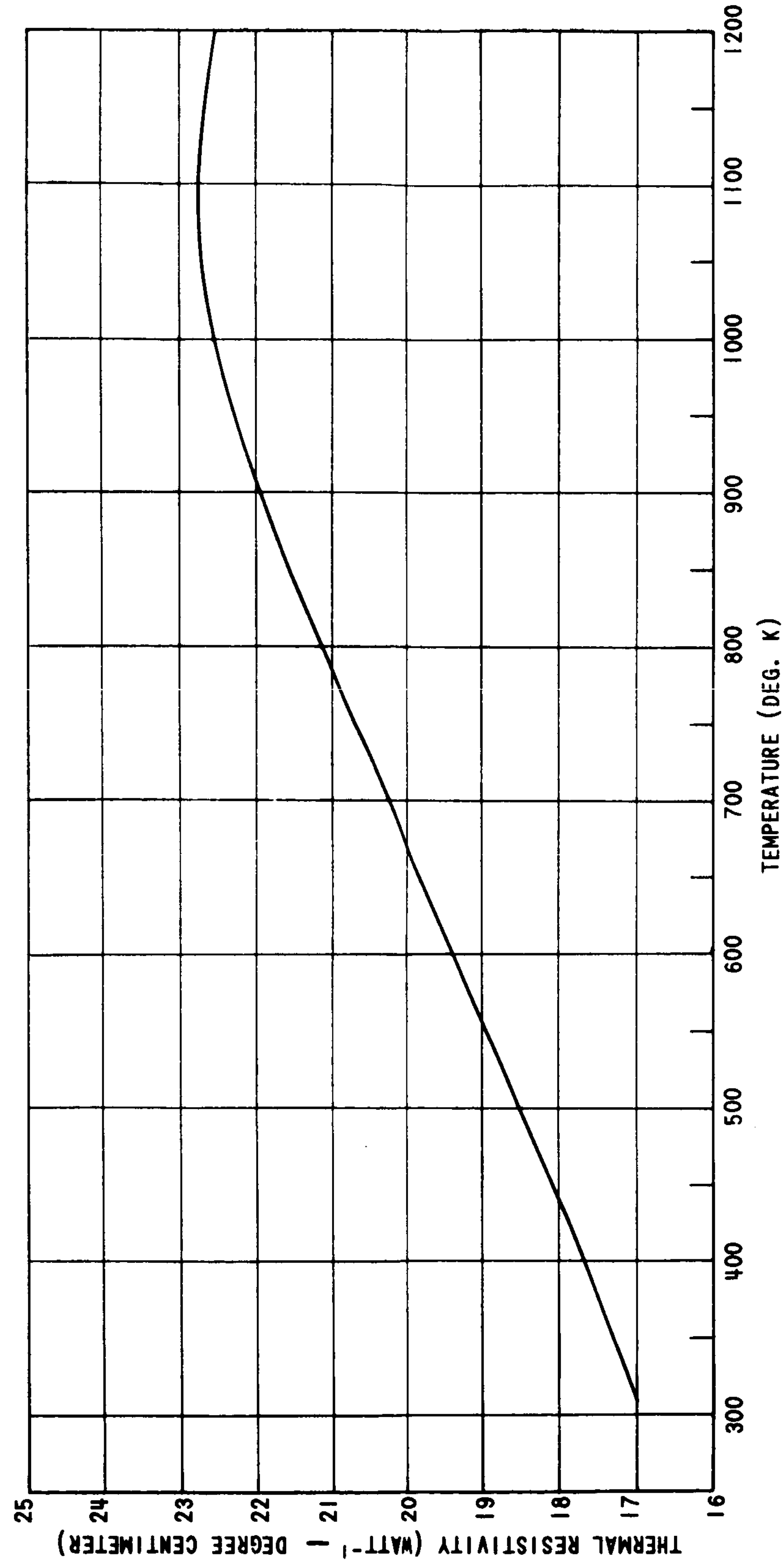


Figure 15 Thermal Resistivity P - Type Silicon Germanium Alloy

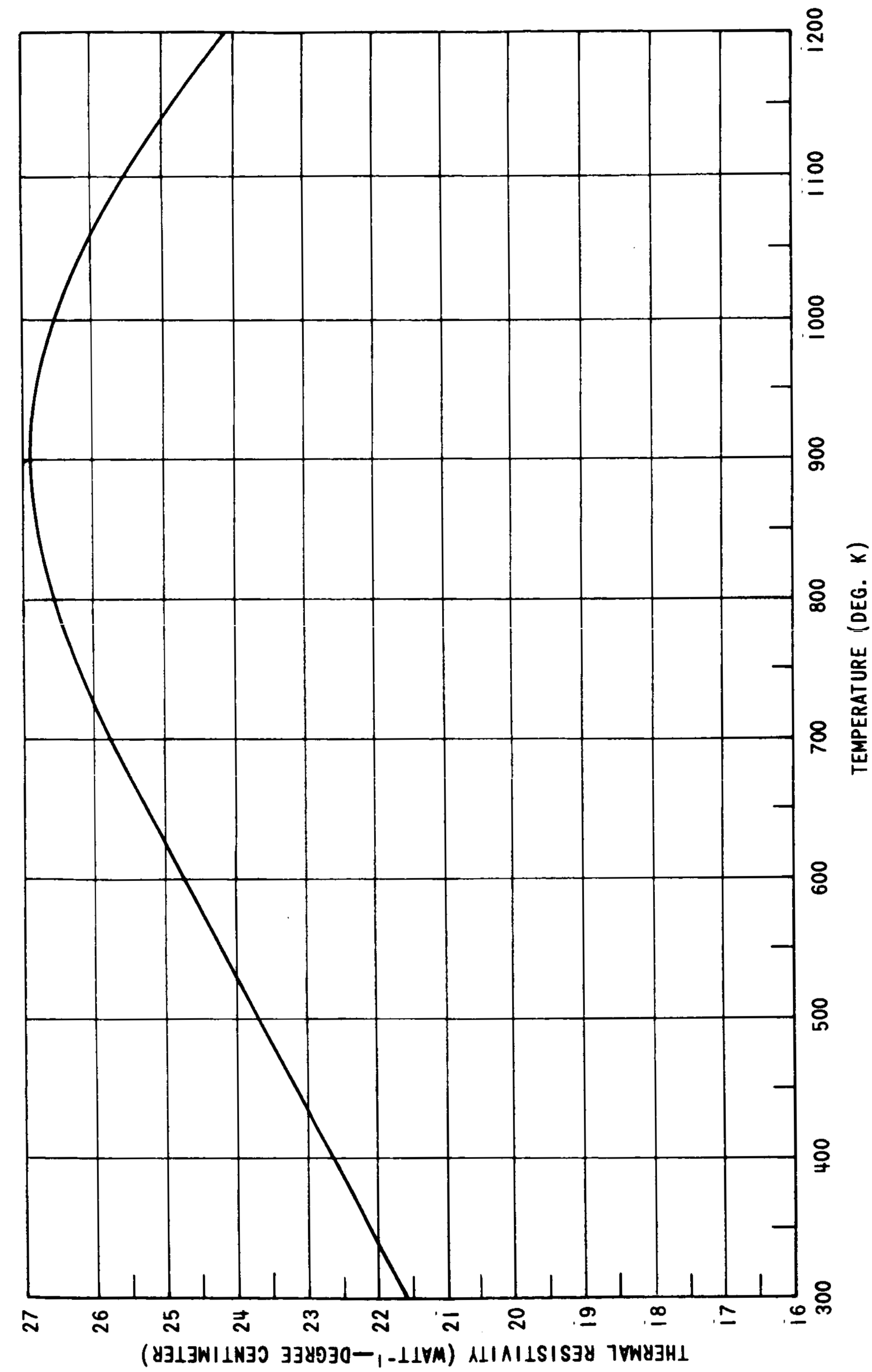


Figure 16 Thermal Resistivity N-Type Silicon Germanium Alloy

tabulation and dimensional values will be found in Figures 9 and 10 as referenced earlier.

Melting point	in excess of 1200°C
Hot tensile strength (500°C)	in excess of 4000 psi
Compressive strength (30°C)	in excess of 146,000 psi
Density	3.1 gms/cc
Coefficient of thermal expansion	5.0×10^{-6} per °C

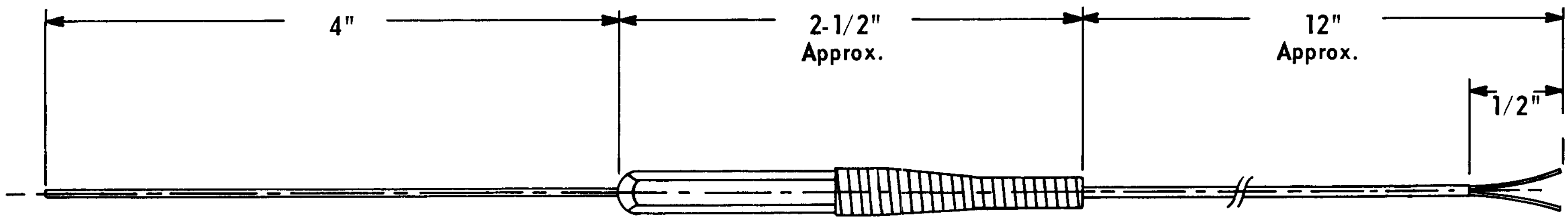
The N-type alloy is phosphorus doped. The P-type alloy is boron doped. A silicon-molybdenum alloy material with thermal expansion characteristics near those of the thermoelement alloys is used for the hot junction shoe material. This same alloy exhibits relatively high values of electrical and thermal conductivity.

The thermocouples, thermal stress compensating pedestal, electrical connectors, ceramic insulators and tungsten compensators are braze-bonded to a copper base plate serving also as the cold junction radiator. Eight test points, extending through the base plate, are provided for each module. Screw terminals at each test point make possible individual couple readings of power output, Seebeck voltage, and internal resistance. In the completely assembled test unit all test points will be wired and terminated in the base mount connectors. See Figures 4, 5, 6, 7, above.

Each module is supplied with one hot junction, one cold junction and one radiator temperature thermocouple. Chromel-alumel type couples are used. The cold junction thermocouple is permanently affixed to each module on the electrical connecting strap immediately adjacent to couple No. 2. The radiator temperature thermocouple is fastened under one of the radiator-to-module pan mounting screws. Both thermocouples use 28 gauge wire.

The hot junction thermocouple mounting has been designed to facilitate replacement without disturbing any other portion of the test unit. Performance of most of the commonly used thermocouple materials has been erratic in the immediate presence of or in direct contact with silicon alloys at normal hot junction temperatures, primarily because of metallurgical and chemical deterioration of the measurement couple. Although test results are limited it appears that a commercially available Inconel 600 sheathed and electrically insulated construction may prove satisfactory for this service. The Inconel sheath acts as a barrier between the silicon alloy material and the measurement couple providing an increased useful performance life to the latter. Figure 17 gives specification details of the thermocouple used for this test unit as supplied by the Claud S. Gordon Company of Richmond, Illinois.

Supplied by: Claud S. Gordon Co.
Richmond, Illinois



SHEATHED THERMOCOUPLE

1. Sheath - 0.020" dia., Inconel-600
2. Ungrounded Junction
3. MgO Insulation
4. Chromel-Alumel (0.002" dia. Approx.) Standard "K" Calibration
5. Operates at 1000° C (1832° F) in 1 x 10^{-5} Torr vacuum

TRANSITION FITTING

1. Chrome plated Brass with Chrome plated steel guard.
2. Sauereisen potting
3. Felted Asbestos between Chromel-Alumel leads and glass braid covered connecting wires
4. Do not use epoxy or plastic in fitting or for abrasion shield
5. Operates up to 530° C (1000° F) in 1 x 10^{-5} Torr vacuum.

CONNECTING WIRES

1. Silicone coated glass braid insulated 0.012" dia-Approx.- Chromel-Alumel wires.
2. Weld or Braze to Thermocouple wires at Transition
3. Strip insulation from end 1/2" of wires.
4. Do not use epoxy or plastic in insulation or at abrasion shield.
5. Operates up to 350° C (660° F) in 1 x 10^{-5} Torr vacuum.

FIGURE 17 SHEATHED MEASUREMENT THERMOCOUPLE SPECIFICATION

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The tip of the 0.020" diameter sheath is inserted into a hole drilled in the "P" doped half of the silicon-moly alloy hot shoe. Prior to insertion the hole is filled with a slurry of powdered boron nitride as a means of isolating the Inconel sheath from the silicon alloy in addition to providing a more intimate contact with the junction region to be measured. The transition fitting mounted upon a ceramic stand-off to the module pan gives rigid support to the thermocouple. All hot junction thermocouple supports are mounted in a similar fashion to that side of each module pan assembly opposite the heater leads. The measurement couple junctions are located in the hot shoe of No. 5 couple for modules 157 and 160 and No. 2 couple for modules 158 and 159. In addition to the hot junction thermocouple in each module, a sighting hole to the intersection of four power couple hot shoes is provided for temperature measurement using the optical pyrometer method. The Micro Optical Pyrometer, Model 95, manufactured by the Pyrometer Instrument Company, Inc., of Bergenfield, N. J. has given excellent results in laboratory measurements at RCA. No stability or measurement accuracy problems occur at the cold junction and radiator temperatures.

The bonds between all couple and module structure interfaces are strong, extremely stable up to rated operating temperatures, exhibit very low contact resistance, and have a high thermal conductivity. When the thermocouples are bonded to the base plate, they become self-supporting cantilever-type structures, free to expand during operation without creating destructive thermal stress conditions.

The physical characteristics of the module are listed as follows:

Element Material

N-type	Phosphorus doped, SiGe Alloy
P-type	Boron doped, SiGe Alloy
Hot Shoe Material	Silicon-Molybdenum Alloy
Overall heat accepting surface dimensions	1-5/8" x 1-1/8"
Emissivity of heat accepting surface	Approx. - 0.8
Total base plate dimensions	$5\frac{1}{2}$ x $2\frac{1}{2}$"
Base plate material	Copper, Ni Plated
Emissivity of base plate	Approx. - 0.5
Module height	Approx. - 1 inch
Module weight	Approx. - 226 gms.

Reference to Figure 10 will clarify module constructional and dimensional details.

IV. OPERATION AND PERFORMANCE

A. Operation

1. Test Set-Up

Requirements for setting up the unit for testing include mounting and preparation of the test chamber, instrumentation, securing the desired test conditions, and initiating the test run.

Mounting of the test unit requires four holes in the test chamber base plate of size and location as shown in Figure 3. Care should be exercised in order to maintain heat exchanger and module frame registry. Since the heat exchanger connections pass through the chamber base, vacuum tight seals must be provided. The heat exchanger feed-throughs are finished with 2 inches of 3/8 x 24 thread for vacuum seal clamping and water connections. All water connections should remain outside the vacuum chamber. The water outlet side of the exchanger is thermocoupled for outlet temperature readings.

Provision should be made for a minimum of 58 electrical feed-throughs. Fifteen chromel-alumel pairs are needed for measurement thermocouples. Twenty-four, 24 gauge, copper wires provide for couple, module and generator voltage and resistance readings. Four, high current (20 amperes) feed-throughs are needed, two for the heater input and two for generator output. If it is desired to operate the two test unit heaters under differing conditions, a fifth high current feed through will be needed. Two connector plugs with 6 to 8 inch "pig tail" leads are included for wiring to existing vacuum chamber feed-throughs.

When water cooling is desired a source providing a constant flow of from 8 to 12 gallons per hour at a known temperature between 20 and 30°C should be assured.

Under typical operating conditions a temperature rise of approximately 6°C will be observed between the inlet and outlet of the heat exchanger.

All temperature measurement thermocouples are "K" calibration, Chromel-Alumel and may be read by any one of several commercially available potentiometer type instruments including recorders. Temperatures to be read will range from 50°C to 900°C under the variety of operating conditions acceptable to the test unit.

Individual power thermocouple, module and generator output voltages will range from 0 to 500 millivolts for each couple, 0 to 2.5 volts for each module, and up to 10 volts for the full generator. The maximum values indicated are for no-load voltage readings at Δ T levels of approximately 750°C resulting from the operation of this test unit. Any voltage measuring instrument having a 1000 ohm per volt sensitivity or better is adequate.

The values of resistance encountered range from 50 milliohms for the individual thermocouple to a maximum of 1 ohm for the total generator. Securing reliable and correct internal resistance values requires some care. A method for reading hot and cold resistance, which was found most satisfactory and was used for this test, is based upon reading an AC voltage developed through the introduction into the generator of a calibrated AC current. A current of one ampere is used which is low enough so that its I^2R heating effect may be neglected. However, this AC current is introduced only during the period resistance readings are taken. An AC voltmeter having characteristics similar to the Ballantine Model 320 should be perfectly adequate.

Generator output current may be read using any normal laboratory instrument capable of reading up to 7.5 amperes.

The test unit heaters are connected in series. However, improved intermodule hot junction temperature uniformity is possible with each heater operating from completely separate, adjustable supplies. Maximum power requirements reach approximately 600 watts at 40 volts and 15 amperes. Sixty cycle AC is used and for greatest performance stability some method of regulation is necessary.

Securing the desired thermal test conditions is largely a matter of deciding upon a hot shoe temperature and adjusting the cold shoe temperature to achieve the Δ T required to produce the electrical output needed. Since these two temperatures are not independent of each other a process of successive approximation must be used to approach the conditions desired.

With the unit completely instrumented and the heater supply connected, close the vacuum system and start pumping down. Bring the chamber pressure to the 1×10^{-4} Torr level. At this point vacuum chamber base plate cooling and test unit heat exchanger cooling should be turned on. Set the heat exchanger cooling water flow to approximately ten gallons per hour. Start applying power to the test unit heater, very slowly, making sure the chamber pressure does not exceed 2.0×10^{-4} Torr. When the hot shoe temperature reaches 300 to 400°C the maximum permissible chamber pressure must be limited to 1×10^{-4} Torr. From this point until the desired hot shoe temperature is reached both chamber pressure and cold shoe temperature should also be monitored with each increase in heater power. Heater input should not be increased beyond the point at which either the hot shoe temperature reaches its maximum rated level of 900°C or the cold shoe temperature reaches its maximum rating of 371°C. During the warm-up and outgassing period it is important to permit the unit temperatures to stabilize after each heater power increase, particularly as either hot shoe or cold shoe temperature limits are approached. Once thermal equilibrium is reached, cold and hot shoe temperature readings will provide a basis upon which to determine the kind and amount of radiator-to-heat exchanger adjustment necessary to approach more closely the conditions desired.

The unit, as delivered, includes maximum thermal coupling between module radiators and the heat exchanger. With a heater power input of 600 watts, T_H and T_C should reach average levels of approximately 900°C and 170°C, respectively. With cooling water flow at 10 gallons per hour and an inlet temperature of 25°C, the water temperature at the outlet will be approximately 31°C. Generator adjustments as delivered will result in conditions providing the maximum ΔT of which the unit is capable. Figure 18 presents the range of test conditions obtainable with maximum radiator-to-heat exchanger coupling.

If T_C is not at the value desired after reaching thermal equilibrium on the first approximation cycle, it will be necessary to adjust the radiator-to-heat exchanger coupling. If T_C is higher than desired and maximum coupling has not been used this coupling must be increased. If too low, the coupling must be reduced.

To make an adjustment the unit must be brought back to room temperature and the vacuum chamber opened up to provide access to the unit. Once the unit is accessible the heat exchanger coupling adjustment can be made. Thermal coupling adjustment is achieved through changes in the conduction path between module radiator wings and the heat-exchanger contact bars at the points of fastening. Maximum coupling is secured through placing a full length copper shim between the two surfaces. Thermal coupling may be reduced successively through replacing the copper shim with stainless steel and then with Hastelloy. Contact shims of these three materials are supplied. Since three bolts are used at each radiator wing for fastening to the heat exchanger, further decoupling steps can be taken through using three washers followed by two, then one and finally no contact at all. At this point minimum coupling is achieved with no water flow in the heat exchanger and heat rejection must depend upon radiation alone.

After adjustment the unit is brought back to temperature and a check made upon the new conditions. This adjustment cycle may be repeated until the desired conditions have been approximated. Usually no more than two cycles are required to reach the test conditions desired and often the first approximation is adequate.

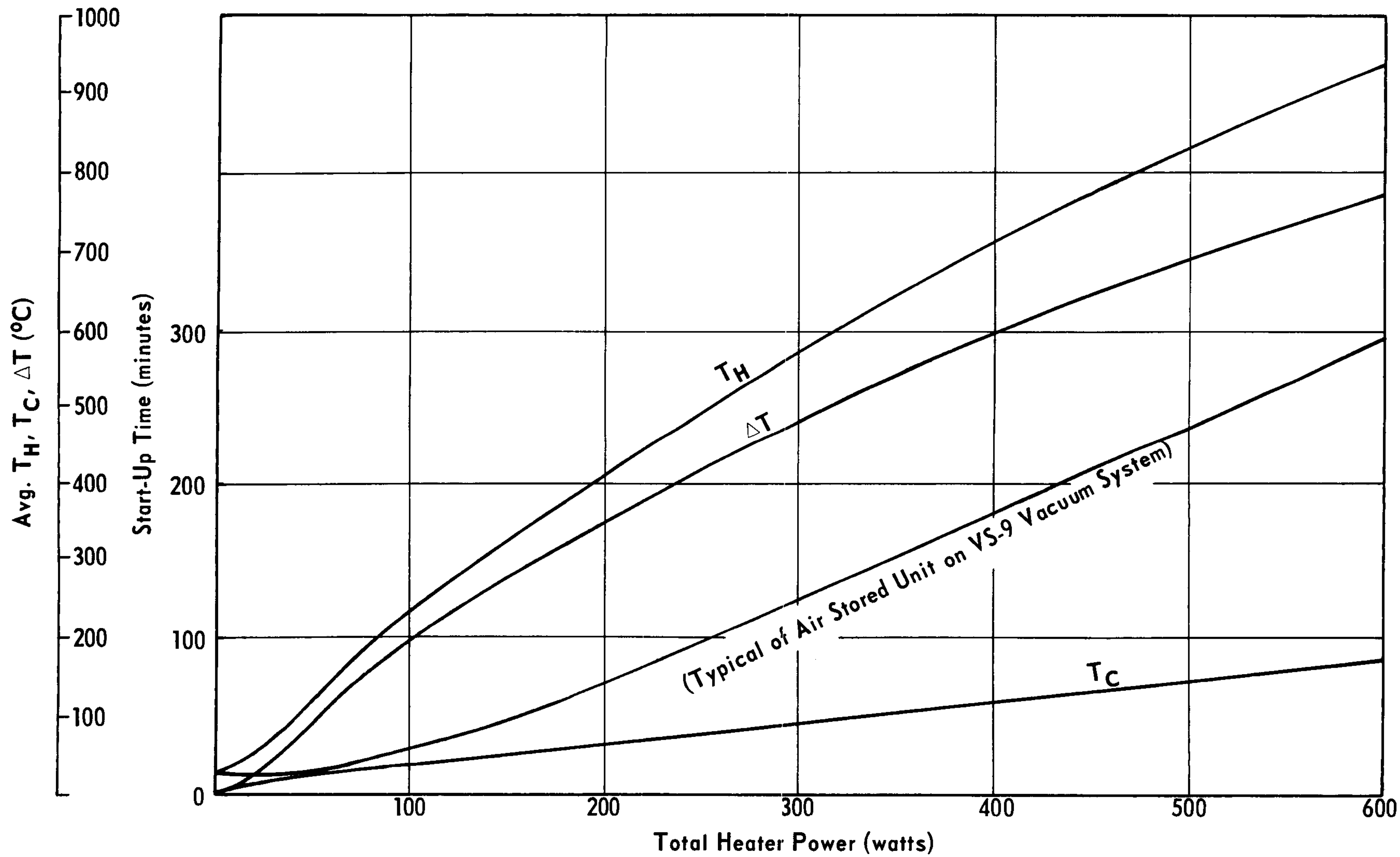


FIGURE 18 TEST UNIT START-UP AND OPERATION (FOR MAXIMUM ΔT CONDITIONS WITH WATER COOLING)

2. Test Run

The unit should be protected from events which could result in operation at hot or cold shoe temperatures exceeding the suggested maximums of 900°C and 371°C respectively. Heater life may be impaired if the test chamber pressure is permitted to remain for any length of time above 1×10^{-4} Torr. A pressure sensitive control such as appears in the Veeco RC3A power supply may be utilized to provide the protection needed.

B. Performance

Before delivery the test unit was to be operated through four thermal cycles during a period of approximately one hundred (100) hours. Actually, the unit was subjected to six complete thermal cycles over a period of three hundred thirty hours. Two hundred twenty five hours of operation at full temperature were encompassed within this period. One try-out cycle of forty-two hours preceded the test run giving the unit a total of three hundred seventy two hours of test time. Figure 19 diagrams the total test period. Plates I, II, III, IV, and V present the actual test data developed during the operating period.

The conditions chosen were intended to determine test unit performance at maximum obtainable ΔT, maximum T_H, hot shoe thermocouple performance at maximum reading temperatures, normal maximum heater input and heat exchanger performance with water flowing. Test conditions were maintained as nearly constant as practicable throughout the period to provide a valid basis for noting performance changes with time. The test conditions for the first cycle differ from those of the remaining cycles only because it proved to be the first approximation for determination of maximum thermal coupling to the heat exchanger. Therefore, its results are not included in the presentations of Figures 20, 21 and 22.

The test conditions desired were $T_H = 900°C$, $T_C = 150°C$, and $\Delta T = 750°C$. Actual average values obtained throughout the test period are shown in the following tabulation.

Unit	T_H(°C)	T_C(°C)	ΔT(°C)
Full Generator	904	169	735
Module 157	913	166	747
" 158	897	183	714
" 159	916	167	749
" 160	888	159	729

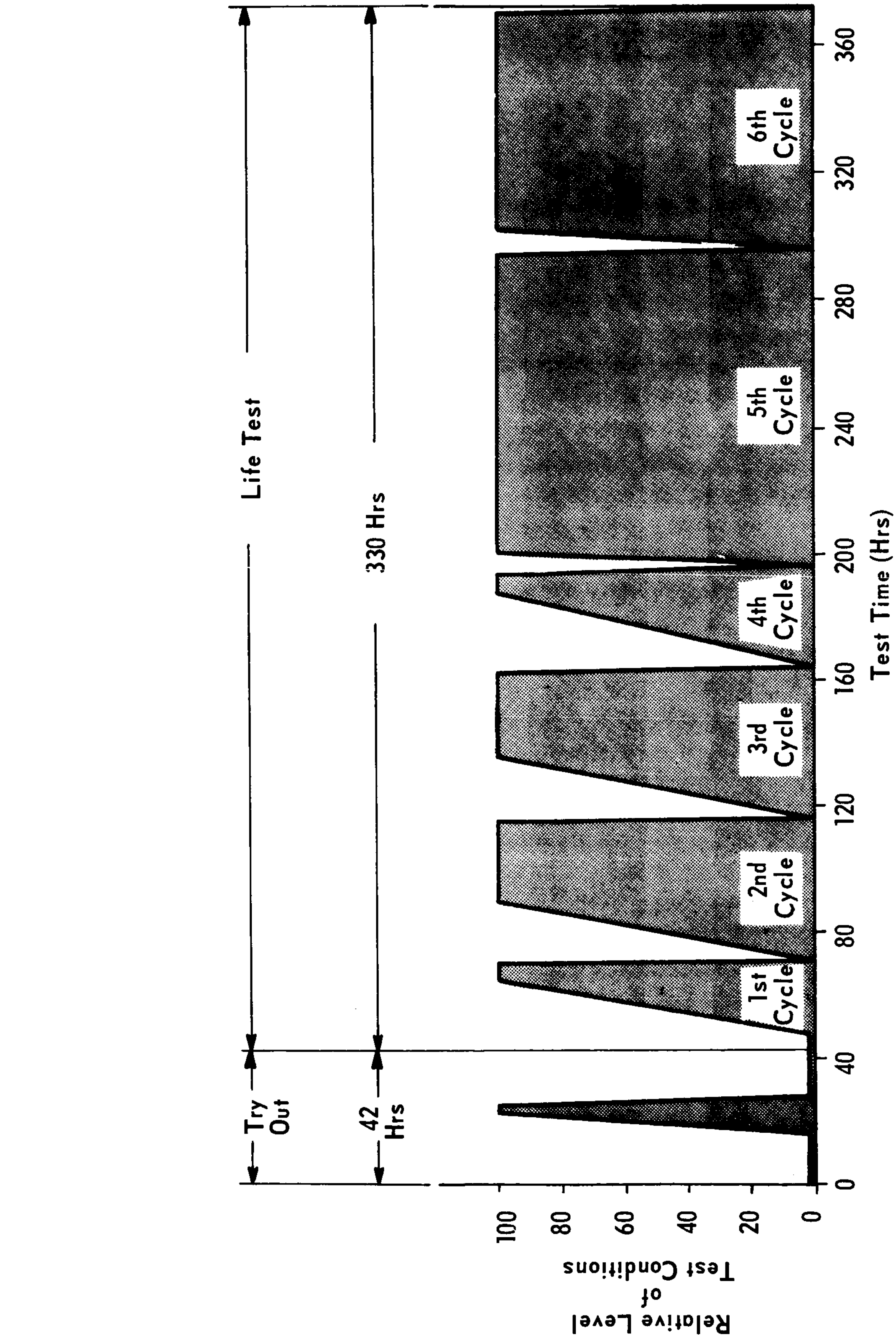


FIGURE 19 INITIAL TEST LOG JPL TEST UNIT T.D.-65-201

JPL TEST GENERATOR

INITIAL LIFE TEST   TOTAL TEST UNIT

Cycle	1st	1st	1st	2nd	2nd	3rd	3rd	3rd	4th	4th	5th	5th	5th	5th	6th	6th	6th
Accum. Hrs.	0	23	29	44	68	88	112	122	135	154	158	225	253	255	261	328	330
Avg. T_H(°C)	-	903	-	895	900	899	895	-	905	-	904	905	910	-	915	*909	-
Avg. T_C(°C)	-	285	-	161	161	170	178	-	161	-	168	167	172	-	182	166	-
Avg. ΔT(°C)	-	618	-	734	739	729	717	-	744	-	736	738	738	-	733	743	-
Output																	
E_L (volts)	-	3.7	-	3.97	3.95	4.00	3.95	-	4.00	-	4.00	3.95	3.90	-	3.95	4.05	-
E_{oc} (volts)	-	7.2	-	7.95	7.90	8.25	8.30	-	8.30	-	8.42	8.40	8.40	-	8.30	8.40	-
R_{gen} (mohms)	298	639	300	575	596	640	655	320	645	325	662	680	660	330	682	680	340
R_L (mohms)	-	690	-	575	596	630	618	-	620	-	620	620	620	-	620	620	-
I (amps.)	-	5.3	-	6.35	6.20	6.40	6.40	-	6.40	-	6.40	6.35	6.40	-	6.30	6.20	-
P_L (watts)	-	19.6	-	25.2	24.5	25.4	25.3	-	25.6	-	25.6	25.1	25.0	-	24.9	25.1	-
Input																	
E (volts)	-	36.5	-	39.0	39.2	39.0	39.0	-	40.0	-	40.0	39.8	39.8	-	39.7	40.0	-
I (amps)	-	14.0	-	14.55	14.5	15.1	15.0	-	15.0	-	15.0	15.0	15.0	-	15.0	15.0	-
P (watts)	-	512	-	568	569	588	585	-	600	-	600	597	597	-	595	600	-
Vacuum (mm Hg)	-	$5x10^{-5}$	-	$2.5x10^{-5}$	$2.5x10^{-5}$	$5x10^{-5}$	$1.5x10^{-5}$	-	$3.6x10^{-5}$	-	$3.7x10^{-5}$	$1.3x10^{-5}$	$8x10^{-6}$	-	$8x10^{-6}$	$3x10^{-5}$	-

*Thermocouple Values

Plate I

JPL TEST GENERATOR

INITIAL LIFE TEST   MODULE NO. 157

Cycle		1st	1st	1st	2nd	2nd	3rd	3rd	3rd	4th	4th	5th	5th	5th	5th	6th	6th	6th
Accum. Hrs.		0	23	25	44	68	88	112	114	135	154	158	225	253	255	261	328	330
Total Module																		
Avg. T_H(°C)		-	910	-	902	910	900	900	-	910	-	905	915	915	-	920	*952	-
Avg. T_C(°C)		-	264	-	162	163	170	178	-	154	-	163	163	167	-	175	161	-
Avg. ΔT(°C)		-	646	-	740	747	730	722	-	756	-	742	752	748	-	745	791	-
E_L (volts)		-	0.87	-	1.02	0.985	1.03	1.03	-	1.06	-	1.07	1.03	1.05	-	1.05	1.08	-
E_{oc} (volts)		-	1.70	-	2.04	1.99	2.10	2.11	-	2.15	-	2.18	2.16	2.16	-	2.15	2.17	-
R (mohms)		74.0	159	74.8	144	149	164	166	80.0	164	82.0	169	174	170	83.5	175	172	85.4
I (amps)		-	5.3	-	6.35	6.20	6.40	6.40	-	6.40	-	6.40	6.35	6.40	-	6.30	6.30	-
P_L (watts)		-	4.61	-	6.48	6.11	6.60	6.60	-	6.81	-	6.85	6.54	6.73	-	6.62	6.70	-
Couples																		
E_L/E_{oc} (mvolts)	#1	-	158/309	-	152/326	150/325	170/356	172/361	-	171/365	-	172/365	168/368	169/361	-	172/369	182/365	-
	2	-	134/274	-	148/310	142/304	158/329	158/332	-	163/342	-	166/342	162/345	165/341	-	169/346	171/349	-
	3	-	193/338	-	202/372	200/369	186/365	184/364	-	194/385	-	195/380	190/381	191/376	-	194/379	197/382	-
	4	-	191/334	-	197/363	194/359	184/359	181/356	-	196/380	-	198/378	193/379	194/373	-	195/376	199/380	-
	5	-	142/285	-	155/319	150/313	157/335	158/330	-	164/346	-	166/346	160/346	161/340	-	165/346	169/354	-
	6	-	166/312	-	155/320	153/317	171/349	173/349	-	171/353	-	173/356	166/356	166/349	-	171/355	174/361	-
R. (mohms)	#1	13.3	28.3	13.3	24.9	26.0	28.8	29.0	14.1	29.0	14.7	29.6	30.5	29.7	14.6	30.8	29.5	15.3
	2	12.6	26.1	12.6	23.4	24.0	26.5	27.0	13.2	26.6	13.5	28.2	28.0	27.4	13.9	28.0	27.9	14.2
	3	12.4	26.9	12.4	24.2	25.0	27.6	28.1	13.4	27.9	13.8	28.7	29.2	28.8	13.7	29.1	28.9	14.0
	4	12.3	26.4	12.3	23.8	24.5	26.8	27.3	13.1	27.0	13.2	28.0	28.4	27.9	13.5	28.7	28.2	13.7
	5	12.5	26.4	12.5	23.9	24.3	26.9	27.5	13.2	27.1	13.8	27.8	28.6	28.1	13.6	28.6	28.5	13.9
	6	12.6	27.0	12.6	24.0	24.6	27.1	27.8	13.4	27.3	13.7	28.2	29.1	28.5	14.0	29.1	28.8	14.3

*Thermocouple Reading

Plate II

JPL TEST GENERATOR

INITIAL LIFE TEST   MODULE NO. 158

Cycle	1st	1st	1st	2nd	2nd	3rd	3rd	3rd	4th	4th	5th	5th	5th	5th	6th	6th	6th
Accum. Hrs.	0	23	25	44	68	88	112	114	135	154	158	225	253	255	261	328	330
Total Module																	
Avg. T_H(°C)	-	905	-	898	903	880	890	-	900	-	905	900	900	-	910	*888	-
Avg. T_C(°C)	-	284	-	173	172	186	197	-	172	-	180	179	185	-	203	178	-
Avg. ΔT(°C)	-	621	-	725	731	694	693	-	728	-	725	721	715	-	707	710	-
E_L (volts)	-	0.89	-	0.925	0.905	0.900	0.900	-	0.91	-	0.92	0.88	0.88	-	0.89	0.90	-
E_{oc} (volts	-	1.78	-	1.94	1.93	1.98	2.00	-	2.02	-	2.06	2.04	1.98	-	2.02	2.08	-
R (mohms)	76.5	166	77.0	147	153	167	171	82.8	169	84.2	173	178	174	86.0	179	179	87.2
I (amps)	-	5.30	-	6.35	6.20	6.40	6.40	-	6.40	-	6.40	6.35	6.40	-	6.3	6.2	-
P_L (watts)	-	4.72	-	5.87	5.60	5.76	5.76	-	5.83	-	5.89	5.58	5.63	-	5.61	5.58	-
Couples																	
E_L/E_{oc} (mvolts) #1	-	133/305	-	108/296	104/295	126/329	129/336	-	120/334	-	126/337	120/337	118/330	-	118/330	124/338	-
2	-	126/259	-	145/312	141/310	134/308	133/313	-	134/314	-	135/319	129/318	129/312	-	137/319	146/332	-
3	-	173/314	-	185/350	185/352	160/335	160/339	-	165/345	-	165/347	160/350	160/344	-	159/340	165/353	-
4	-	176/317	-	190/354	191/358	168/342	169/346	-	178/358	-	179/360	175/363	173/356	-	175/356	184/366	-
5	-	130/272	-	151/316	149/315	146/321	148/325	-	152/331	-	154/334	149/337	148/330	-	151/332	163/346	-
6	-	158/306	-	134/300	128/298	161/339	162/346	-	165/351	-	164/351	156/353	154/344	-	155/344	162/356	-
R (mohms) #1	15.5	32.2	15.6	27.4	28.8	31.4	32.1	16.3	32.0	17.1	32.5	33.3	32.7	17.0	33.6	33.2	17.2
2	12.5	27.1	12.8	24.2	25.1	27.4	27.9	13.5	27.3	13.7	28.0	29.0	28.1	14.0	28.7	29.2	14.2
3	12.2	26.4	12.3	23.7	24.8	27.1	27.8	13.2	27.3	13.6	27.9	28.8	28.3	13.6	28.9	28.9	13.9
4	12.1	26.4	12.3	23.8	24.8	27.0	27.7	13.2	27.2	13.2	27.8	28.8	28.1	13.6	28.7	29.1	13.8
5	12.2	26.7	12.5	23.7	24.7	27.0	27.6	13.1	27.1	13.6	27.6	28.4	28.0	13.5	28.6	28.8	13.8
6	12.6	27.7	12.8	24.0	25.0	27.9	28.7	13.5	28.1	13.7	28.8	29.8	29.2	14.2	29.9	30.0	14.4

*Thermocouple Reading

Plate III

JPL TEST GENERATOR

INITIAL LIFE TEST   MODULE NO. 159

Cycle	1st	1st	1st	2nd	2nd	3rd	3rd	3rd	4th	4th	5th	5th	5th	5th	6th	6th	6th
Accum. Hrs.	0	23	25	44	68	88	112	114	135	154	158	225	253	255	261	328	330
Total Module																	
Avg. T_H(°C)	-	925	-	912	915	920	910	-	910	-	910	905	930	-	930	*921	-
Avg. T_C(°C)	-	309	-	160	159	167	176	-	160	-	166	165	169	-	180	164	-
Avg. ΔT(°C)	-	616	-	752	756	753	734	-	750	-	744	740	761	-	750	757	-
E_L (volts)	-	0.89	-	1.06	1.06	1.04	1.05	-	1.07	-	1.08	1.05	1.04	-	1.07	1.10	-
E_{oc} (volts)	-	1.76	-	2.05	2.065	2.10	2.12	-	2.14	-	2.18	2.16	2.12	-	2.16	2.18	-
R (mohms)	72.5	162	73.3	143	150	162	164	79.2	163	80.1	167	173	168	81.8	173	172	82.5
I (amps)	-	5.30	-	6.35	6.20	6.40	6.40	-	6.40	-	6.40	6.35	6.40	-	6.30	6.20	-
P_L (watts)	-	4.61	-	6.73	6.58	6.67	6.73	-	6.85	-	6.92	6.67	6.66	-	6.75	6.82	-
Couples																	
E_L/E_{oc} (mvolts) #1	-	150/300	-	161/326	162/332	171/348	177/355	-	169/349	-	169/351	165/355	164/350	-	175/359	180/361	-
2	-	129/275	-	160/324	156/324	156/329	158/336	-	165/341	-	165/344	161/348	160/341	-	163/344	171/349	-
3	-	179/323	-	206/373	204/372	190/365	192/369	-	200/380	-	202/385	198/386	196/379	-	199/379	207/385	-
4	-	169/321	-	205/380	205/381	186/368	186/372	-	195/382	-	197/387	193/388	193/381	-	195/380	196/389	-
5	-	126/257	-	157/307	157/307	164/319	165/325	-	166/329	-	169/334	165/336	165/330	-	166/330	169/343	-
6	-	153/303	-	170/339	170/340	178/358	184/366	-	180/365	-	171/370	176/371	175/364	-	180/365	179/375	-
R (mohms) #1	12.6	27.8	12.8	23.9	25.0	27.3	27.9	13.5	27.8	13.9	28.1	29.2	28.7	14.0	29.0	29.0	14.2
2	12.1	27.0	12.6	23.7	24.8	27.0	27.5	13.2	27.1	13.3	27.8	28.6	28.1	13.7	28.5	28.8	14.0
3	12.0	26.9	12.2	23.8	24.9	27.2	27.7	13.1	27.3	13.6	28.0	28.9	28.1	13.4	28.3	28.2	13.5
4	12.6	28.4	12.8	25.1	26.2	28.3	28.9	13.6	28.8	13.7	29.1	29.9	29.1	13.9	29.3	29.7	14.1
5	10.9	24.3	11.3	21.5	22.5	24.3	24.9	12.0	24.7	12.4	25.0	26.1	25.4	12.4	25.7	26.0	12.6
6	12.5	28.0	12.8	24.1	25.6	27.8	28.5	13.6	28.1	13.9	28.8	29.7	29.1	14.3	29.7	29.6	14.3

*Thermocouple Reading

Plate IV

JPL TEST GENERATOR

INITIAL LIFE TEST MODULE NO. 160

Cycle	1st	1st	1st	2nd	2nd	3rd	3rd	3rd	4th	4th	5th	5th	5th	5th	6th	6th	6th
Accum. Hrs.	0	23	25	44	68	88	112	114	135	154	158	225	253	255	261	328	330
Total Module																	
Avg. T_H(°C)	-	872	-	869	868	895	880	-	900	-	895	900	895	-	900	*876	-
Avg. T_C(°C)	-	281	-	148	148	156	162	-	158	-	163	162	165	-	172	160	-
Avg. ΔT(°C)	-	591	-	721	720	739	718	-	742	-	732	738	730	-	728	716	-
E_L (volts)	-	0.97	-	0.98	0.95	0.98	0.98	-	0.95	-	0.97	0.93	0.93	-	0.96	0.98	-
E_{oc} (volts)	-	1.84	-	1.97	1.96	2.03	2.02	-	2.01	-	2.05	2.03	1.99	-	2.05	2.04	-
R (mohms)	73.0	159	73.5	140	147	159	161	79.3	160	80.2	165	171	166	81.9	171	170	83.3
I (amps)	-	5.30	-	6.35	6.20	6.40	6.40	-	6.40	-	6.40	6.35	6.40	-	6.30	6.20	-
P_L (watts)	-	5.14	-	6.23	5.90	6.27	6.27	-	6.08	-	6.20	5.90	5.96	-	6.05	6.08	-
Couples																	
E_L/E_{oc} (mvolts) #1	-	156/306	-	126/289	120/290	154/332	151/331	-	149/327	-	153/336	146/335	146/329	-	151/334	144/333	-
2	-	128/271	-	154/318	150/319	150/324	150/324	-	150/324	-	154/331	148/331	149/326	-	157/332	150/335	-
3	-	189/340	-	194/366	194/370	182/362	180/361	-	184/367	-	187/374	181/373	181/368	-	189/372	188/374	-
4	-	191/334	-	194/356	191/358	183/354	182/355	-	175/351	-	179/356	172/356	173/354	-	180/359	180/360	
5	-	139/275	-	165/320	161/320	156/321	158/321	-	150/316	-	154/321	149/324	150/320	-	155/324	156/328	-
6	-	165/314	-	134/296	124/295	158/333	158/334	-	146/324	-	149/328	142/329	142/325	-	146/326	146/331	
R (mohms) #1	12.7	27.8	12.9	23.5	24.7	27.1	27.7	13.6	27.5	13.9	28.1	28.9	28.4	14.1	28.7	28.9	14.2
2	12.0	26.5	12.4	23.4	24.3	26.5	26.8	13.0	26.9	13.2	27.3	28.1	27.8	13.4	28.0	28.3	13.7
3	12.6	27.8	12.6	24.3	25.4	27.7	28.0	13.4	28.1	13.8	28.8	29.3	29.0	13.9	29.2	28.9	14.0
4	12.0	26.1	12.1	23.2	24.2	26.3	26.8	13.0	27.0	13.1	27.3	28.2	27.8	13.4	28.2	28.3	13.7
5	11.6	25.0	12.0	22.2	23.1	25.1	25.3	12.7	25.2	13.1	25.9	26.9	26.1	13.1	26.3	26.8	13.4
6	12.5	27.7	12.7	23.3	24.5	26.9	27.3	13.5	27.2	13.5	27.8	28.7	28.1	14.0	28.4	28.9	14.3

*Thermocouple Reading

Plate V

Avg. T_H = 904°C, T_C = 169°C, ΔT = 735°C

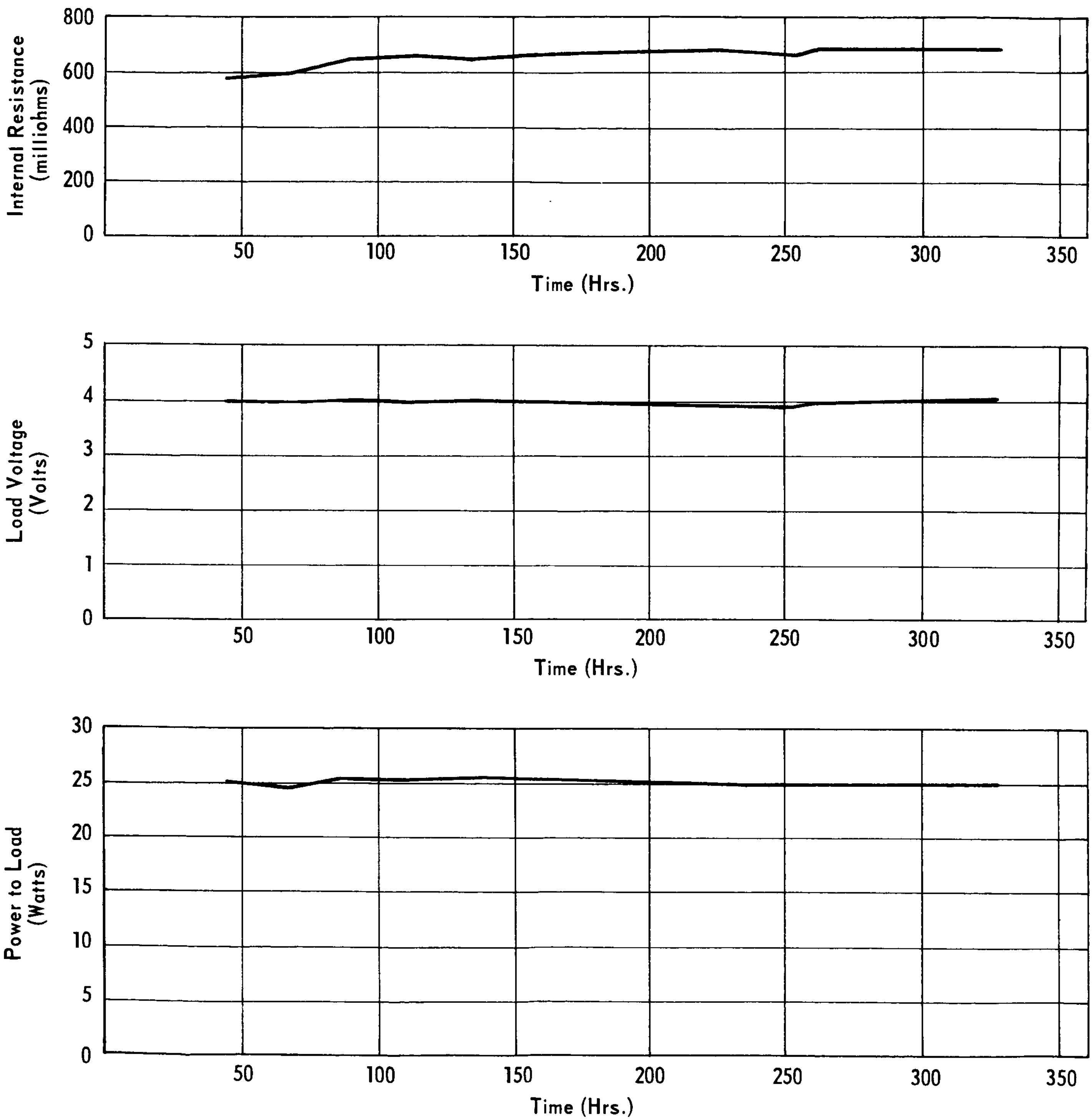


FIGURE 20 GENERATOR PERFORMANCE (TOTAL TEST UNIT)

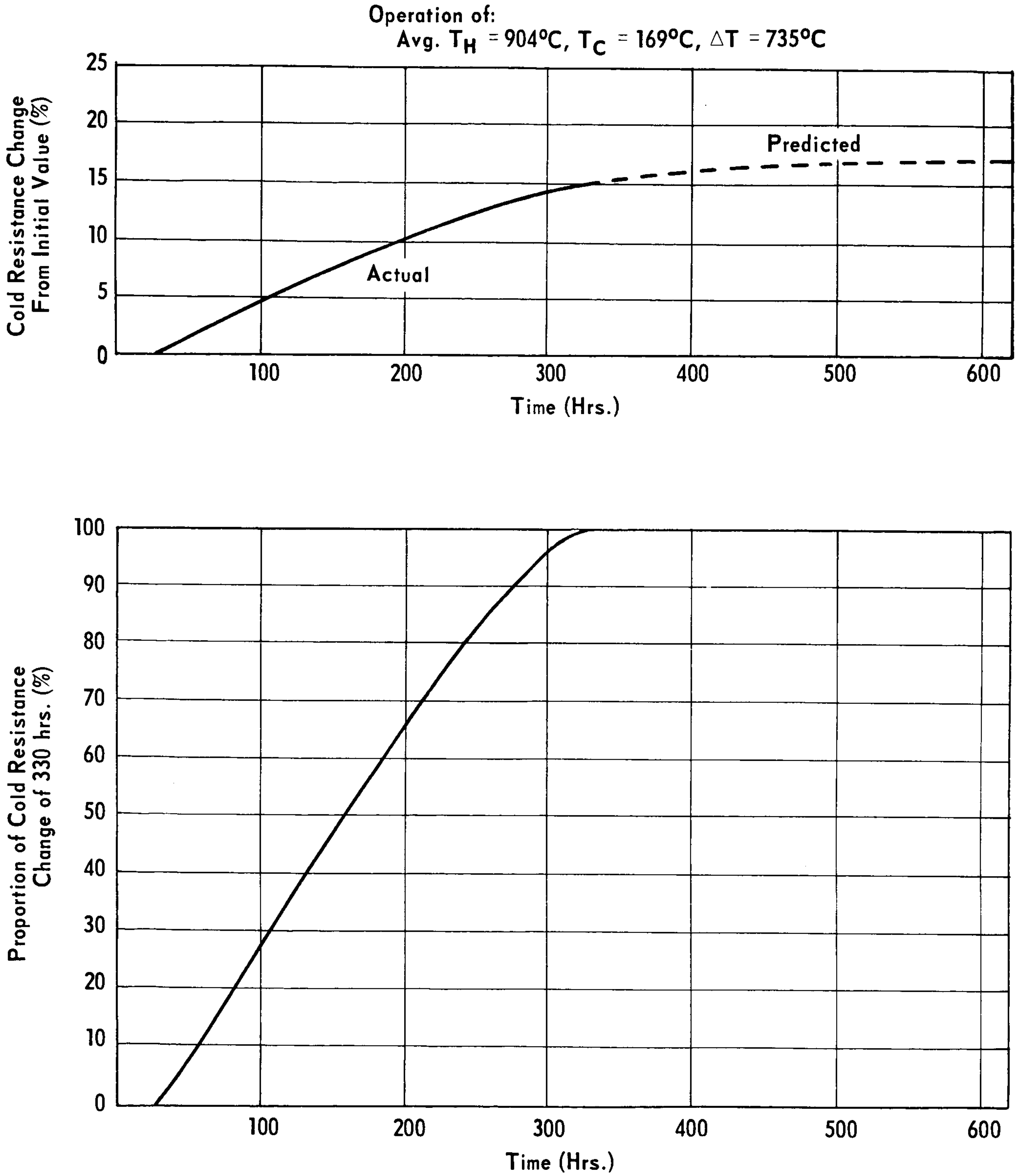
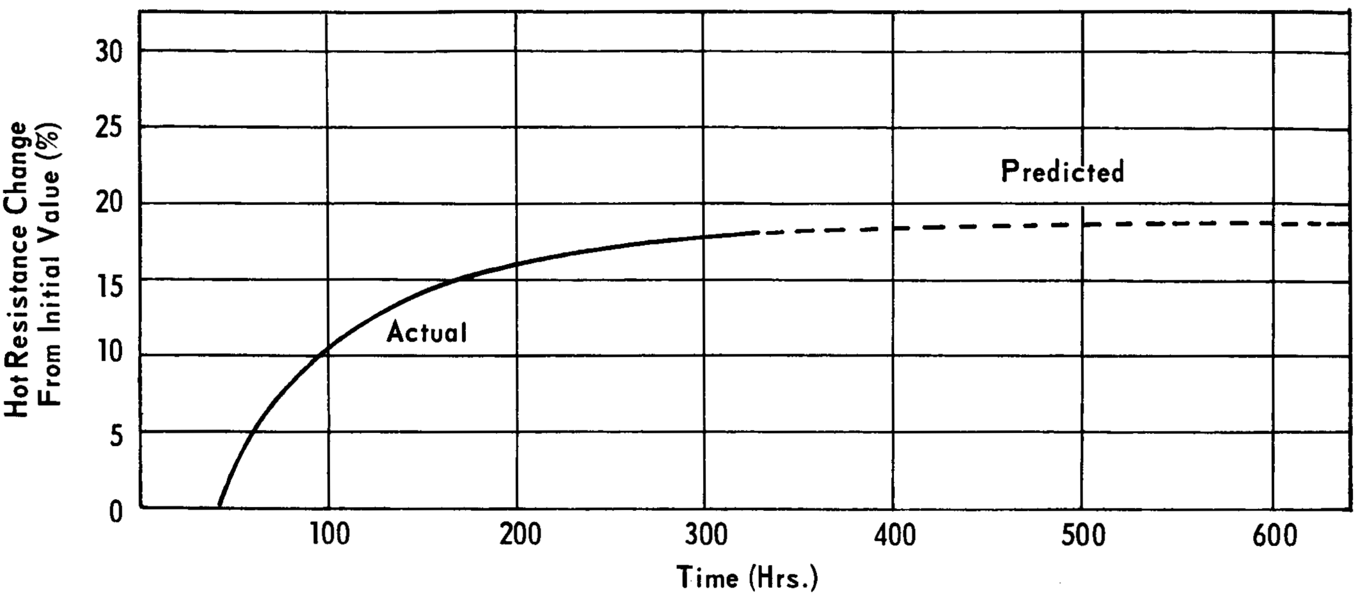


FIGURE 21 GENERATOR PERFORMANCE (COLD RESISTANCE VS. TIME)

Avg. $T_H = 904°C$, $T_C = 169°C$, $\Delta T = 735°C$



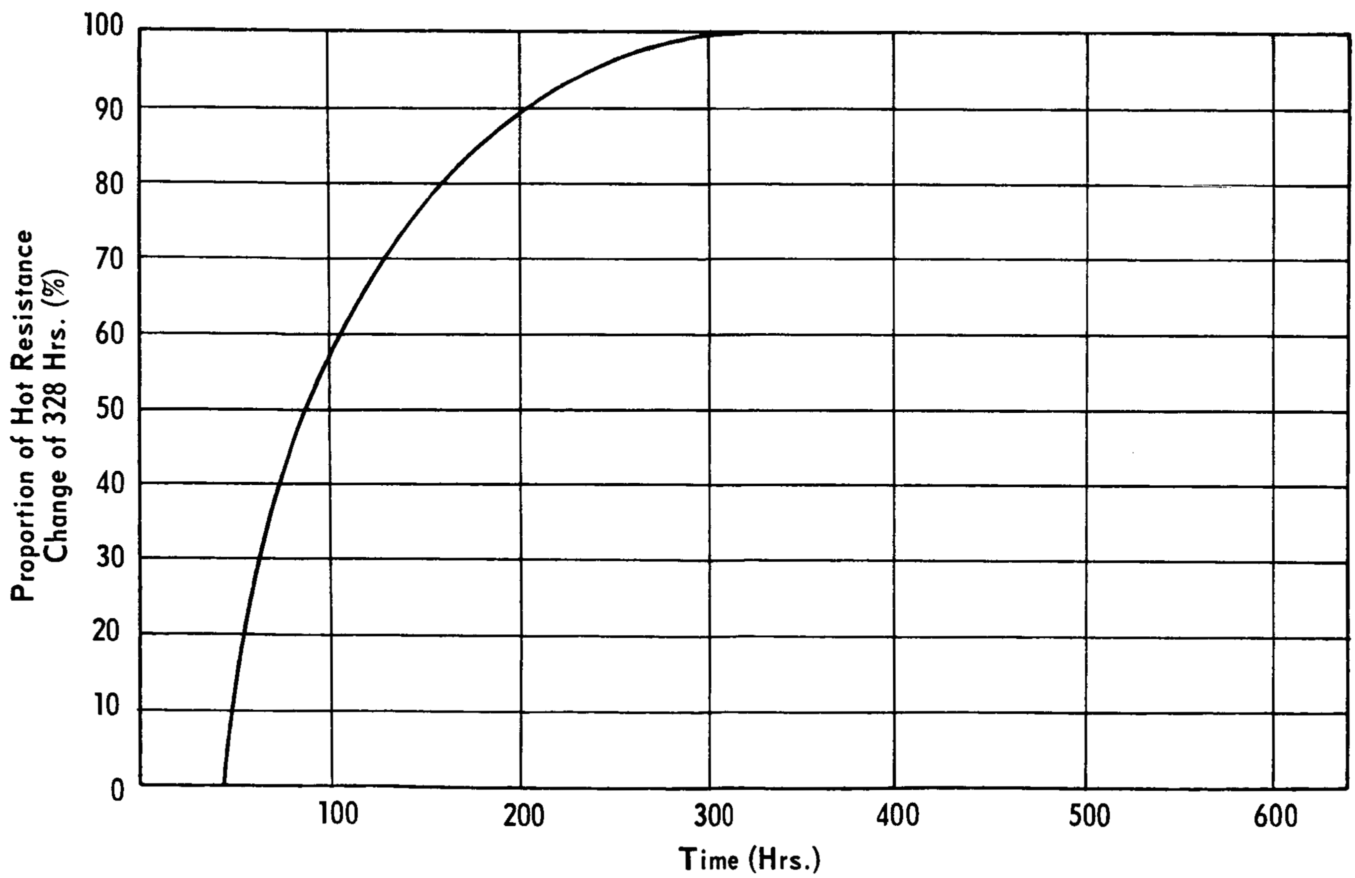


FIGURE 22 GENERATOR PERFORMANCE (HOT RESISTANCE VS. TIME)

Hot shoe temperature readings were taken using the optical pyrometer with the exception of those at the 328 hour point. The optical method was used for reasons of consistency because of difficulty with the special sheathed thermocouples used for the first time in this unit. Sheathed thermocouples as delivered initially by the Claud.S. Gordon Company used an epoxy potting compound in the transition fitting between the couple sheath and the lead wires. Although this compound was rated for operation up to 200°C, experience with the initial couples resulted in five failures out of ten units at temperatures under 100°C. The failure mechanism appeared to be a separation of the thermocouple wire resulting from the high thermal expansion characteristic of the epoxy material. Reference to Figure 17 will help clarify this discussion of the thermocouple problem. It was felt this initial thermocouple would perform within its ratings, as tests revealed the method used for mounting the transition fitting would prevent its operating at temperatures greater than 50% of the maximum permissible cold shoe temperature of 371°C or a maximum of 186°C.

New thermocouples were secured from the Claud S. Gordon Co. using a low expansion Sauereisen compound for the transition fitting. The manufacturer's temperature rating for this design is 532°C. No difficulty is expected from this higher temperature construction. It was subjected to a series of cycles up to its rating without any evidence of damage resulting.

No evidence of sheath or thermocouple deterioration appeared through the first 240 hours of operation at 900°C in contact with the silicon-molybdenum alloy hot shoe. Much longer periods of operation will be required to ascertain the adequacy of the sheathed construction when used in the presence of silicon alloys.

The test unit, as delivered, provides for ease of hot shoe thermocouple replacement without disturbance to any other portion of the test unit should failure occur within a given test period.

Agreement between optical pyrometer and thermocouple temperature readings on the average was very good. Comparisons made during the 5th and 6th cycles between the two reading methods show average optical readings to be 910°C and average thermocouple readings to be 901°C. This provides an average difference of essentially 1%. The maximum differences in individual readings were in the order of 3.5 to 5%. On the average the thermocouple reading was lower than the optical reading.

Figure 20 shows that the generator developed voltage and power-to-load remained essentially constant at 4.0 volts and 25 watts, respectively, throughout the test. Generator hot resistance increased by some 18% over the initial value. Figures 21 and 22 provide curves of cold and hot resistance change and rates of change for the test period. Under the test conditions chosen the total resistance change should stabilize at approximately 20% at an operating time of from 1000 to 1500 hours. As can be seen, approximately 75% of the expected change has already occurred at the 330 hour point.

V. CONCLUSIONS

RCA has fabricated a silicon-germanium thermoelectric test unit for the Jet Propulsion Laboratory. It is adaptable to a range of test conditions encompassing those encountered in practical space power system environments. As a result it will provide useful data for assessing the application of silicon-germanium thermoelectric devices to space power needs.

Initial life testing to 330 hours at maximum ΔT conditions indicates a performance in agreement with that of calculation and experience for couples of the design used. Provisions have been made for test condition and performance monitoring applicable to mechanized readout.