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SIMULATED RADIOISOTOPE THRUST SYSTEM AND COMPONENT DEVELOPMENT

FINAL REPORT

By

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prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Contract NAS 5-9670

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Final Report

For

SIMULATED RADIOISOTOPE THRUST SYSTEM AND COMPONENT DEVELOPMENT

Contract No. NAS 5-9670

Prepared For

National Aeronautics & Space Administration
Goddard Space Flight Center
Greenbelt, Maryland

Prepared By

Nuclear Systems Programs
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Cincinnati, Ohio 45215

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I SUMMARY

This report summarizes the work performed under contract NAS 5-9670 toward the development of both electrically heated and radioisotope-heated thrusters for attitude control and station keeping of space satellites.

A single-jet thruster designated TSK 2000-1P was designed, fabricated, and performance tested at GE after which it was preflight qualified at GSFC.

A more complex thruster, consisting of four attitude-control thrusters and one station keeping thruster grouped around a common heater, designated TMJ 2000-5P, was also designed, fabricated, and tested.

Two versions of a radioisotope-heated thruster were fabricated - one with a radioisotope heat source and the other with an electrical simulator. Preliminary tests were performed with the electrically heated version at GE propulsion laboratory while the "hot" fueled tests were performed under AEC sponsorship at Monsanto's Mound Laboratories.

A higher temperature (3000°F) simulated radioisojet thruster was designed after preliminary heater tests had been performed satisfactorily. This effort was terminated prior to fabrication of the thruster hardware.

An ammonia decomposition catalyst study was performed under sub-contract to Englehard Industries with decomposition demonstrated at temperatures as low as 1500°R. One of the TSK 2000-1P thruster bodies was modified to include a catalyst bed and the thruster, designated

TSK 2000-1C, tested over a wide range of temperatures. A significant increase in delivered specific impulse with the ammonia decomposition catalyst was seen during these tests.

Thermal storage material addition as a means to increase average specific impulse during a pulse was investigated analytically and found to be unattractive for the typical missions analyzed.

A major effort was made to develop a long-life heater to operate at 2000°F for 10,000 hours. 6600-hour life was demonstrated with a mechanical failure occurring in the external lead wire to terminate testing. Cycle life of over 120 cycles from room temperature to 2000°F was demonstrated with a modified platinum wire designated thermoplatinum fg.

II INTRODUCTION

The performance of work under this contract was directed toward the development of four thruster types for GSFC. Two of the designs were specifically designed for electrical resistance heating, with one a single-nozzle version for station keeping and the other a multijet thruster with four attitude-control nozzles and one station-keeping nozzle. The remaining two types were designed for operation with radioisotope heaters - one for operation at 2000°F and the other for operation at 3000°F. The 2000°F thruster was designed to be operated with both an electrical heater and a radioisotope heat source. The 3000°F thruster was designed to be tested with an electrical heater only.

In conjunction with the thruster development, a heater improvement task was carried out. The heaters designated HSK 2000-20P, HMJ 2000-30P, and HSK 2000-70P were tested at 2000°F for 1500 hours after a series of preliminary screening tests for 200-hour periods. Post test analyses including complete metallurgical examinations were performed at the conclusion of each test.

Associated supporting investigations such as component vibration tests, valve endurance tests, catalytic decomposition measurements, and a thermal storage parametric study were carried out during the period of the program.

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III DISCUSSION OF WORK PERFORMED

A. TSK 2000-1P Thruster

The TSK 2000-1P thruster is a resistance-heated thruster designed for station-keeping operation at a nominal core temperature of 2000°F. The thrust level assigned for this function with this thruster is 0.020 lb. at 1-1/2 atmospheres chamber pressure.

The design of this thruster is based on the proven thermodynamic and fluid dynamic designs generated under Contract NAS 5-9013 but modified to provide mechanical resistance to the rigors of launch vibration and acceleration as well as resistance to the temperature and humidity expected while at the launch site.

The thruster design which has evolved, utilizes a flow annulus to provide heat transfer to the propellant, the inner surface of which is the exterior surface of the heater assembly instead of the inner body previously used. By removing that component from the design, the temperature drop between the heater wire and the gas side surface was reduced materially, thereby insuring longer anticipated heater life. An additional effect of the elimination of the inner body is a reduction in the overall diameter of the thruster body assembly, which in turn reduces the heat rejection through the heat shielding.

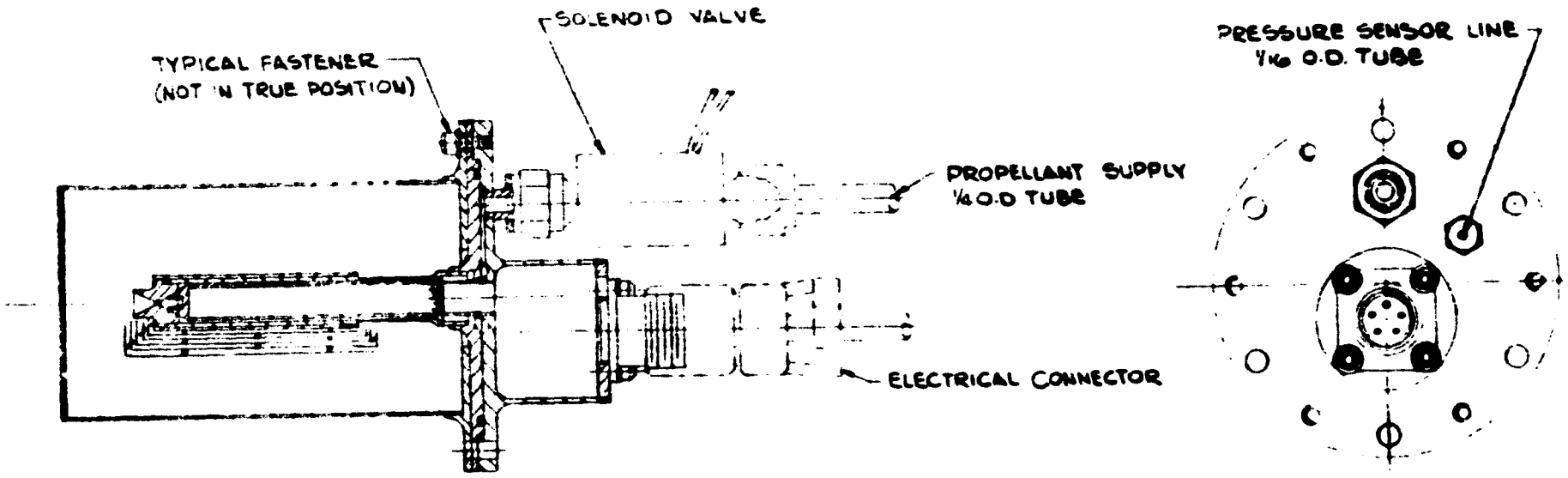
The TSK 2000-1P thruster incorporates three major sub-assemblies: the heat shielding package, the thruster body, and the heater. A gas

seal is made by the use of a silicone rubber O-ring seal. An Apex seal consisting of a "V" cross-section stainless steel ring coated with silver was on hand to be used in the event that flange temperatures exceeded the maximum allowable operating temperature for silicone rubber. Subsequent testing indicated sufficiently low temperatures in that area to preclude the need for such a seal.

The rear of the thruster body utilizes a 3-1/4" diameter mounting flange for attachment of the thruster to the space vehicle. The thruster body/heater sub-assembly is cantilevered from this flange projecting approximately 3" from it. Electrical connections to the heater are made by means of a commercially available connector plug. Two of the pins carry heater power while two others, fabricated from chromel and alumel, provide connection to a chromel/alumel thermocouple mounted in the heater at the extreme nozzle end.

A direct pressure measurement at the convergent section of the exhaust nozzle is not feasible in this design without compromising its simplicity and reliability. The preferred location, therefore, is at the mounting flange where a measurement of annulus inlet pressure is made and can be used for thrust correlation. An engineering sketch of the TSK 2000-1P design is shown in Figure 1.

Preliminary tests were performed with simulated thrusters to determine the effects of vibration on the structural integrity of thin-walled thruster support tubes. The first tests were performed



Scale = 0 1"

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Figure 1. Resistance Jet Unit TSK 2000-1P Engineering Sketch

with two thruster models of the type shown in Figure 2. This geometry, which was generated prior to the new TSK 2000-1P design, closely approximated the design of the earlier TSK 2000-1 thruster developed under Contract NAS 5-9013 with some modifications to simulate the heater support tube. Two tube sizes were used: one with a 1/4" OD by 0.010" wall, the other with a 3/8" OD by 0.015" wall. The vibration spectrum covered was as follows:

Mode - sinusoidal in three axes
Max acceleration - 10 g's
Max displacement - 1/4" single amplitude
Frequency range -6-2000 cycles/sec
Sweep time per octave - 2 minutes

Both specimens were dye penetrant inspected prior to vibration and after vibration. Precise measurements of thruster orientation were also made prior to and after vibration.

Upon completion of the vibration testing, the 3/8" support tube version was again measured and found to have shifted less than 0.05°. The second specimen (1/4" support tube) failed during vibration in the second transverse mode. However, prior to the transverse acceleration, the specimen had been inadvertently bent approximately 5° from the vertical, thereby greatly clouding the results of this portion of the testing.

While these samples provided some indication of the reliability of a cantilevered thruster, they did not represent the more advanced TSK 2000-1P design. In fact, due to the weight of these thruster bodies, the results obtained were considered quite conservative.

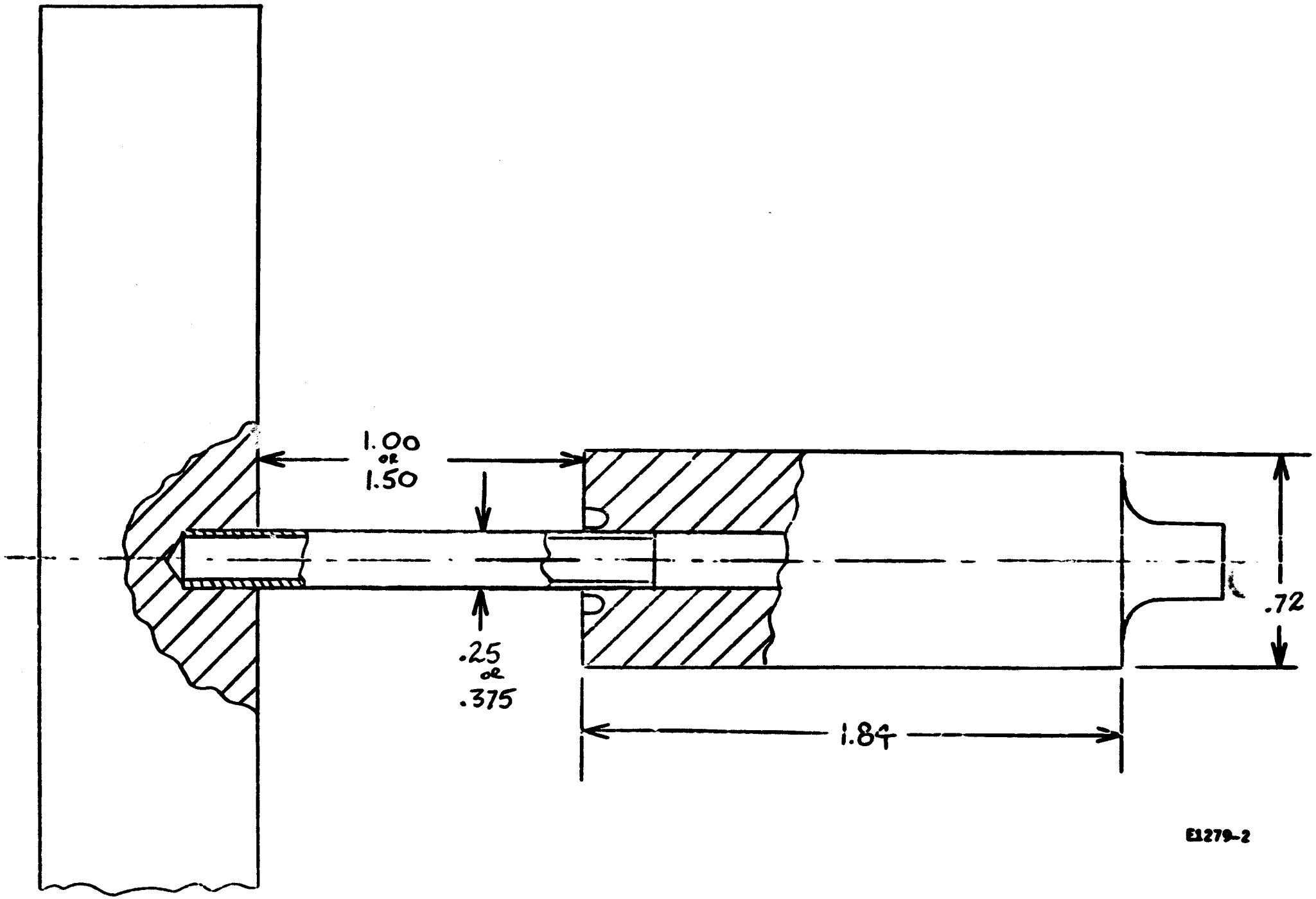


Figure 2. Thruster Vibration Test Specimen - First Model

Two additional vibration samples as shown in Figure 3 were fabricated with a geometry closely simulating the new thruster design of Figure 1. The inner support tubes corresponding to the heaters were fabricated of 1/4" tubing and the outer thruster body embodied a 3/8" minimum diameter.

The vibration spectrum was again investigated for both thrusters - one by itself and the other with a 30-layer Nichrome V heat shielding package surrounding it. The results obtained were exceptionally good with no measurable permanent deformation of the support tubes.

One of the critical assembly procedures is the alignment of the heater in the heater support plate, since the thruster body and nozzle assembly is piloted on the heater. To provide this alignment, the welding jig shown in Figure 4 was fabricated and proved to be successful. By actual measurement performed at GSFC, the nozzle axis was shown to be off the vertical from the mounting flange by only 35 seconds of arc. Once the assembly is made, the heater can be replaced, if necessary, by using the same welding jig, since the contact surface in the jig exactly simulates the internal contour of the thruster nozzle.

Heat shielding for this thruster initially consisted of 40 layers of 0.002" molybdenum foil separated by 0.014" diameter Nichrome V wire. This selection of molybdenum was based on its low emissivity compared with Nichrome V although the Nichrome V separating wire was retained because of its low thermal conductivity.

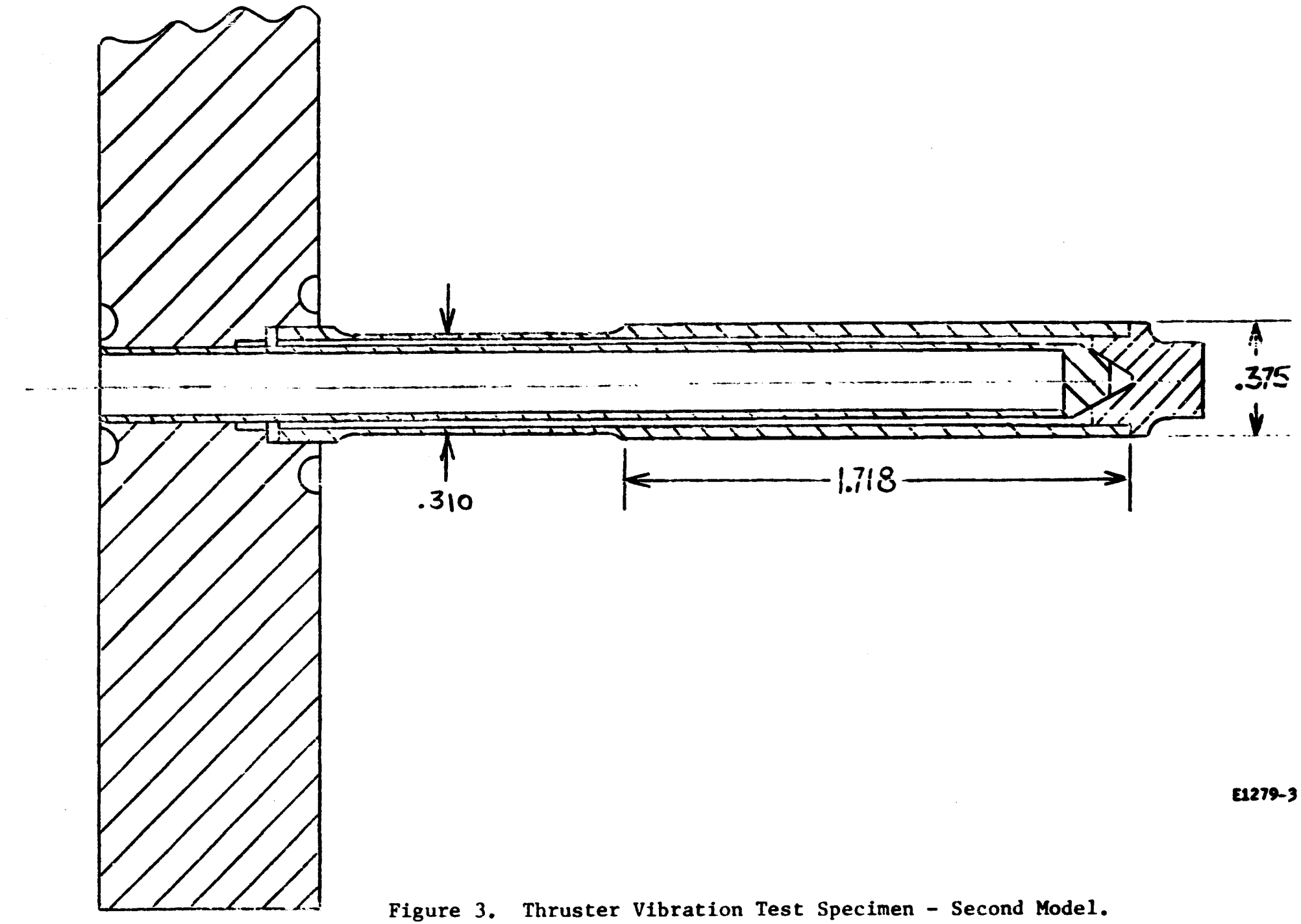


Figure 3. Thruster Vibration Test Specimen - Second Model.

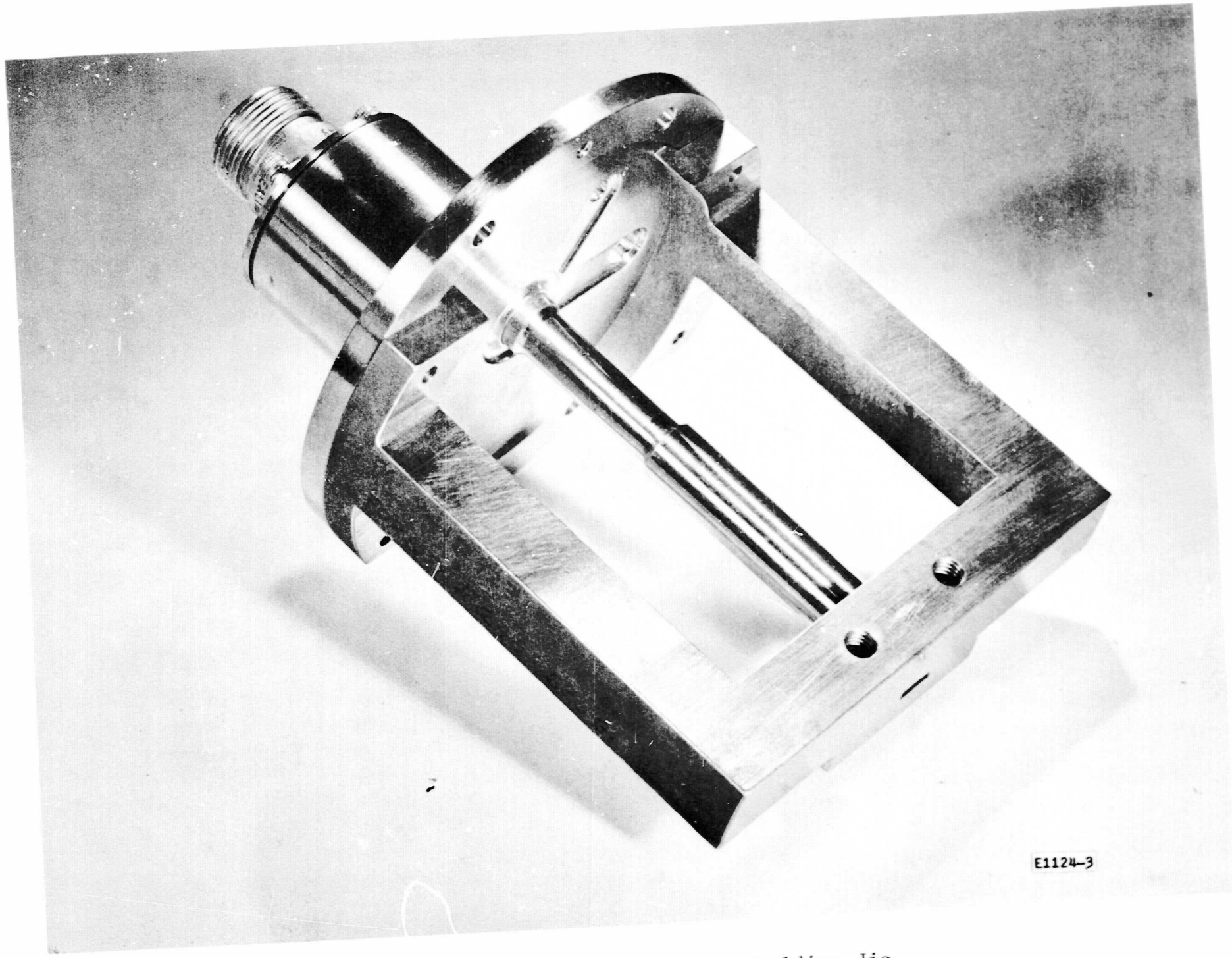


Figure 4. HSK-2000-20 Heater Welding Jig.

The power/temperature tests performed at GSFC showed a substantial increase in power requirements over those required with laboratory engineering models previously tested. These increased losses were traced to the high conductive losses through the heater support tube and the thruster support tube. The 0.010" thickness in these walls was a compromise between structural rigidity, and low cross sectional area to minimize conductive heat transfer. The results of this test are shown in the curve of Figure 5.

A series of power/temperature tests was run with various configurations of heat shielding/thruster/heater combinations to determine the effect of each component on the overall system losses. These runs were broken down as follows:

1. TSK 2000-1P S/N 020-002 complete welded assembly with 40 layers of 0.002" molybdenum heat shielding with modified separating wire location.

2. TSK 2000-1P S/N 020-003 with 30 watt heater not welded in place with 40 layers of 0.002" molybdenum shielding with modified separating wire location.

3. S/N 020-002 thruster (with welded heater) with S/N 020-003 heat shielding.

4. S/N 020-003 thruster (with unwelded heater) with S/N 020-002 heat shielding.

5. S/N 020-002 heat shielding with no thruster body or flange with 1/2" diameter heater.

6. S/N 020-003 heat shielding with no thruster body or flange with 1/2" heater.

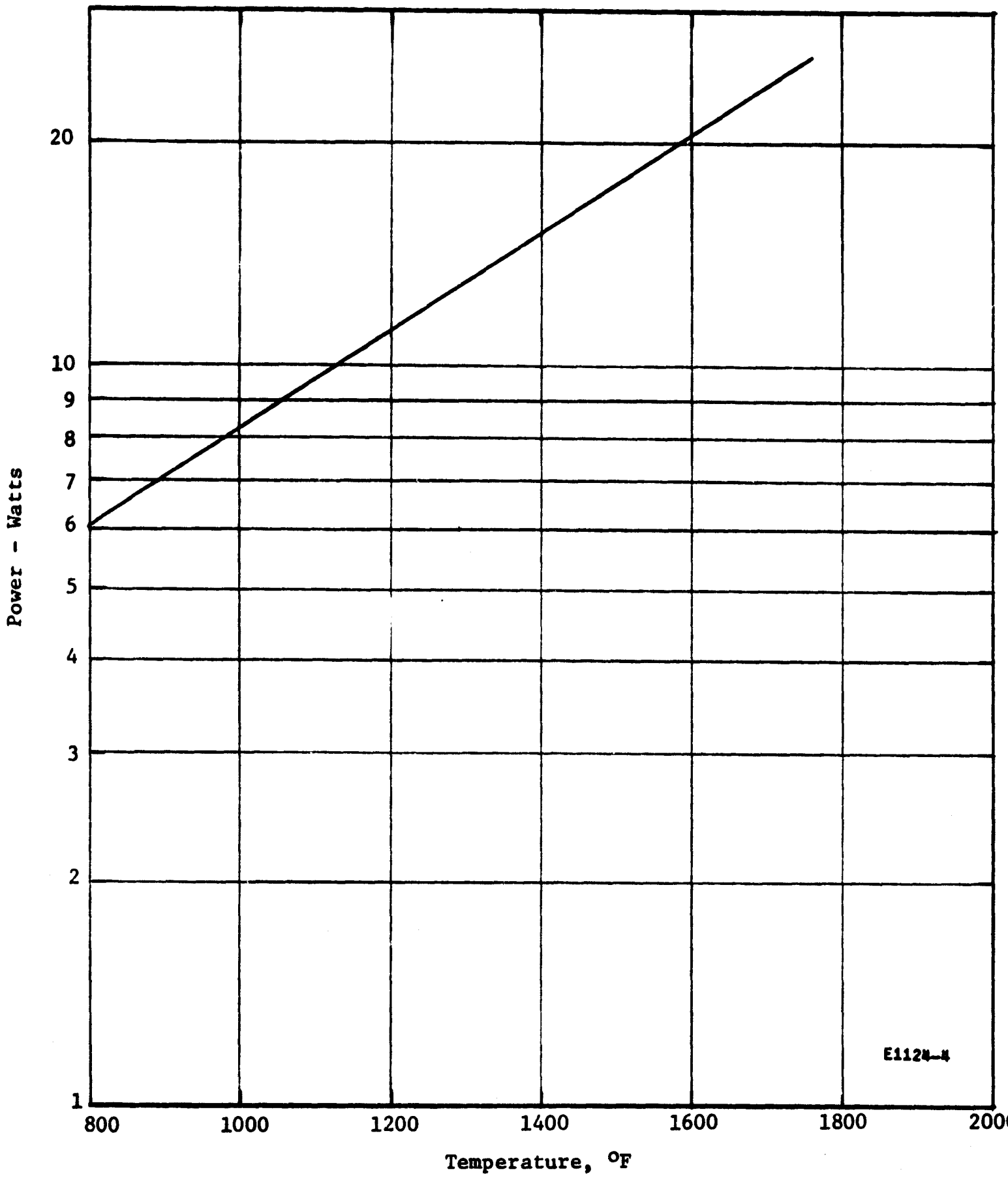


Figure 5. Power Vs. Temperature for TSK 2000-1P Thruster With Molybdenum Heat Shielding.

7. 40 layers of 0.003" Nichrome V in S/N 020-003 shell.

8. 40 layers of 0.003" Nichrome V in S/N 020-003 shell with cone covering nozzle exit shield edges.

9. TSK 2000-1P S/N 020-002 complete welded assembly with 40 layer Nichrome V heat shielding.

These tests provided the following results: There was a marked difference between the two molybdenum heat shielding packages although there were no major deviations in the assembly techniques between these two thrusters. S/N 020-002 with a welded heater required 35 watts at 2000°F, but only 28 watts in the same configuration but with the S/N 020-003 heat shielding. S/N 020-003 with an unwelded heater required 25 watts at 2000°F and 28 watts in the same configuration but with the S/N 020-002 heat shielding. This would indicate between a 3 and 7 watt difference in the two packages excluding other interaction effects.

The 40-layer package of Nichrome V was almost identical to the molybdenum package (S/N 020-002). With a cone installed, the Nichrome V package became slightly more effective. When installed on the TSK 2000-1P S/N 020-002 thruster/heater assembly, the power/temperature curve was comparable with the curve generated at GSFC with the molybdenum heat shielding package. From this curve, it appears that 34 watts will be required for operation with a core temperature of 2000°F.

The steady-state power/temperature curves for the configurations tested during this investigation are shown in Figure 6.

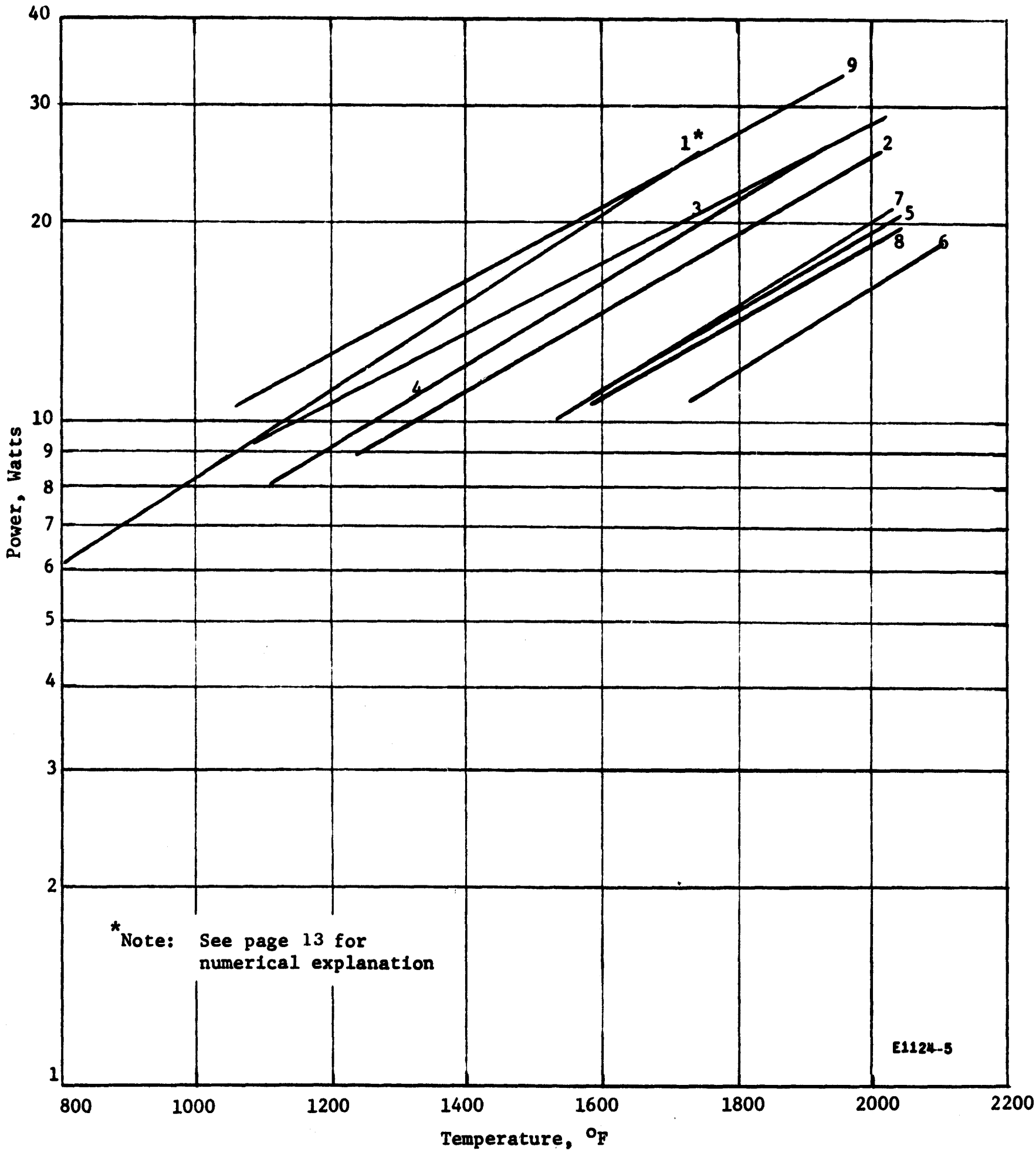


Figure 6. Power Vs. Temperature for TSK 2000-1P Thruster/Heat Shielding Configuration.

Since the effectiveness of heat shielding can be compared on a relative basis by the shape of a plot of temperature vs. time after power off, cool-down curves were obtained for all configurations. From the curves of Figure 7 it can be seen that for complete thrusters, the cool-down rate is essentially independent of heat shielding tested. This also holds true for the heat shielding packages with even less deviation than found with the assembled thrusters.

The final heat shielding package used with the thrusters delivered to GSFC consisted of 40 layers of 0.003" Nichrome V separated by 0.014" diameter Nichrome V wire. The choice of Nichrome V was made based on the inherent reproducibility of manufacture of the system as compared with the random effectiveness of molybdenum foil.

The flow control valve used with the TSK 2000-1P thruster is a Carleton model 1809-001-30, a photo of which is shown in Figure 8. The first of these valves received was subjected to a series of performance tests to determine voltage/current characteristics and minimum holding voltage after which leak rates of less than 0.005 std cc/min. were measured. The valve was subsequently vibrated in the sinusoidal mode between 5 and 2,000 cps and the leak rate again checked, with no significant increase in leak rate measured. Following this the valve was subjected to over 1,000,000 cycles with no significant change in leak rate.

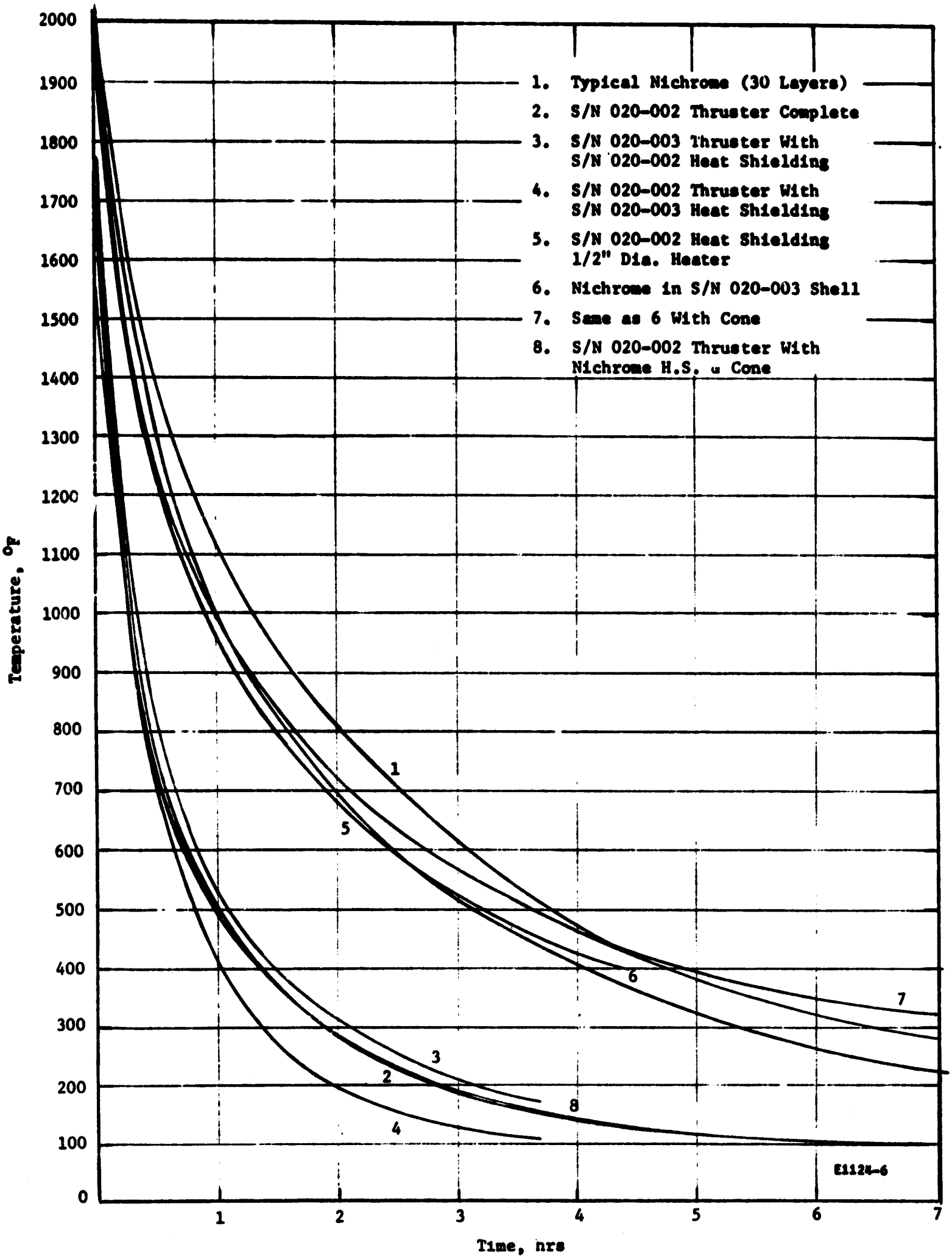


Figure 7. Cool Down Rates for Various Thruster/Heat Shielding Configurations.

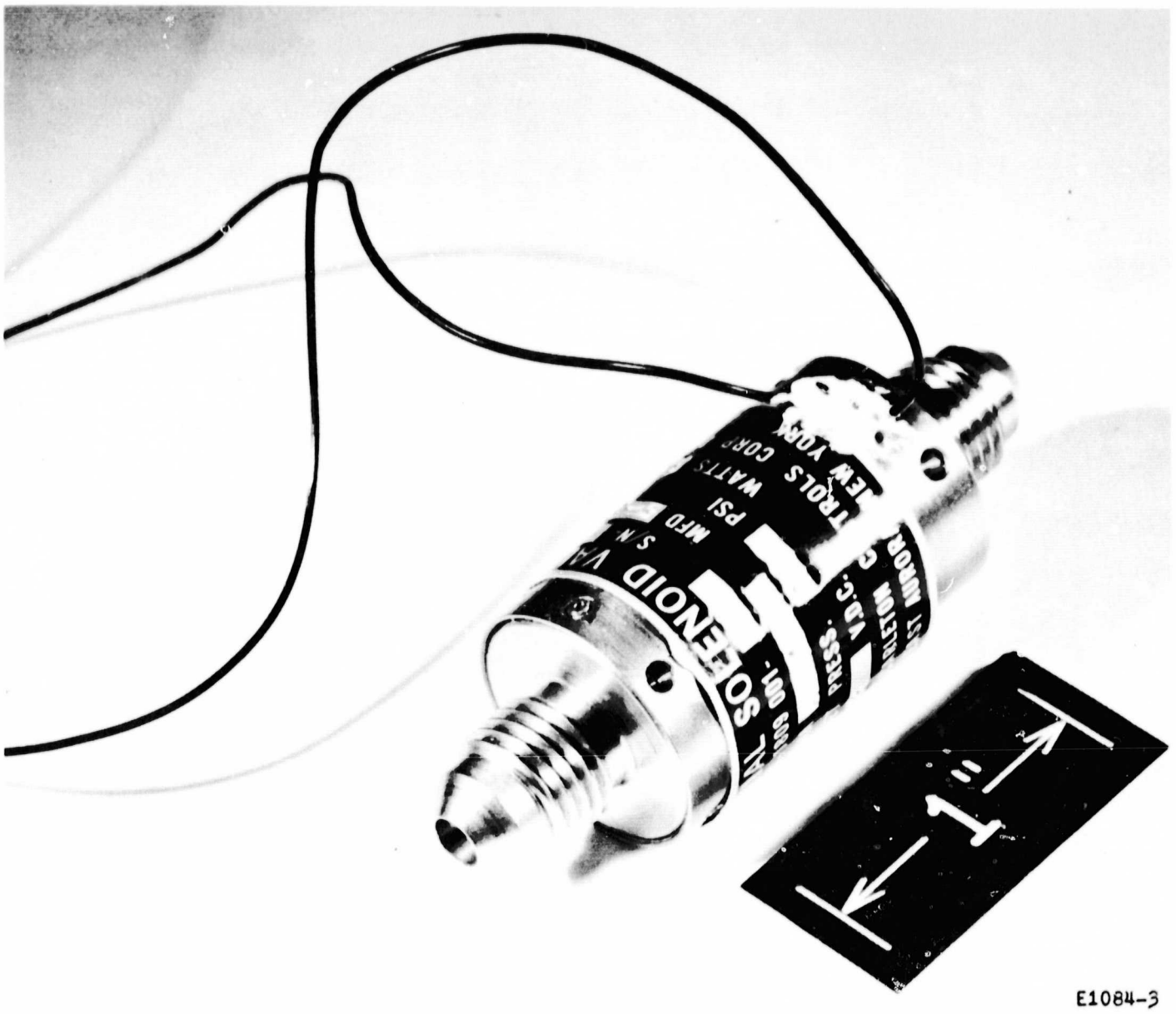


Figure 8. Carleton Model 1809-001-30 Flow Control Valve. (C66060123)

Initially, some problems with the valve seats were noticed after the valves had been subjected to ammonia for 10 to 20 hours. This was traced to the bonding agent used to bond the soft neoprene seat to the metal support which failed in the presence of ammonia. A series of trials were run at Carleton Controls and the problem was solved by bonding the neoprene on a wire screen which was mechanically attached to its support. Tests on new valves with this modification proved the effectiveness of this fix.

An analytical investigation was made to determine the maximum and minimum thrust which could be obtained from a nozzle optimized to deliver at least 250 seconds in a geometry the same as that used on the current TSK 2000-1P thruster. For this investigation, operating pressure was limited to three atmospheres. From the curve of Figure 9 it is seen that with a throat diameter of 0.032 inches, a maximum thrust level of 0.050 lb. can be obtained. At the low end of the scale a minimum of 0.015 lb. is possible before a fully developed boundary layer occurs. Operation below 0.015 lb. is possible but a degradation in delivered specific impulse would be the result.

Individual components for the TSK 2000-1P thruster as shown in Figure 10 have been weighed with the weights listed in Table I. The total system weight after assembly was 754 grams or 1.67 lb.

The final TSK 2000-1P station keeping thruster assembly consisted of three major components: heater, thruster out body, and heat shielding package. An exploded view showing the breakdown of the thruster into these components is provided in Figure 11.

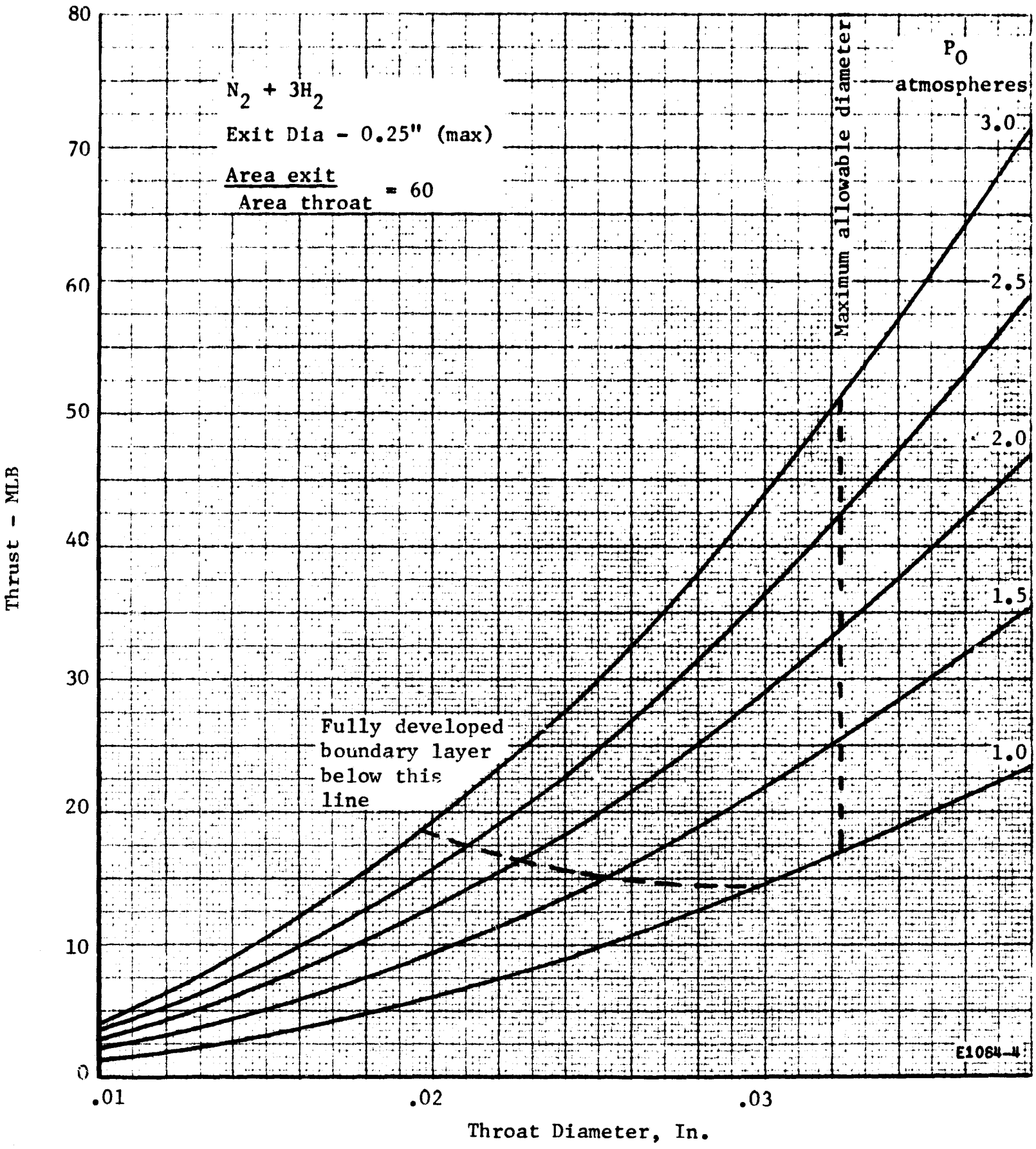


Figure 9. Possible Operating Map for TSK-2000-1P Size Nozzle Geometry.

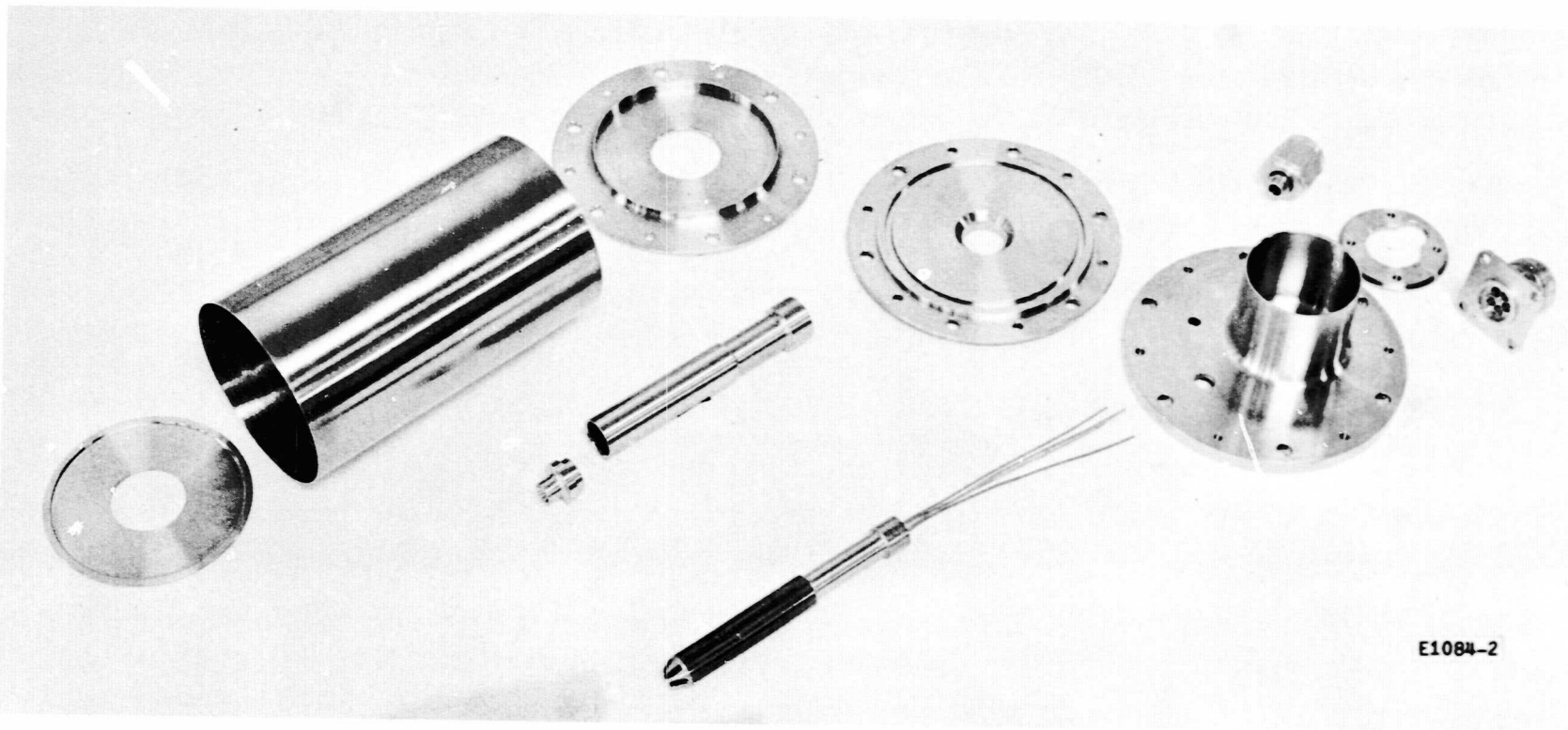


Figure 10. **TSK-2000-1P Station Keeping Thruster Components.** (C66051825)

TABLE I

TSK-2000-1P S/N 1 COMPONENT WEIGHTS

P/N	Description	Wgt - gms
246R896P2	Heater (HSK-2000-20 S/N 21)	28.52
" P3	Nozzle	5.15
" P4	Thruster Body	18.32
" P5	Heat Shield Inner Can	8.688
" P6	Heat Shielding Cover Plate	8.5
" P7	Heat Shielding Outer Can	67.47
" P8	Heat Shielding Base Plate	67.85
" P9	Thruster Base Plate	100.41
" P10	Heater Support Plate	169.38
" P11	Connector Plate	10.51
" P12	Propellant Connector	13.71
" P13	Pressure Tap	1.691
" P14	Electrical Connector	18.93
" P15	Lock Washers (6)	.964
" P16	Connector Screws (4)	1.788
" P17	Assembly Screws (6)	3.30
" P18	O-ring	.677
	Heat Shielding	239.051
	Aluminum Beads (40)	1.30
	Total Component Wgts.	766.21

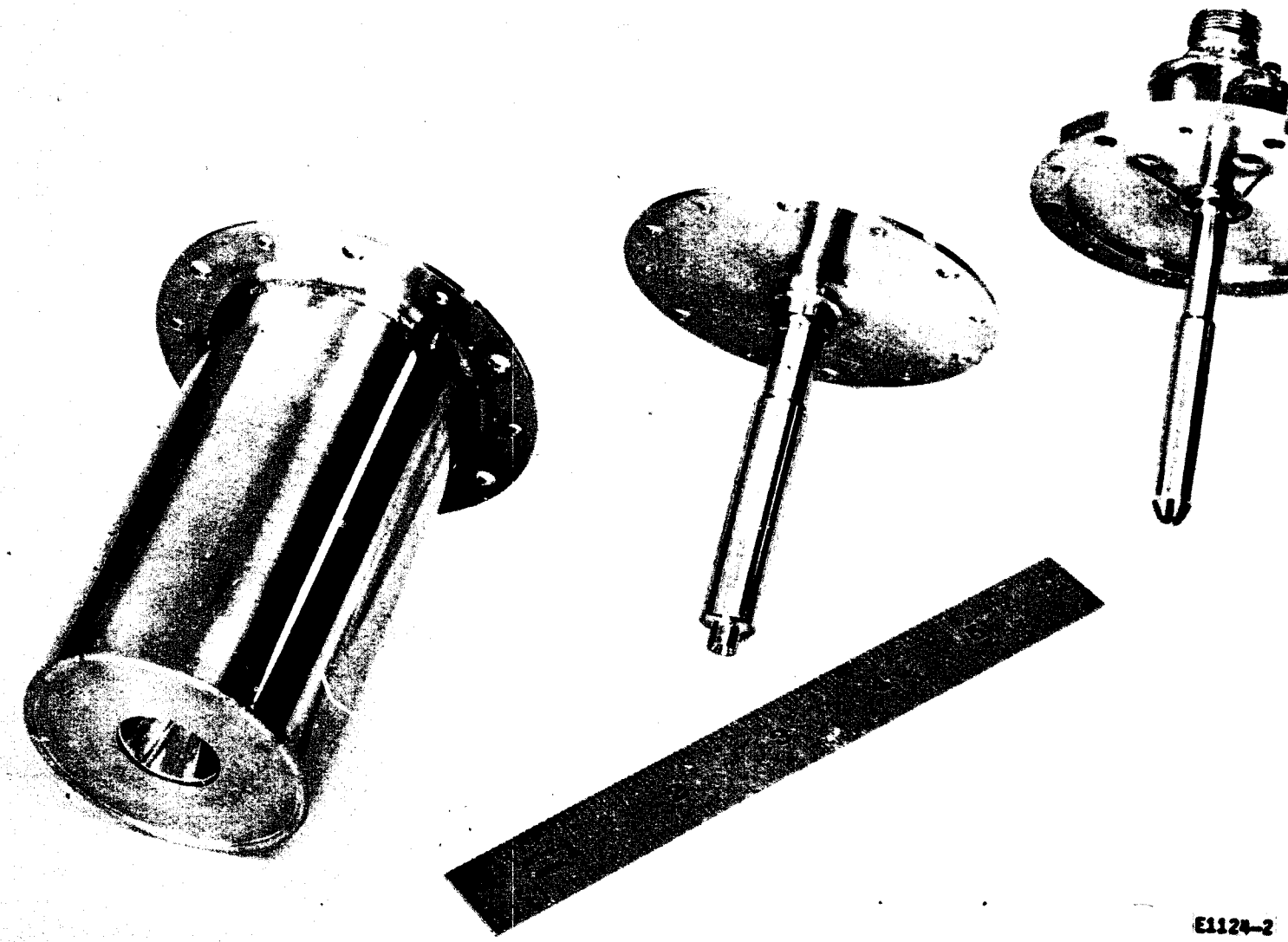


Figure 11. TSK-2000-1P Thruster Exploded View.

An overall view of the assembled thruster is shown in Figure 12.

Upon completion of the assembly of the thruster units they were delivered to GSFC for evaluation. Apart from the heat shielding and power/temperature testing performed in the General Electric Propulsion laboratory no further testing was performed prior to delivery of the units.

A mockup of the TSK 2000-1P thruster showing details of construction with a simulated heat shielding package was fabricated and delivered to GSFC. A photo of this mockup is shown in Figure 13.

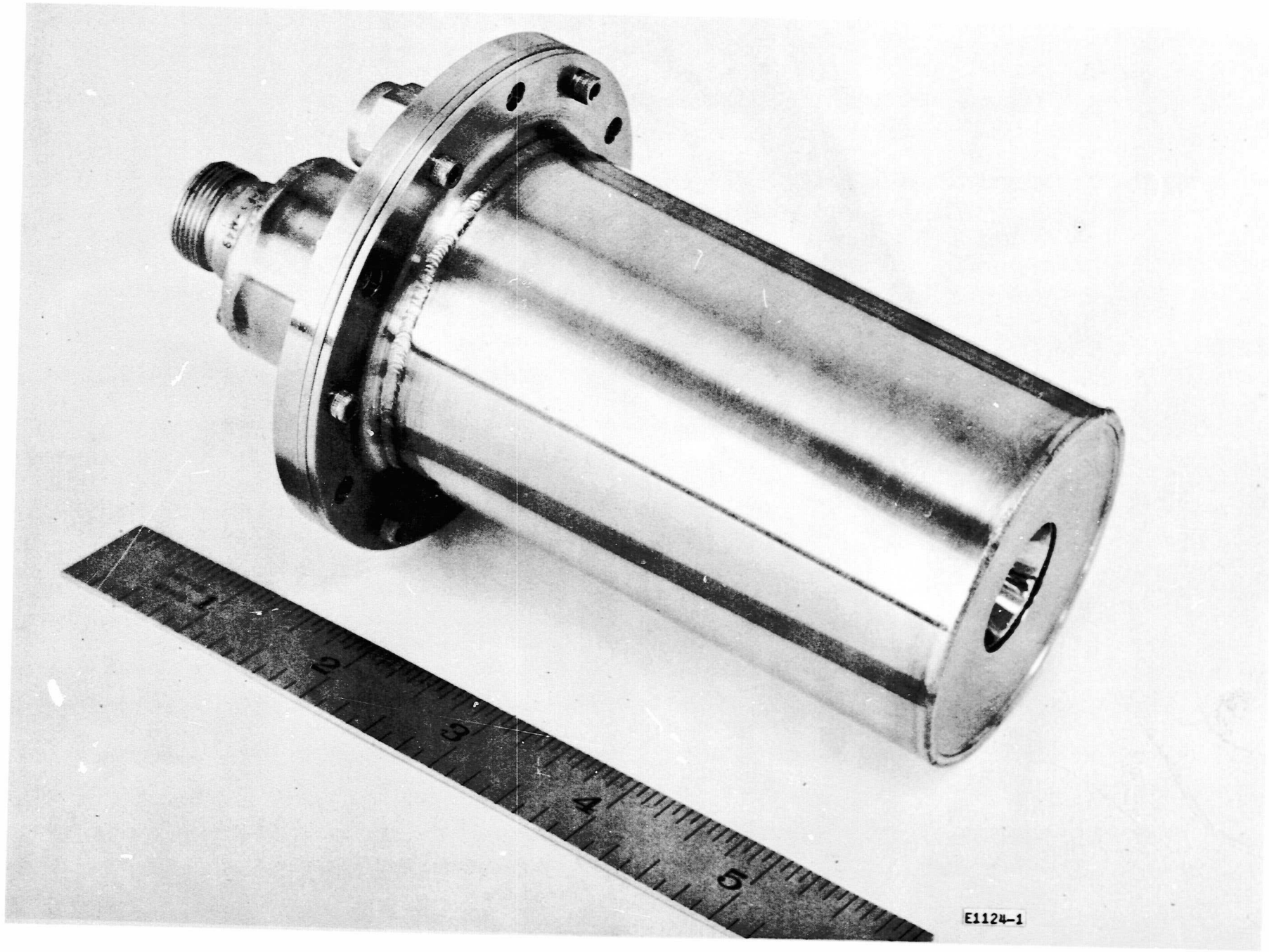


Figure 12. TSK-2000-1P Thruster Assembled View.

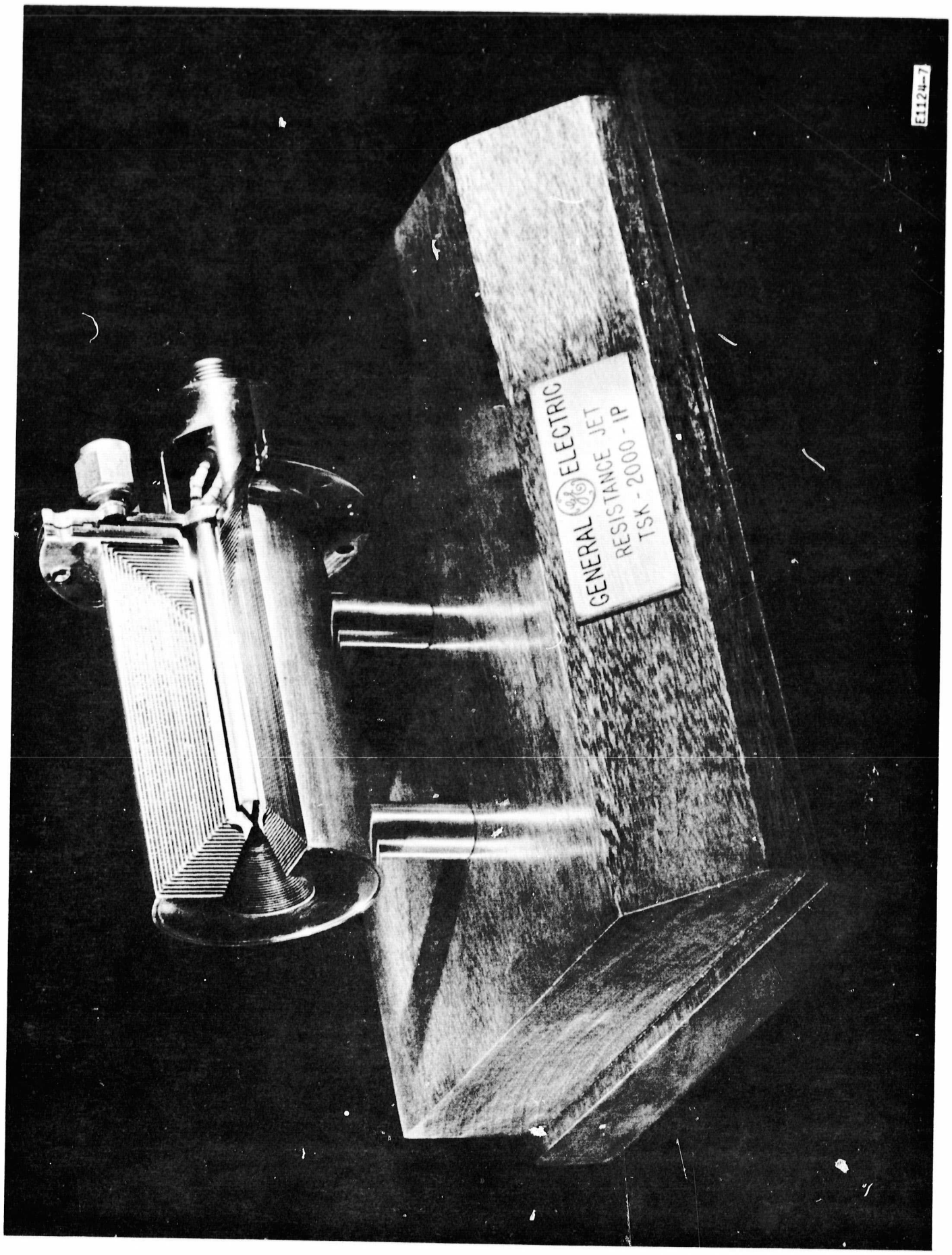


Figure 13. TSK-2000-1P Mock-Up.

B. TMJ 2000-5P Multijet Thruster

The design of the combined attitude-control and station-keeping thruster consists of five separate flow paths with individual thrust nozzles, each independently supplied by propellant-flow control valves mounted at the support flange. The internal flow path configuration developed with the TMJ 2000-5 thruster under Contract No. NAS 5-9013 is retained with modification in diameters to allow reduction in overall thruster body size.

Since the thruster body consists of five axially oriented flow paths, each mutually independent, the utilization of the heater exterior surface as the inner flow path surface as in the TSK 2000-1P design is not applicable. Therefore, in this design the heater does not come in contact with the propellant and insertion and removal of the heater can be made without disturbing the flow path.

As in the case of the TSK-2000-1P heater design, the electrical heater connections and internal thermocouple connections are made through a commercially available connector plug supported on a combination mounting flange and thruster support flange.

The heater utilized in the TMJ-2000-5P thruster is of the same basic construction as those used in the TSK 2000-1P single jet thrusters except that the number of wire turns has been changed to provide a power rating of 30 watts instead of 20 watts. The particular heater used in the S/N 030-001 assembly is sheathed with Hastelloy X and was subjected to an annealing cycle

prior to final machining. In order to keep the interior insulating components of the heater from expanding and cracking the sheath, the heater was annealed by thrusting into an 1850° furnace; this had the effect of expanding the sheath first and then the interior of the heater, thereby eliminating the probability of a tensile stress failure.

The thruster body is brazed to its support flange and subsequently heat shielded with 40 layers of Nichrome V foil. Because of the protrusion of the radial nozzles from the side of the thruster body, the heat shielding package cannot be removed from the assembly as a separate unit.

As can be seen from the sketch of Figure 14 the TMJ 2000-5P can be broken down into two sub-assemblies. One sub-assembly consists of the thruster body mounted on a support flange with an integral heat shielding package permanently installed in place. The other sub-assembly consists of the heater mounted on a separate flange which is bolted to the thruster body sub-assembly.

Materials used in the construction of the TMJ 2000-5P multi-jet thruster are the same as for the TSK 2000-1P single-jet thruster. Hastelloy X is used for the thruster body, exhaust nozzle, and heater sheath with 304 SS for the remainder of the structural members not in direct contact with the ammonia propellant.

Ten attitude control nozzles were fabricated and the four with

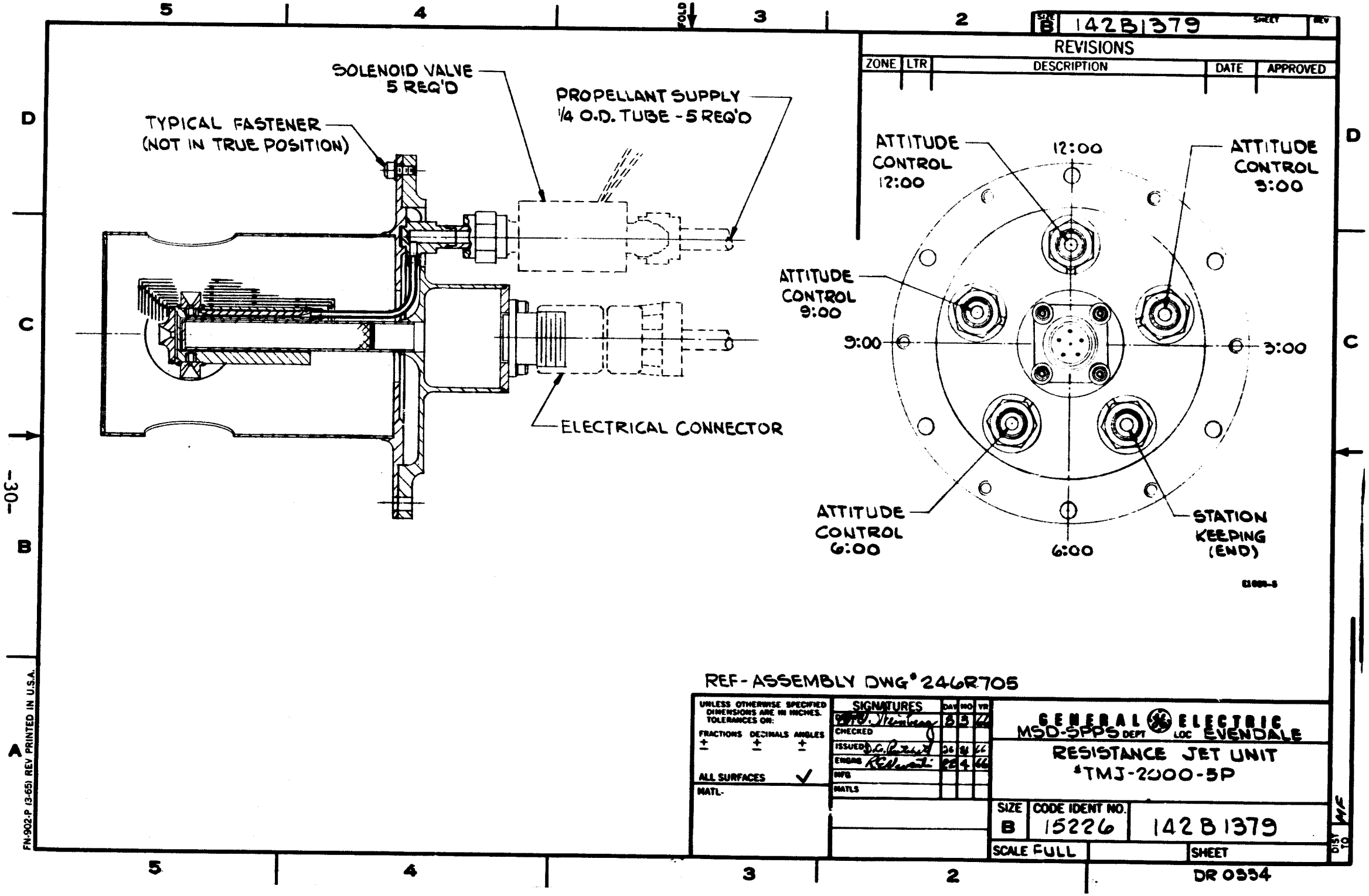


Figure 14. **Engineering Sketch of TMJ-2000-5P Thruster. (142B1379)**

the most identical effective throat diameters were chosen for this assembly. A Sheffield flow gauge* was used to determine the relative size of these nozzles with the results as indicated in Table II. The maximum difference in relative size between the nozzles S/N 2 and S/N 4 was only 0.20 with a maximum deviation of only 2% from the average diameter used. The components which made up the TMJ 2000-5P assembly are shown in Figure 15 and the assembled unit in Figure 16.

Two different types of heaters were built for test with the multijet thruster. One, as shown in Figure 15, was designed to be welded in the heater support flange similar to the TSK 2000-1P design. The other, designed to be slipped into the thruster body with no connection to the flange, was shortened to eliminate the thin-walled support section, leaving only the lead wires and thermocouple leads protruding from the thruster body and through the heat shielding to the electrical connector. The use of these two types of heaters provided a means of evaluating the thermal conductivity losses in the support section of the heater.

For the first tests a shortened heater was installed. Lead wires and thermocouple wires were insulated from the heat shielding and from each other by 1/8" dia. x 3/16" long fish spine alumina insulators strung on the wires between the heater and the electrical connector.

*Sheffield Corporation, Subsidiary of Bendix Corporation, Dayton 1, Ohio.

TABLE II

COMPARISON OF RELATIVE TMJ-2000-5P ATTITUDE CONTROL NOZZLE SIZES

Order of Size	Serial No.	Relative Size
1	8	5.35
2	6	5.60
3	10	5.70
4	5	5.95
5	2*	6.05
6	9*	6.10
7	3*	6.25
8	4*	6.25
9	7	6.60
10	1	6.60

* Used in S/N 030-001 Assembly

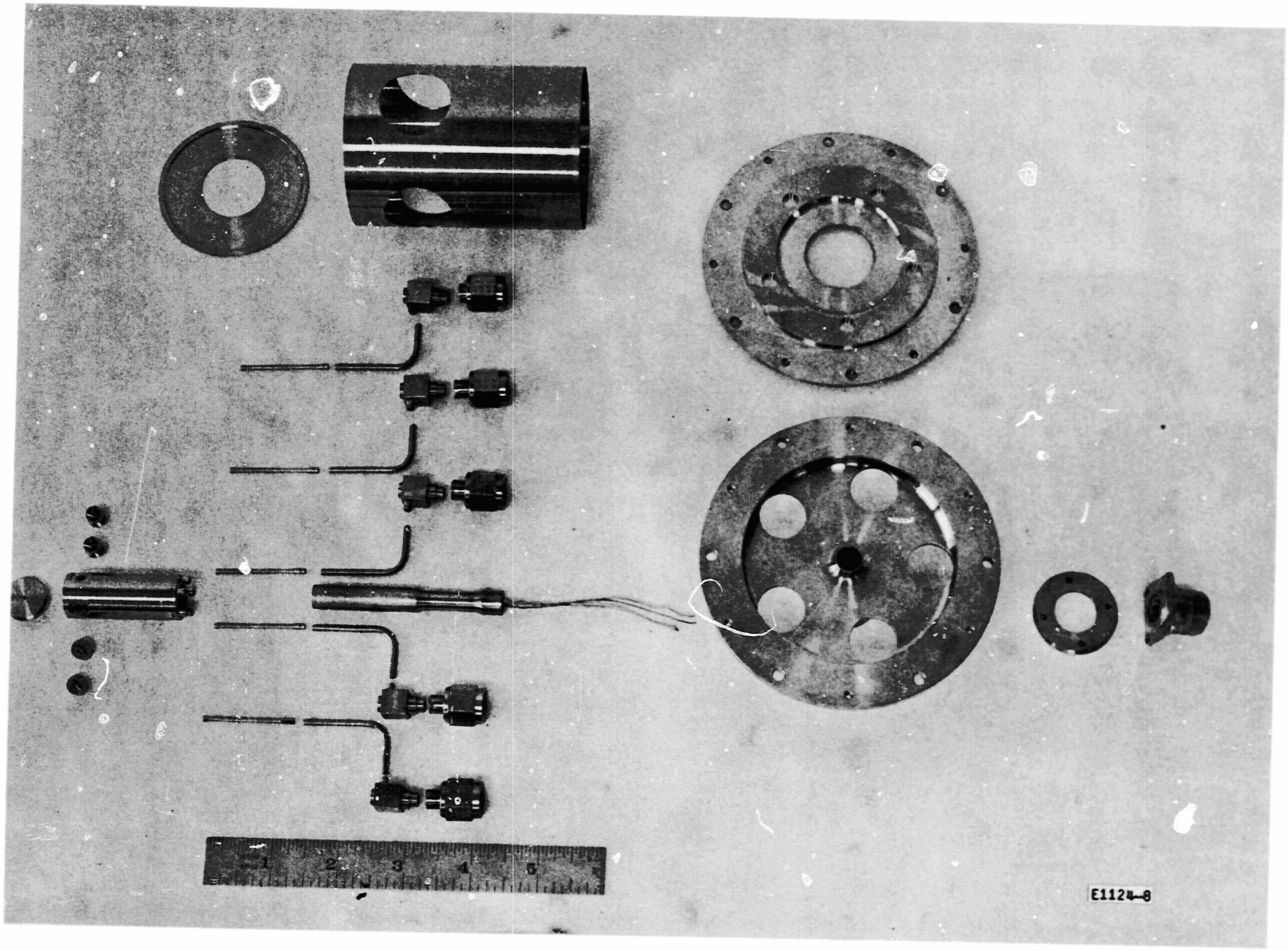


Figure 15. TMJ-2000-5P Multijet Components.

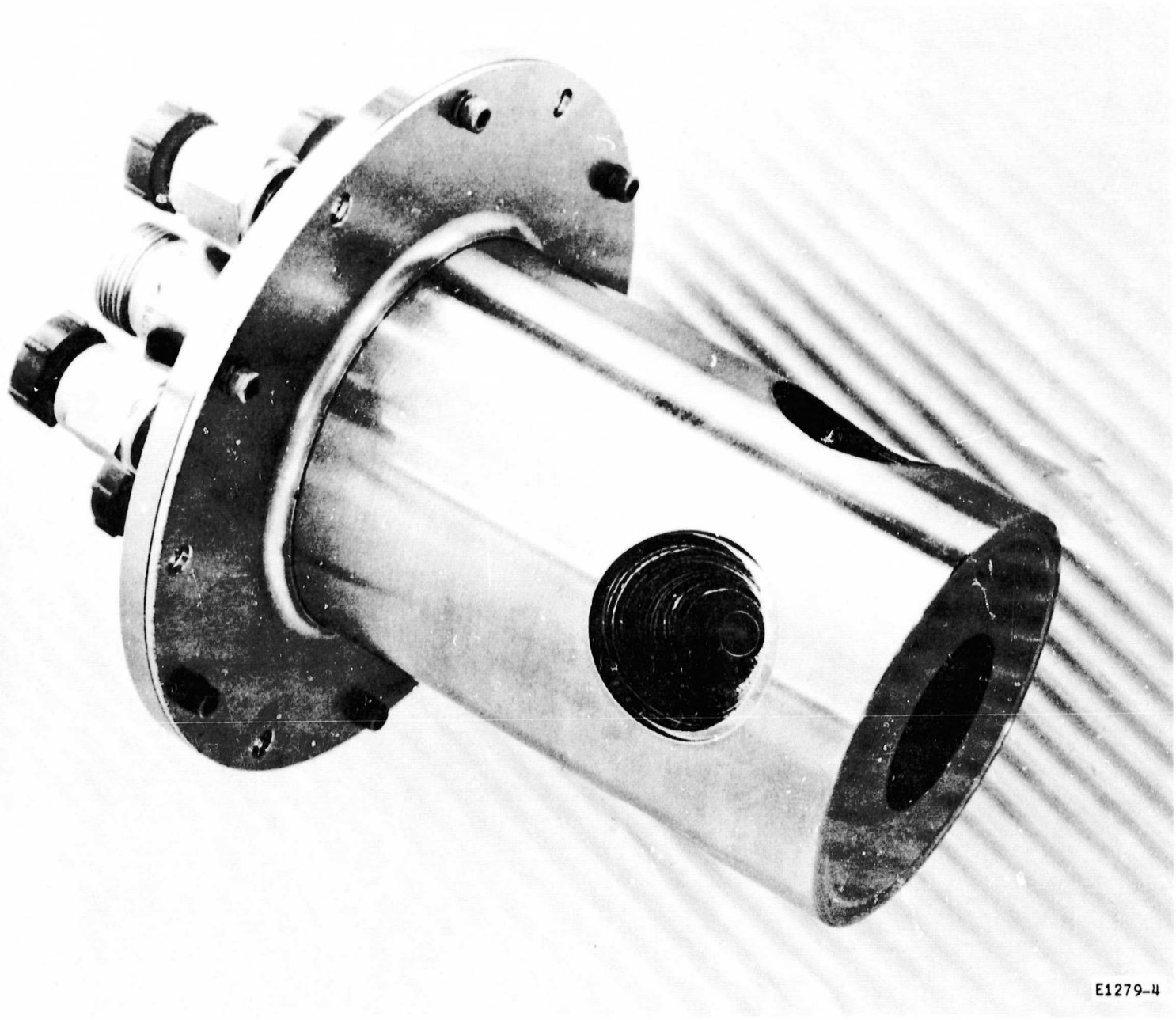


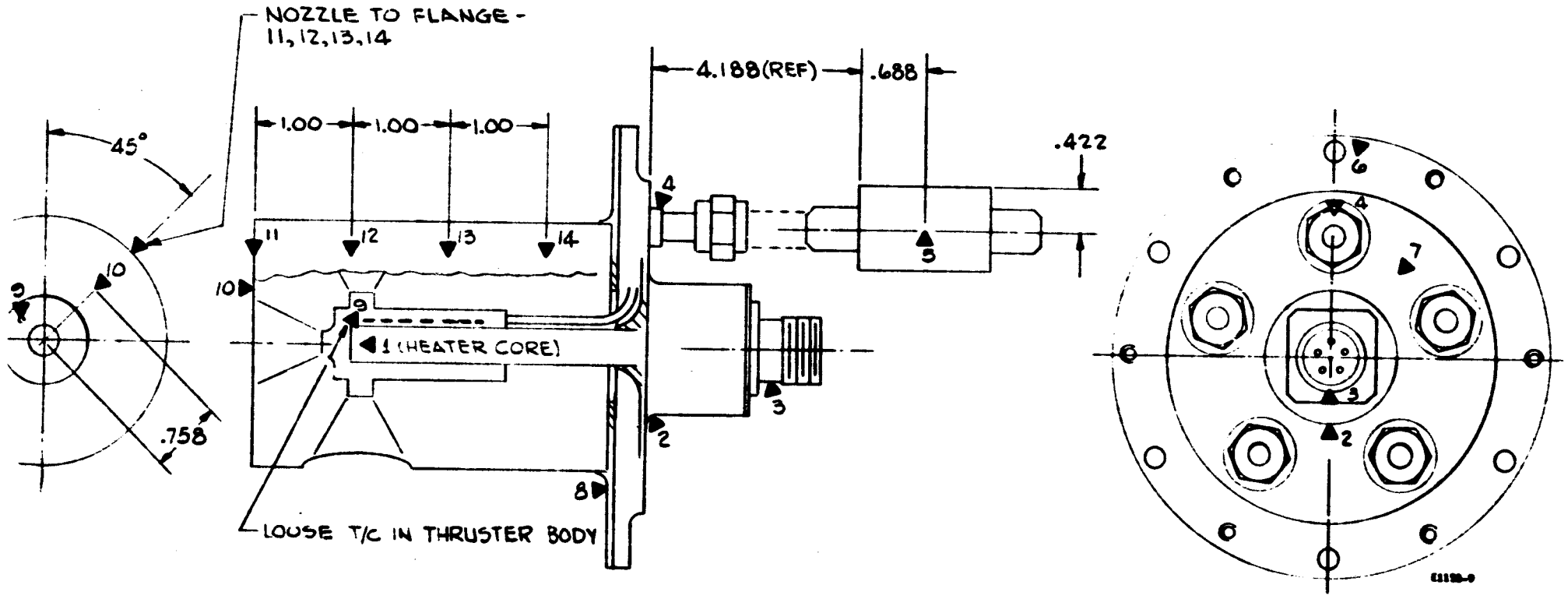
Figure 16. TMJ 2000-5P Multijet Thruster. (C67041250)

Thermocouples were mounted on the thruster in the locations indicated in Figure 17.

With this shortened heater, at a power input of 33.92 watts, a core temperature of 1906°F was recorded. An additional 10 watts were required to increase the core temperature to 2080°F. The data obtained during this test is recorded in Table III and shown as a plot of temperature vs. power in Figure 18.

A second test of temperature vs. power was made with a heater welded to the mounting flange as originally designed. With this configuration the power required to bring the core temperature up to 1915°F was 48.5 watts or almost 15 watts more than with the shortened heater. The data obtained during this test is provided in Table IV with a plot of temperature vs. power in Figure 19. During this test the temperature difference between the core and thruster body was 33° with the core temperature at 1915°F. Since the body thermocouple was located in the same radial location as the flow paths it should be a good indicator of gas temperature.

With the thruster oriented in the thrust rig such that the axial, or station-keeping, thruster axis was horizontal a measurement of thrust over a range of operating pressures was made. Although the station-keeping thruster was designed to deliver 0.050 lb. thrust at a nominal chamber pressure of 1.5 atmospheres only 0.009 lb. were delivered at that pressure. The data obtained with this nozzle over a range of pressures from 0.5 to 1.5 atmospheres is plotted as thrust vs. chamber pressure in Figure 20.



REF-ASSY DRAWING # 246R705
▲ - THERMOCOUPLE LOCATION

Figure 17. Thermocouple Locations TMJ 2000-5P Thruster.

TABLE III

RESULTS OF POWER/TEMPERATURE TEST WITH TMJ 2000-5P THRUSTER WITH FORESHORTENED HEATER

Heater			Temp °F		
Volts	Amps	Watts	T/C #1	T/C #13	T/C #14
4.6	1.213	5.579	1023	128	137
6.6	1.590	10.50	1303	157	160
11.20	2.32	25.98	1725	227	227
15.40	2.837	43.69	2081	282	280
13.25	2.56	33.92	1906	253	253
9.95	2.105	20.94	1606	207	210
6.77	1.635	11.07	1258	155	158
13.45	2.60	34.97	1901	251	249

NOTE: Thermocouple locations per Figure 17.

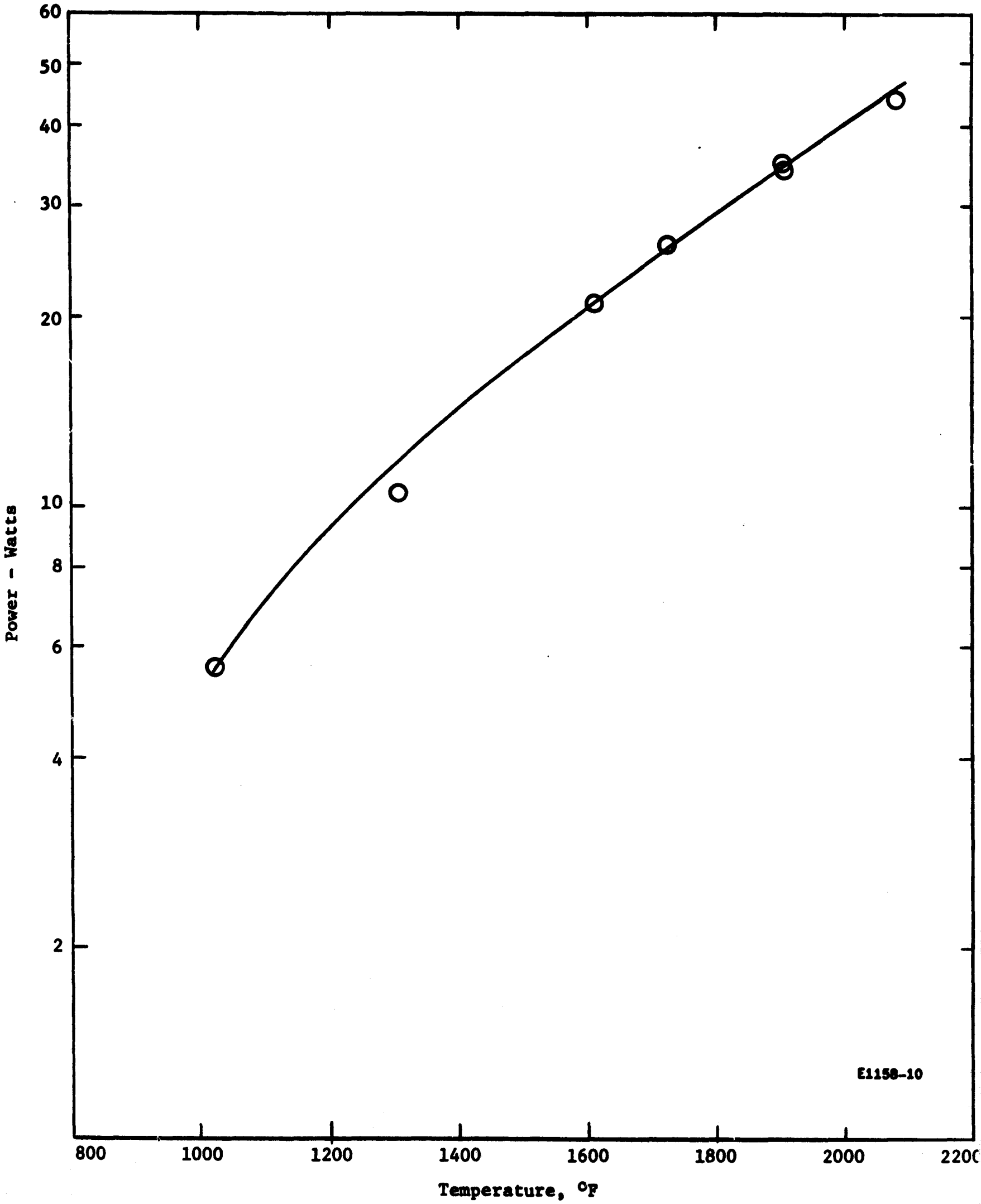


Figure 18. Temperature/Power for TMJ 2000-5P Thruster With Short Heater.

TABLE IV

RESULTS OF POWER/TEMPERATURE TEST WITH TMJ 2000-5P THRUSTER WITH WELDED IN HEATER

Heater			Temp °F			
Volts	Amps	Watts	T/C #1	T/C #2	T/C #9	T/C #13
6.00	1.64	9.85	932	213	872	153
12.00	2.51	30.02	1570	318	1529	238
16.15	3.00	48.5	1915	373	1882	292

NOTE: Thermocouple locations per Figure 17.

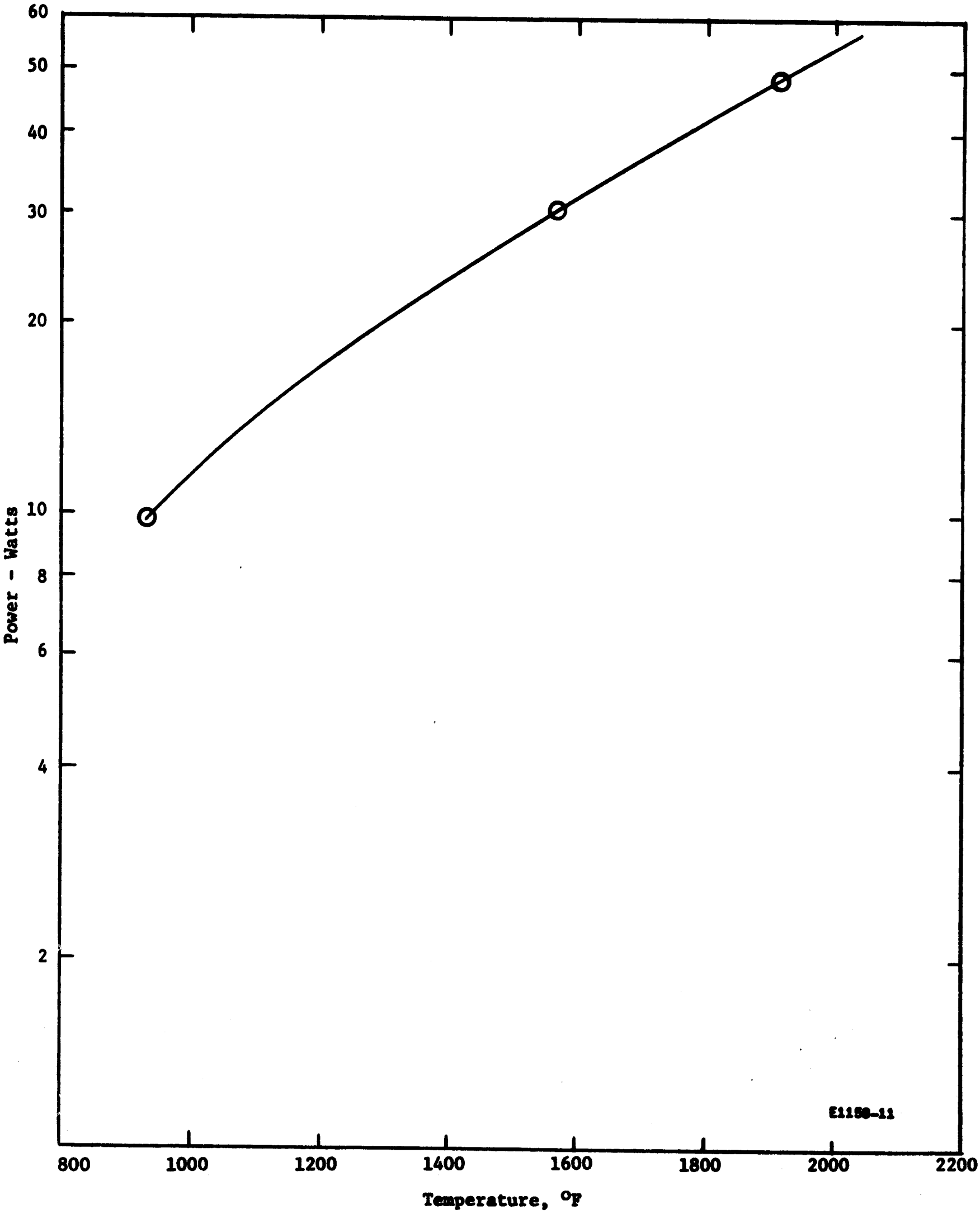


Figure 19. Temperature/Power for TMJ 2000-5P Thruster With Welded in Heater.

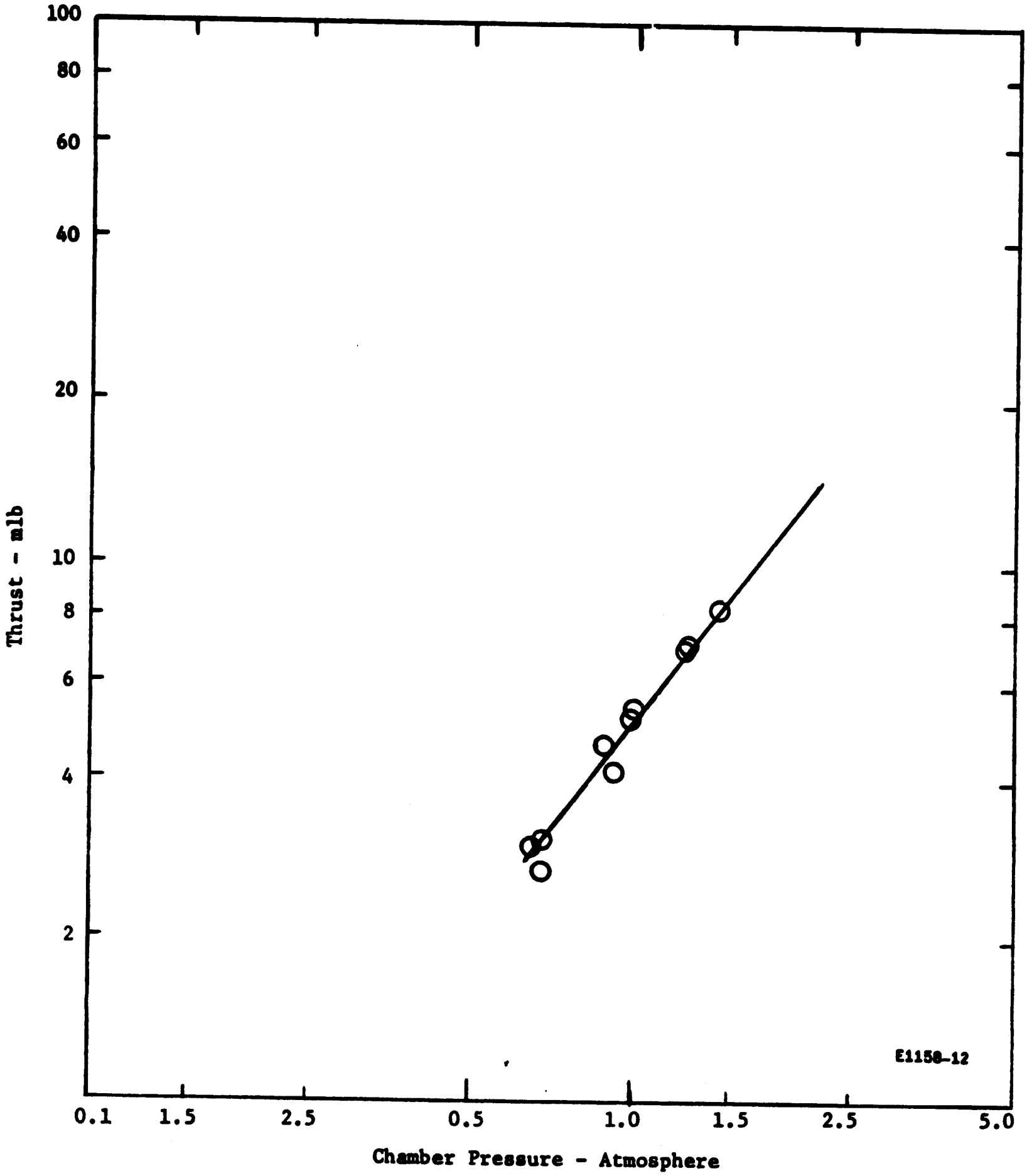


Figure 20. Thrust vs. Chamber Pressure for TMJ 2000-5P Station Keeping Nozzle.

The discrepancy between predicted thrust/pressure relationship and empirical data can be accounted for in the location of the pressure tap. Since chamber pressure is measured downstream of the flow control orifice but upstream of the thruster body with its internal restrictions the high pressure drop is obviously caused by the restrictive dimensions of the annulus pins.

Initial thrust/specific impulse measurements were made with the thruster core temperature maintained at 1985°F. With the supply pressure set at 80.4 psia, which provides a nominal 24 psia chamber pressure and thrust of 9 mlb, the solenoid valve was opened and propellant allowed to flow. In 600 seconds the core temperature had dropped to 1450°F, to 1375°F in 1200 seconds, and to 1360°F in 2400 seconds. At 4680 seconds the minimum temperature appeared to have been reached at 1355°F. A plot of temperature vs. time during this test is provided in Figure 21. Since thrust and orifice pressure were constantly monitored specific impulse could be calculated at any point during the run. The calculated specific impulse dropped from 190 seconds at the start of the run to 107 seconds at the end - considerably lower than anticipated from the calculated values.

Additional tests at 700°F, 1400°F, and 2000°F provided comparable results, in each case the specific impulse being at least 20% below predicted values.

One of the attitude-control nozzles (nozzle #4) was checked and

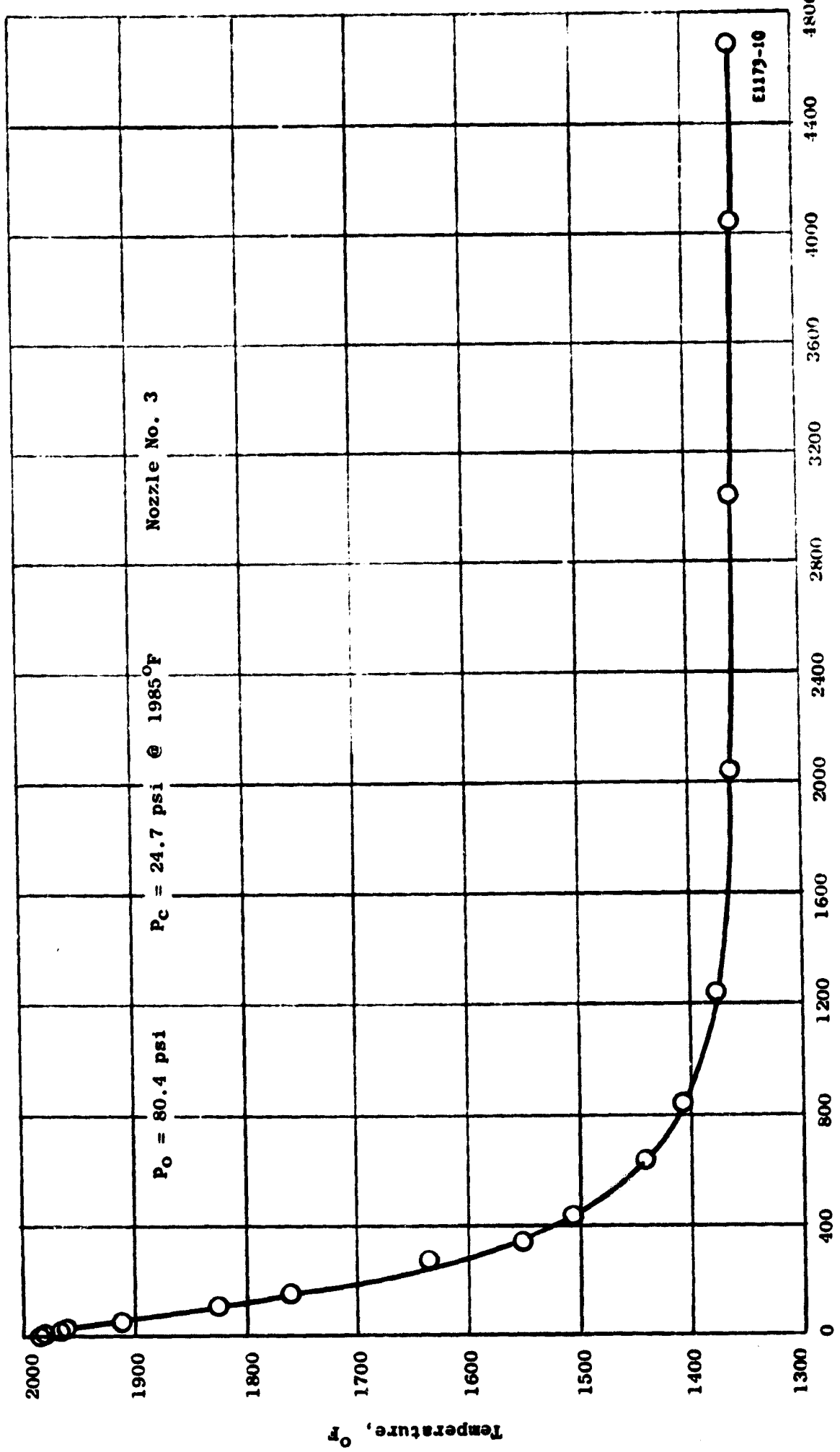


Figure 21. TMJ 2000-5P Cool Down - Base Line Full Flow.

it too provided markedly reduced performance providing less than 180 seconds at 1940°F.

Following these tests the thruster was removed from the test facility and the data intensively evaluated. It was concluded that the major source of performance degradation was in the exhaust nozzle inlet contour. By mounting similar nozzles on short lengths of tubing with the thrust axis coaxial with the tube and later perpendicular to the tube, it was proven during a short series of tests that the inlet conditions occurring in the thruster nozzle itself were contributing to this performance degradation. Subsequently, a new thruster body was built up with modified nozzles and its performance re-evaluated. At a core temperature of 2080°F specific impulse measurements as high as 244 seconds were made. A plot of specific impulse vs. chamber pressure for nozzle #3 during these tests is provided in Figure 22.

Similarly for nozzle #4 with this new configuration nozzle the specific impulse measurements were higher as shown in Figure 23. In both cases, however, the relationship between chamber pressure, as measured, and thrust was not as predicted thereby limiting the operating range of the thruster.

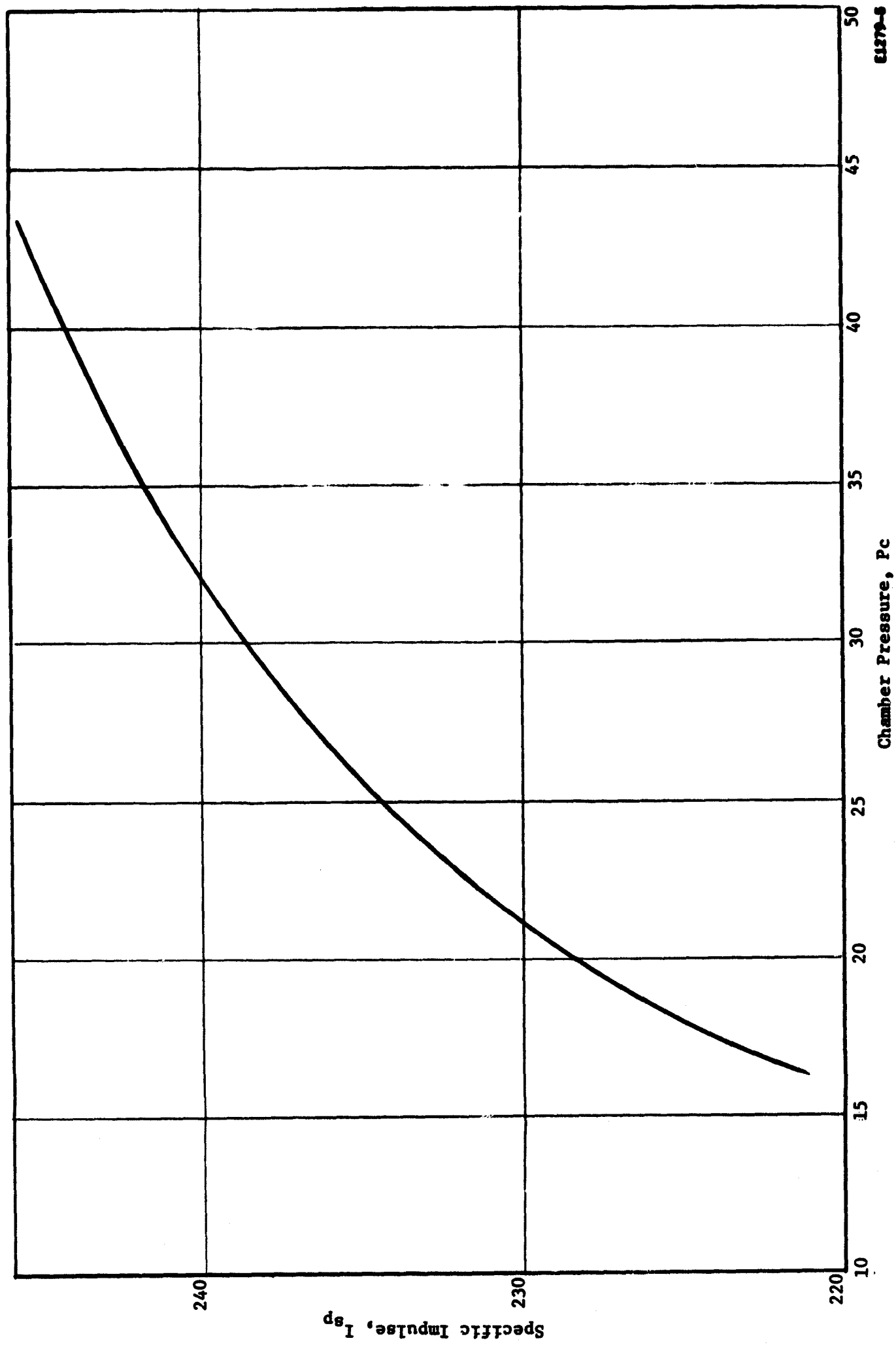


Figure 22: Specific Impulse vs. Chamber Pressure – Nozzle #3 TMJ 2000-5P
Temperature ~ 2000°F.

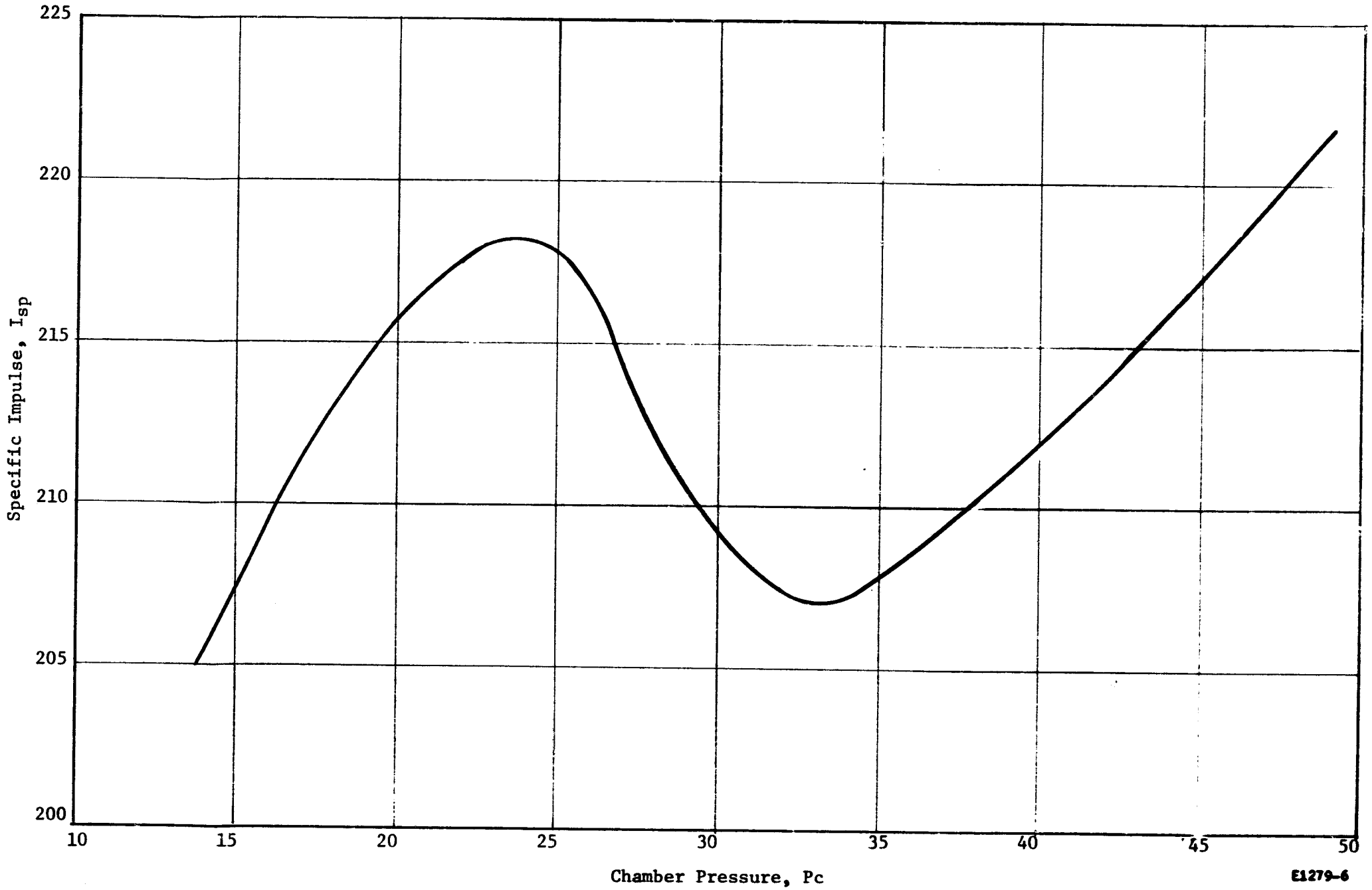


Figure 23. Specific Impulse vs. Chamber Pressure - Nozzle #4 TMJ 2000-5P Temperature $\sim$ 2000°F.

C. TSK 2000-1RE Simulated Radioisojet

The TSK 2000-1RE Simulated Radioisojet thruster developed under this program is shown in cross section in Figure 24. The configuration utilizes a heater capsule containing approximately 60 thermal watts of Pu 147 Oxide which can maintain the body temperature at close to 1700°F. The isotope capsule can be removed from the system and an electrical heater/inner thruster body inserted for tests under normal safety conditions without insuring the additional problems of radioactivity hazard safety.

Radioisotope sizing was made based on the physical and thermal properties of the fuel form. With this available information, an optimization of L/D was made using both of the existing heat transfer computation programs -- "HIS" for internal heat generation, and "HERS" for external losses through heat shielding. With Nichrome V heat shielding, this optimization occurred at an L/D of approximately 1.5. With molybdenum heat shielding, the optimized L/D shifted close to 2.5. Curves of L/D vs. heater temperature for this 60-watt heater for 10, 20, and 30 layers of heat shielding are provided in Figures 25 and 26.

From past experience, it was known that a capsule configuration such as a right circular cylinder with thin-walled construction had little chance of surviving re-entry impact on a hard surface without rupturing. For this reason, the final configuration has domed ends, hemispherical for a first approximation, with the

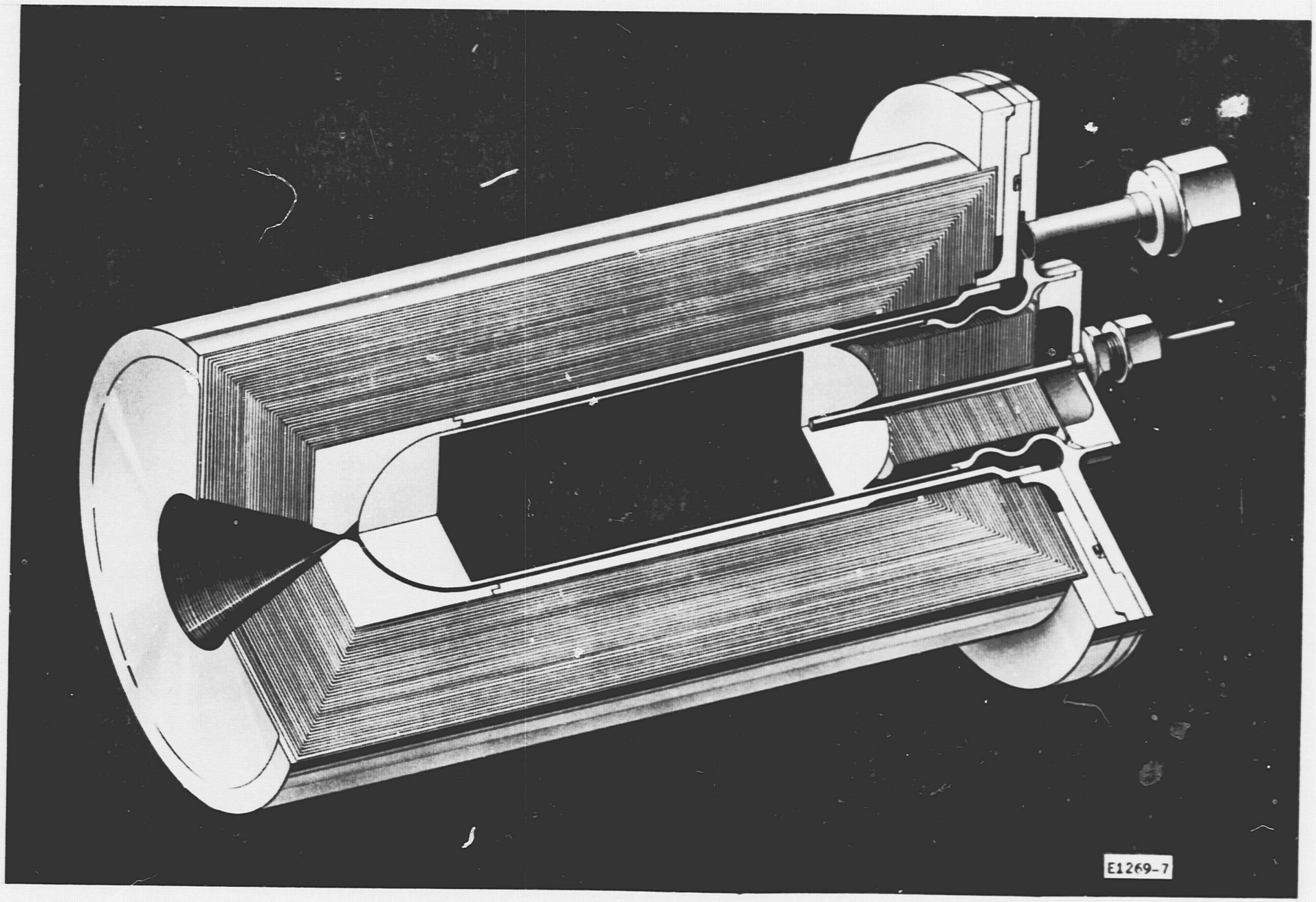


Figure 24. TSK 2000-1RE Simulated Radioisojet Thruster Cross Section. (CDC 7305)

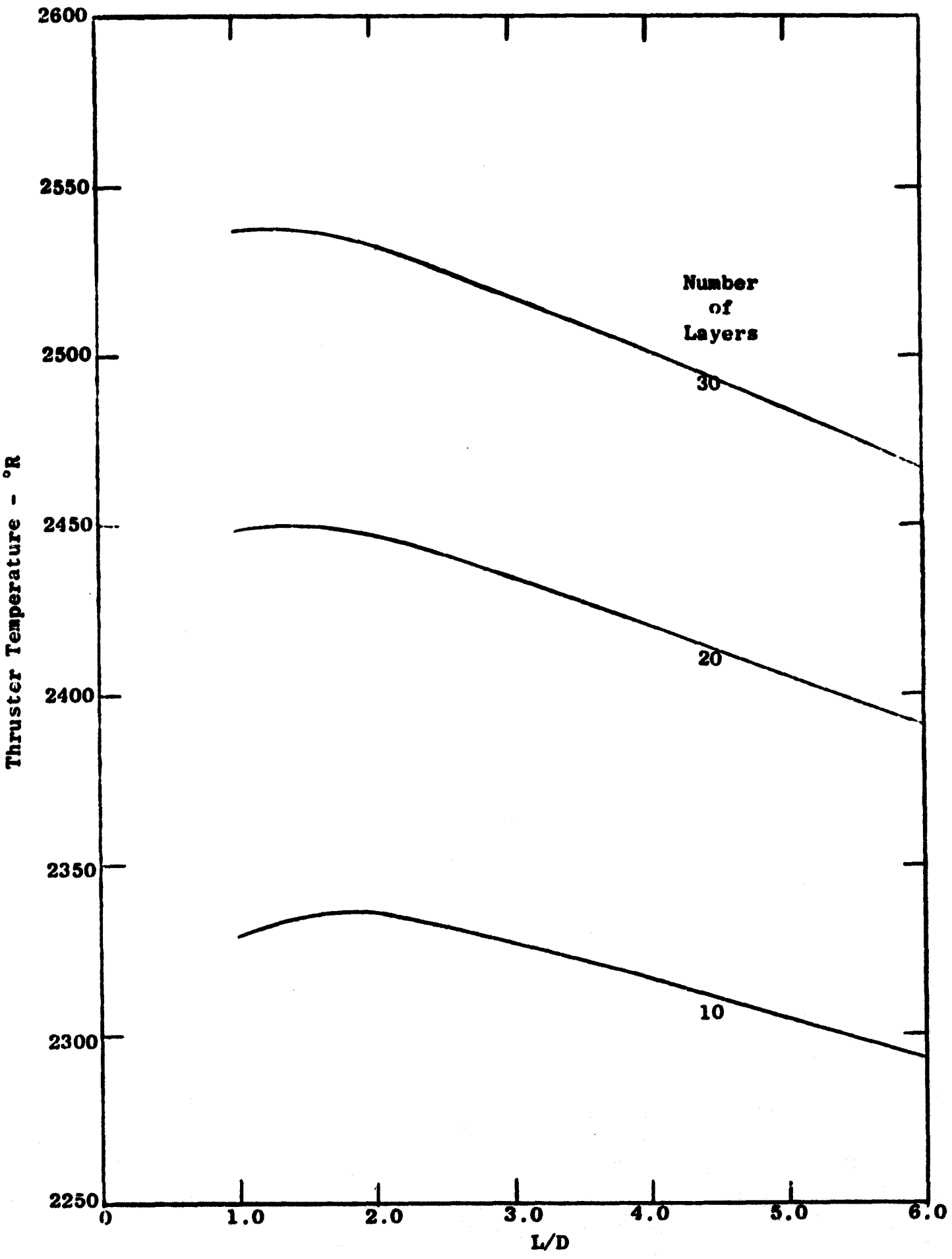


Figure 25. Maximum Operating Temperature vs. L/D for 60 Watt Radioisojet - Nichrome V Shields

E1279-8

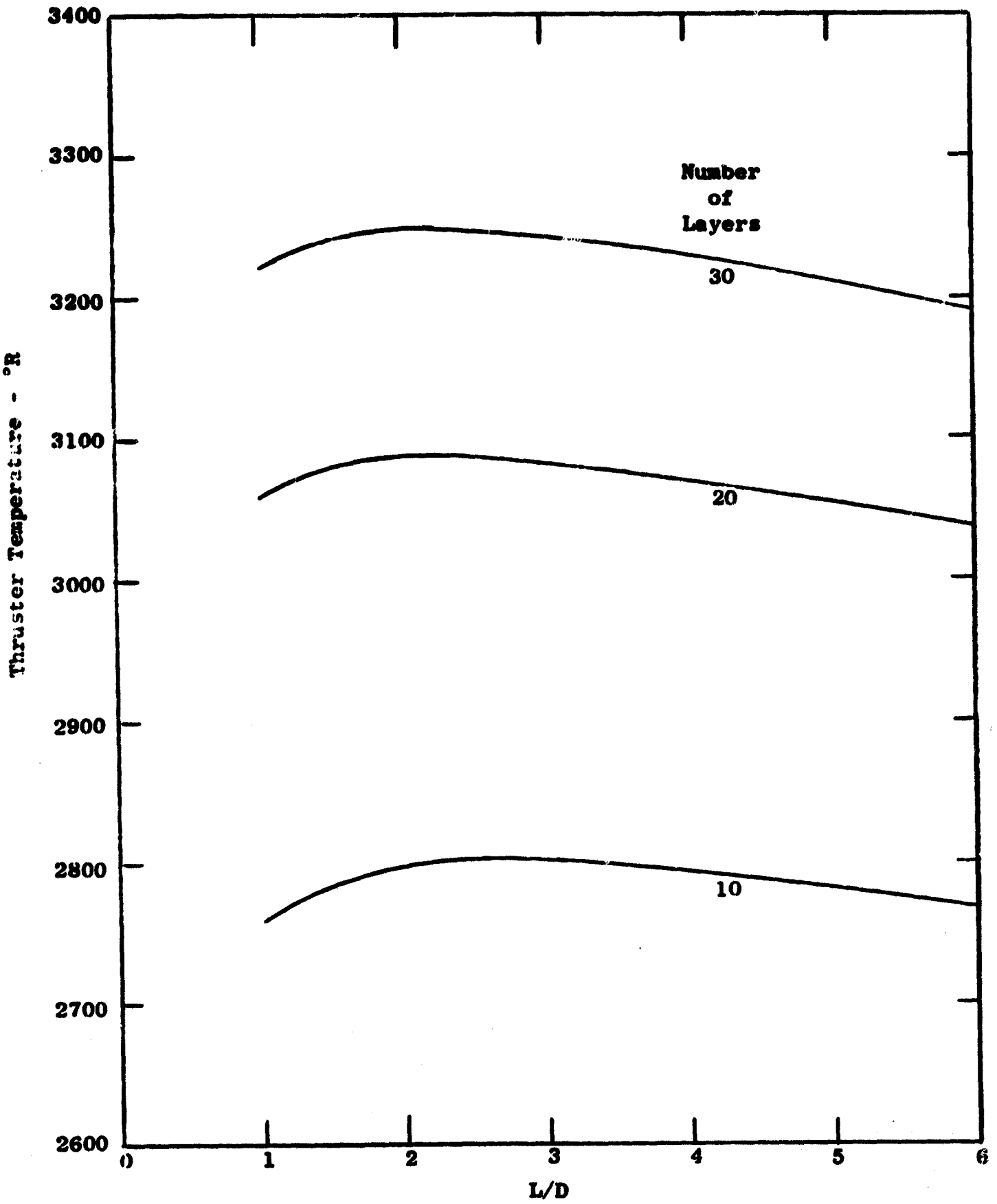


Figure 26. Maximum Operating Temperature vs. L/D for 60 Watt Radioisojet - Molybdenum Shields

E1279-9

material of these ends being the same as the outer layer of the capsule cladding.

The TSK 2000-1RE design is such that this capsule cladding does not form the inner wall of the propellant flow annulus but this capsule unit is inserted into a tubular section with hemispherical ends and supported from the rear mounting flange. A propellant seal similar to the O-ring seal used in the TSK 2000-1P is incorporated into the design, thereby allowing the inner body and heater capsule to be removed as a unit from the thruster body and heat shielding sub-assemblies. The seal is an Apex metal seal instead of an O-ring because of the higher temperatures anticipated in the flange area with this design.

As part of the radioisojet development program, hot thrust measurements were performed at the Mound Laboratories. A modified version of the GE resistance jet thrust rig was designed, fabricated, and installed in a test facility at that laboratory. In this thrust rig the thruster is supported on a base plate suspended by three flexure straps which allow translation of the base plate along a horizontal plane when thrust is applied. Displacement is determined by measuring the readout of a calibrated Daytronic displacement transducer model 103C-200. From the anticipated total suspended weight of approximately 12 lbs., it was calculated that the sensitivity of the thrust rig is such that one millipound of thrust will produce one mil deflection of the thrust rig.

All capsule compatibility studies and fabrication development for the finished capsule were carried out at Battelle Northwest Laboratories. A Pm, 47 Oxide heat source was fabricated and supplied to Mound Laboratories, on schedule, where it was inserted into the G.E. supplied thruster for performance testing.

The results of this program have been reported in Radioisojet Program Summary Report, May, 1967, Hitman Associates Report No. HIT-255, wherein the design of the thruster is discussed in more detail and the results of the test program are described.

D. TSK 3000-1RE Simulated Radioisojet Thruster

Some effort was expended early in the contract period toward the development of a 3000°F simulated radioisojet. The primary results of this effort were in the demonstration of a heater operating at 3000°F in a configuration compatible with the proposed design. Details of the heater design and test results are described in Section III-G.

While the results of the heater tests were encouraging the extension of existing technology required to develop a satisfactory 3000°F thruster was adjudged to be inconsistant with the intent of the program. On this basis the effort on this portion of the program was terminated prior to fabrication of the proposed thruster.

E. Heat Shielding Development

As an adjunct to the primary task of thruster development a heat shielding development program was carried on. Under this program, various types of heat shielding materials and configurations were tested with a dual purpose. Primarily, the objective was to develop a reliable, efficient heat shielding package for use under vacuum conditions with a 2000°F thruster. Secondarily, an attempt was made to develop a heat shielding package to allow operation of a thruster at rated power on the launch pad for periods up to 48 hours with no significant changes in overall heat transfer caused by surface oxidation.

Nichrome V, which has an effective emissivity of approxmiately 0.4 in the configuration tested, has been the standard heat shielding material used thus far. As an alternate, molybdenum was chosen because of its low emissivity and high temperature capabilities which allows growth of the resistance jet to higher temperature operation.

Packages of both these materials in the same configuration, each with Nichrome V wire layer separation, were fabricated and tested to determine heat losses as a function of input power with a 3/8" diameter heater. After establishing the initial performance of each unit, they were vibrated under the same conditions outlined for the thruster environmental test. Both units were then retested to determine if the severity of the vibration testing had caused

permanent changes in heat shielding effectiveness with the results as shown in Figure 27. As can be seen from the curves, there was no measurable change with the Nichrome V package and less than 10% deviation from the original data with the molybdenum foil.

From the curves of Figure 25 and Figure 26 which were generated for the radioisojet L/D optimization, it can be seen that for the same power input a molybdenum heat shielding package allows operation of a thruster at considerably higher temperatures and, conversely, the power required to operate at any given temperature is substantially reduced by substituting an equal number of layers of molybdenum foil for the Nichrome V foil.

While these results indicated a definite advantage in using molybdenum foil, subsequent tests resulted in a lack of reproducibility in performance. On this basis means of providing low emissivity coatings on the Nichrome V to provide the same results were looked into as an alternate approach.

Small discs of Nichrome V foil were coated with a 1000Å cerium oxide layer and this in turn was coated with 2000Å coating of gold. Samples were subjected to 1000°F, 1400°F, and 1800°F in air, 1000°F in NH_3 and 1000°F in vacuum for periods of 50 hours each. From the results of these tests it was concluded that the upper limit for utilization of this low emissivity coating is between 1000°F and 1400°F since the gold was still intact at 1000°F but had diffused into the Nichrome V at 1400°F. At the upper limit it is still below the operating temperature of a significant portion of a typical 2000°F heat shielding package.

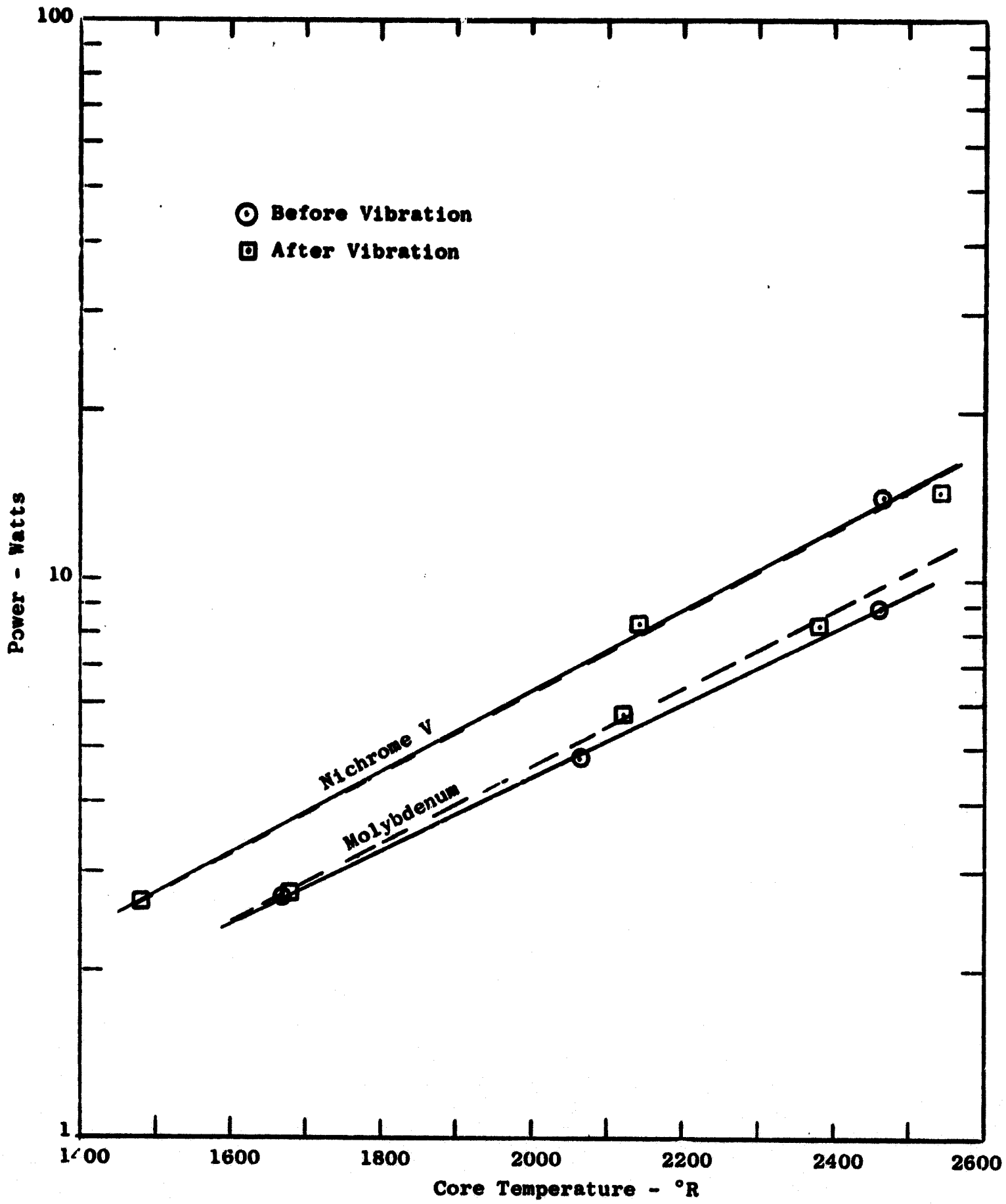


Figure 27. Heat Shielding Effectiveness Before & After Vibration

E1279-10

In an effort to find a high emissivity coating for use on the exterior thruster surfaces to reduce the operating temperature of these surfaces two materials were procured from Product Techniques, Inc. One of these, PT 201, is a thermal setting epoxy which can withstand 500°F, while the other, PT 404A, is a silicon ceramic type material that can be used up to 2000°F.

Small Nichrome V discs of the same type used for the low emissivity coating tests were coated with the material and subjected to 500°F in vacuum. From the photograph of Figure 28, it can be seen that the PT 404A was virtually unaffected while the PT 201 coating blistered and cracked after exposure to 500°F in vacuum for 50 hours.

In addition to these vacuum tests, samples were heated to 500°F in air. In these tests, both the PT 201 and PT 404A samples showed considerably less degradation in appearance than the samples tested in vacuum had shown. The results of these tests are also summarized in Table V.

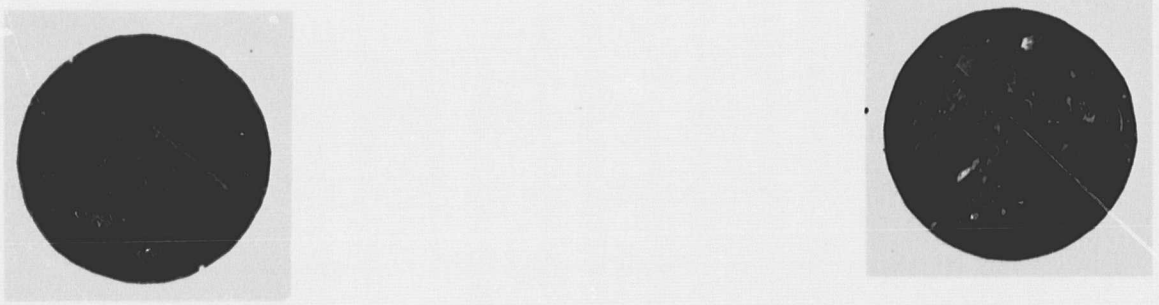
An iron titanate coating was applied to a sample Nichrome heat shielding package as shown in Figure 29 and did provide a reduction in surface temperatures as shown in Table VI. From the temperature power curve of Figure 30, the change in slope associated with tests performed after coating indicates an increase in conduction losses. This effect resulted from dishing in of the heat shielding can ends during spraying which compressed the individual layers of

PT-404

PT-201



BEFORE



AFTER 50 HOURS AT 500° F IN VACUUM

E1124-11

Figure 28. High Emissivity Coating Test Specimens Before and After Test.

TABLE V

SUMMARY OF HIGH & LOW EMISSIVITY COATING TEST RESULTS

Coating	Base	Coating Thickness	Exposure Temp., °F	Exposure Atm.	Exposure Time	Remarks
Gold with cerium oxide diffusion barrier	Nichrome V	1000 Å cerium oxide, 2000 Å gold	1000	vac.	50 hr.	No apparent change in surface appearance.
"	"	"	"	air	"	"
"	"	"	1400	air	"	Light oxidation
"	"	"	1800	air	"	Heavy oxidation - plate badly warped
"	"	"	1000	NH_3	"	Surface darkened - considerable diffusion of gold into Nichrome V
PT 201	"	Approx. .010"	500	vac.	"	Surface bubbled and cracked
"	"	"	500	air	"	No apparent change
PT 404A	Nichrome	Approx. .005"	500	vac.	"	No apparent change
"	"	"	500	air	"	No apparent change

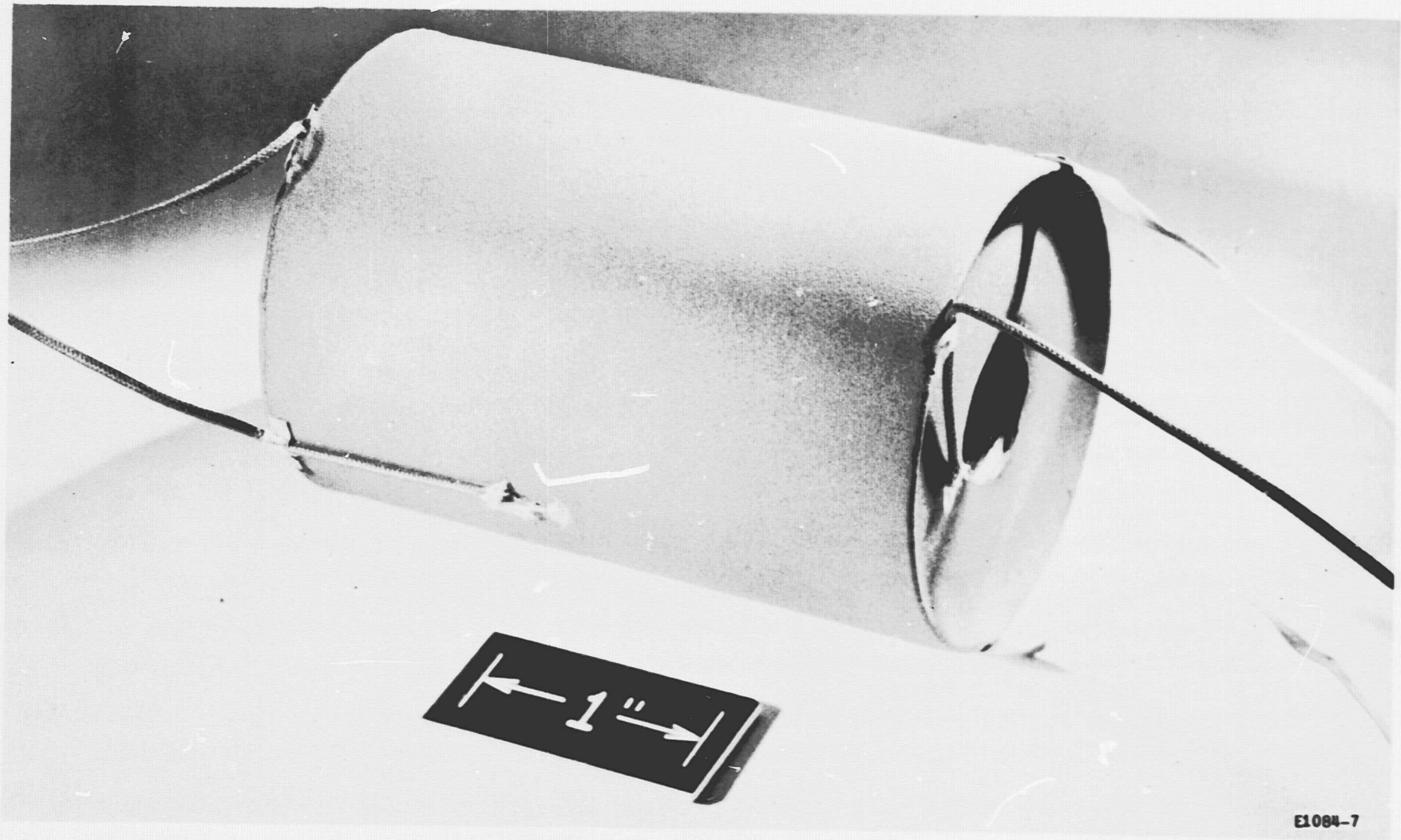


Figure 29. Iron Titanate Coated Heat Shielding Package. (C66050324)

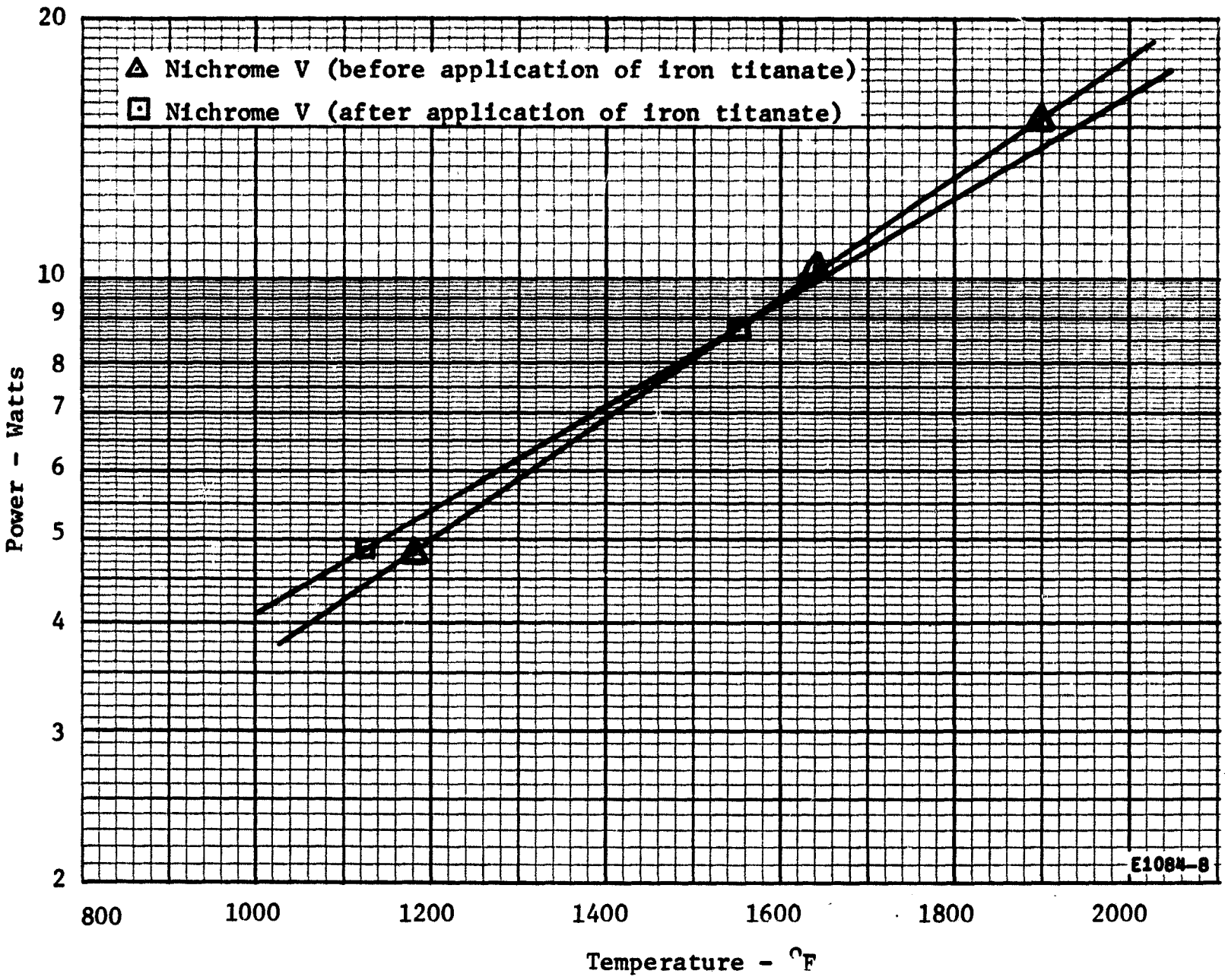
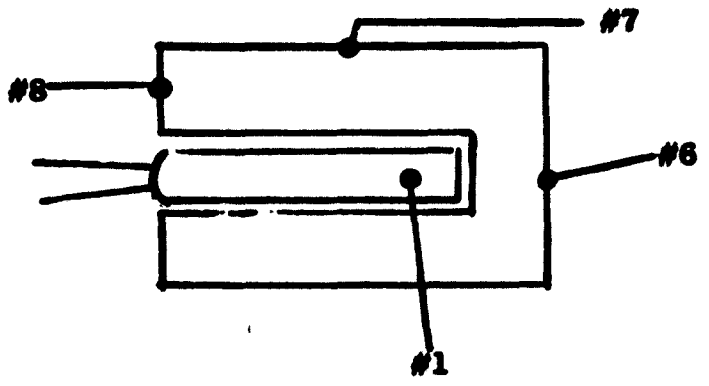


Figure 30. Temperature vs Power for Nichrome V Heat Shielding Test Package (Iron Titanate Experiment).

TABLE VI

IRON TITANATE EXPERIMENT

SURFACE TEMPERATURE MEASUREMENTS



Before Coating

Watts	T/C #1 °F	T/C #6 °F	T/C #7 °F	T/C #8 °F
4.84	1181	162	158	177
10.4	1638	262	257	300
15.3	1894	330	322	383

After Coating

Watts	T/C #1 °F	T/C #6 °F	T/C #7 °F	T/C #8 °F
4.92	1125	130	120	158
8.80	1557	164	147	214

Effective Emissivity Without Coating - .6

Effective Emissivity With Coating - .9

heat shielding by approximately 10%. Effective surface emissivity calculations showed a change from approximately 0.6 prior to spraying to 0.9 after application of the iron titanate.

Additional heat shielding tests were performed to determine the effects of an ammonia atmosphere on tantalum foil. The temperature-power curve shown in Figure 31 was first generated by operating in a vacuum of 10^{-8} torr over a range of temperatures. At 2500°F, the vacuum tank was flooded with ammonia gas at slightly less than one atmosphere and allowed to remain there for periods from one-half hour to four hours. The data obtained after immersion in NH_3 at 2500°F fell close to the original curve indicating that no significant surface emissivity changes occurred. Since no vibration loads will be seen by a heat shielding package after insertion into orbit, any possible embrittlement of the weld joints caused by either the hydrogen or nitrogen decomposition products should be inconsequential.

Further investigation of tantalum at higher temperature appears warranted from these results. First tests with the 3000°F heater assembly were performed with tantalum heat shielding.

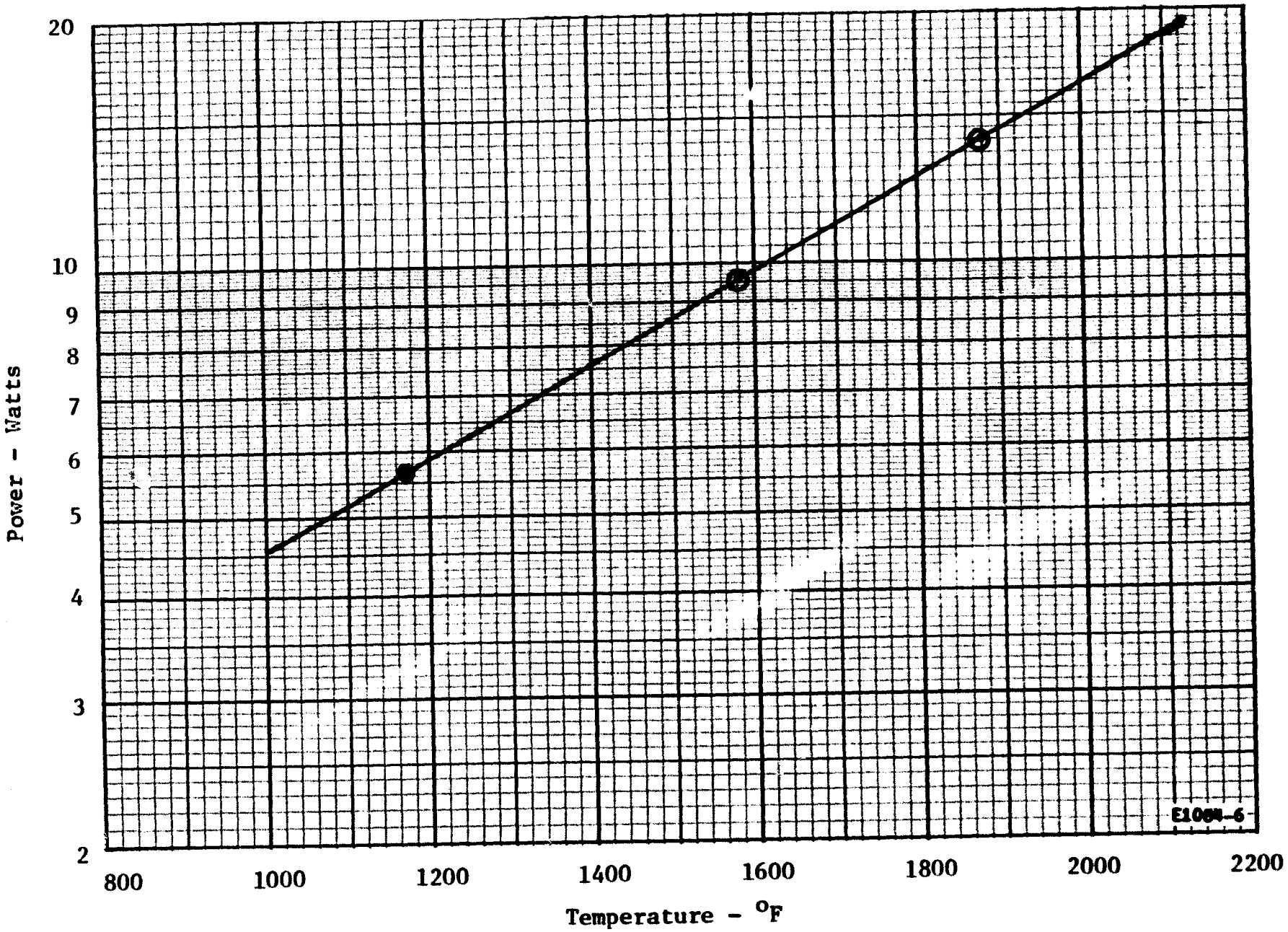


Figure 31. Temperature vs Power for Tantalum Heat Shielding Test Package.

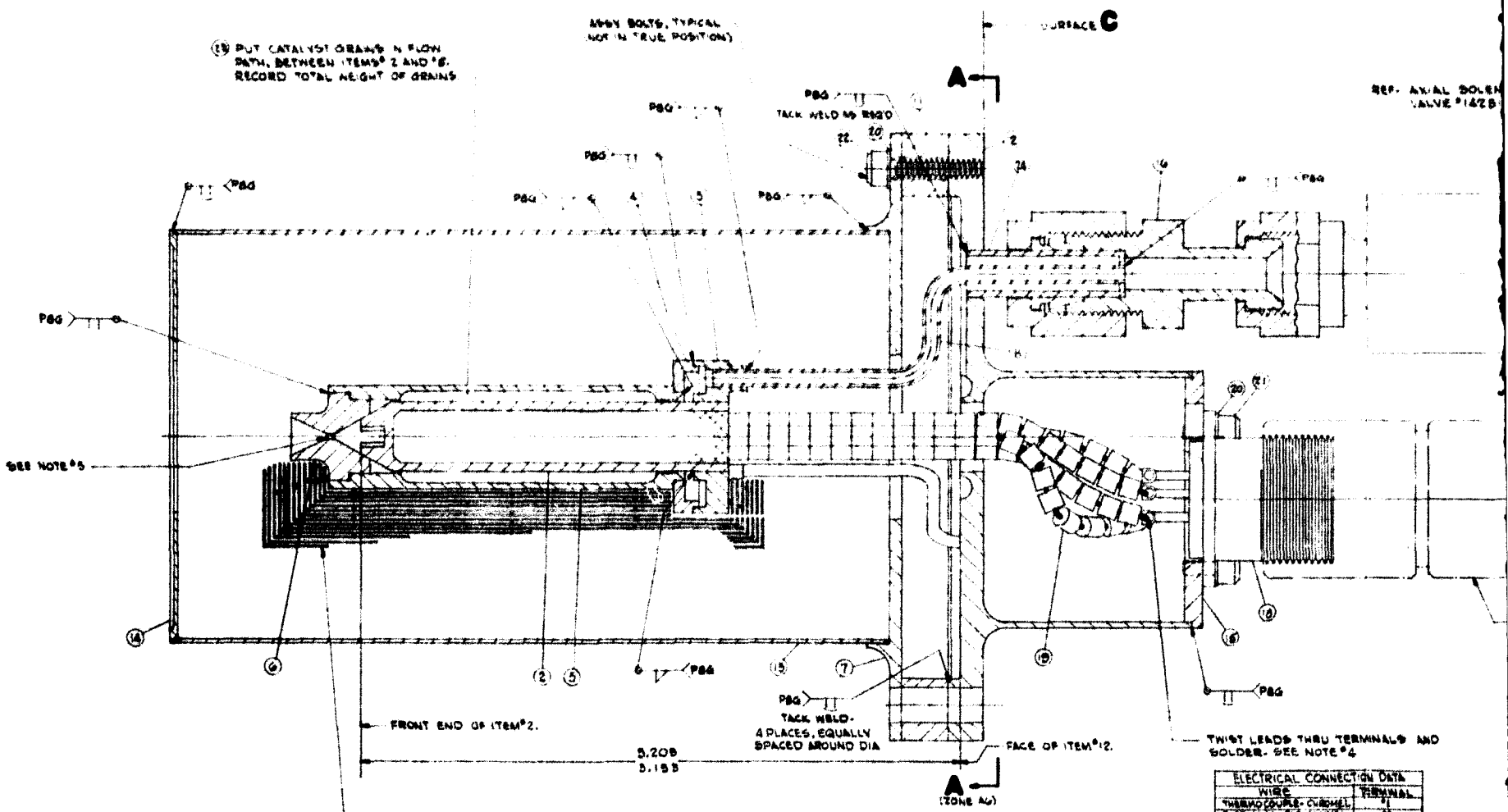
F. Ammonia Catalysis

It has long been established that the effective delivered specific impulse with ammonia can be increased significantly by decomposing it into Nitrogen and Hydrogen. This can be accomplished in one of two ways: either by increasing the operating temperature to such a high level that decomposition takes place at a high rate in the gas independent of contact with any surface material or by providing a decomposition catalyst which will promote decomposition at much lower temperatures. Obviously the second approach provides the desired end effect with the least expenditure of power. For this reason a development program was established with Englehard Industries to evaluate state of the art catalysts for this application.

Three catalysts designated C-4160, C-4052, and C-4173 were tested in a bed containing 3.1 cc of each catalyst in a volume designed to simulate the space velocity expected in a typical thruster. Each catalyst was allowed to remain in the reactor for approximately 500 hours with the degree of decomposition of the effluent gas monitored continuously. Two of these catalysts (C-4160 and C-4173) maintained their effectiveness providing at least 90% decomposition at 1500°F after 500 hours at 1900°F and pressures of 10^{-4} torr.

A thruster designated the TSK 2000-1C was fabricated for use in determining the effect of using a catalyst in a true thruster configuration. (An engineering sketch) of this design is shown in Figure 31-A.

FOLDOUT FRAME 1



(i) ASSEMBLY

35 LAYERS OF HEAT SHIELDING CONSISTING OF ALTERNATE LAYERS OF .014 DIA NICHROME V WIRE AND .003 THK SHEETS OF NICHROME V. TACK WIRE AROUND ITEM°5. WRAP CYLINDER OF FOIL OVER WIRE AND TACK. APPLY FOIL END AND TACK. WRAP WIRE AROUND CYLINDER AND ON END AND TACK. WRAP CYLINDER OF FOIL OVER WIRE AND TACK. APPLY FOIL END AND TACK. FOLLOW ABOVE PATTERN TO COMPLETE SHIELD.

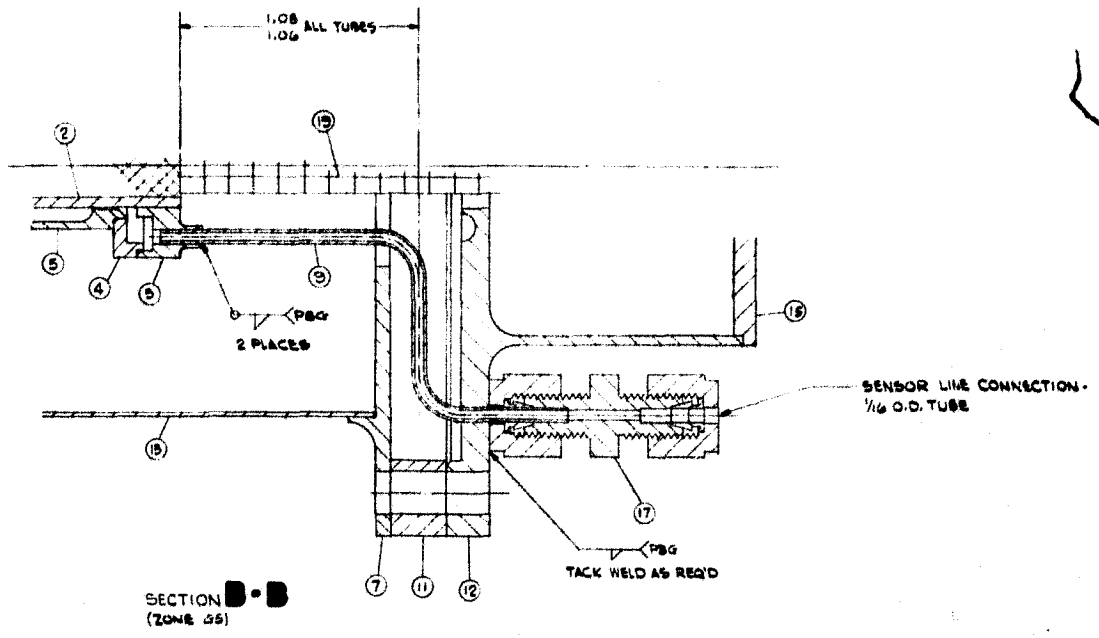
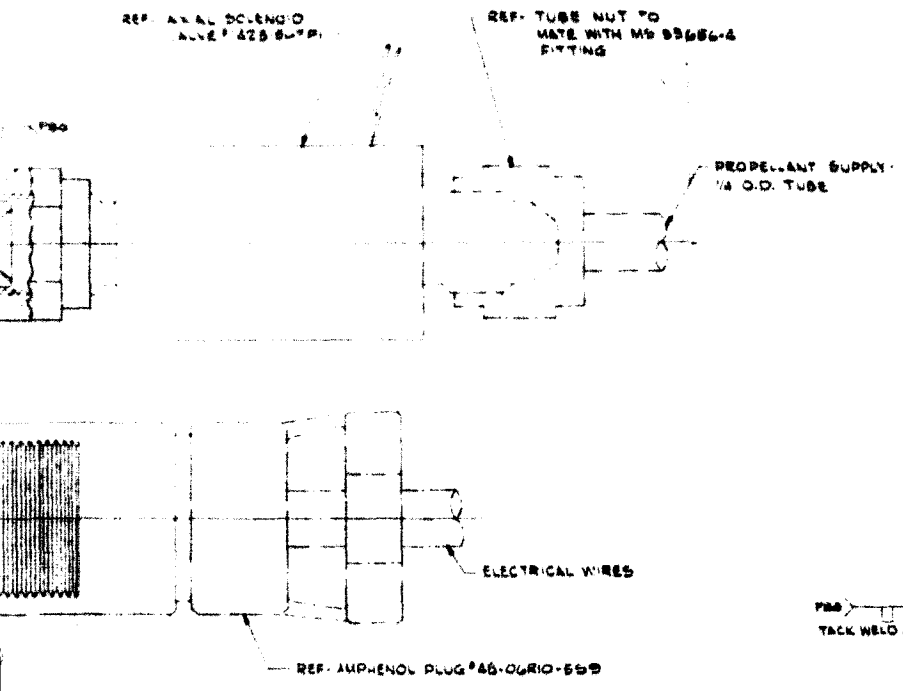
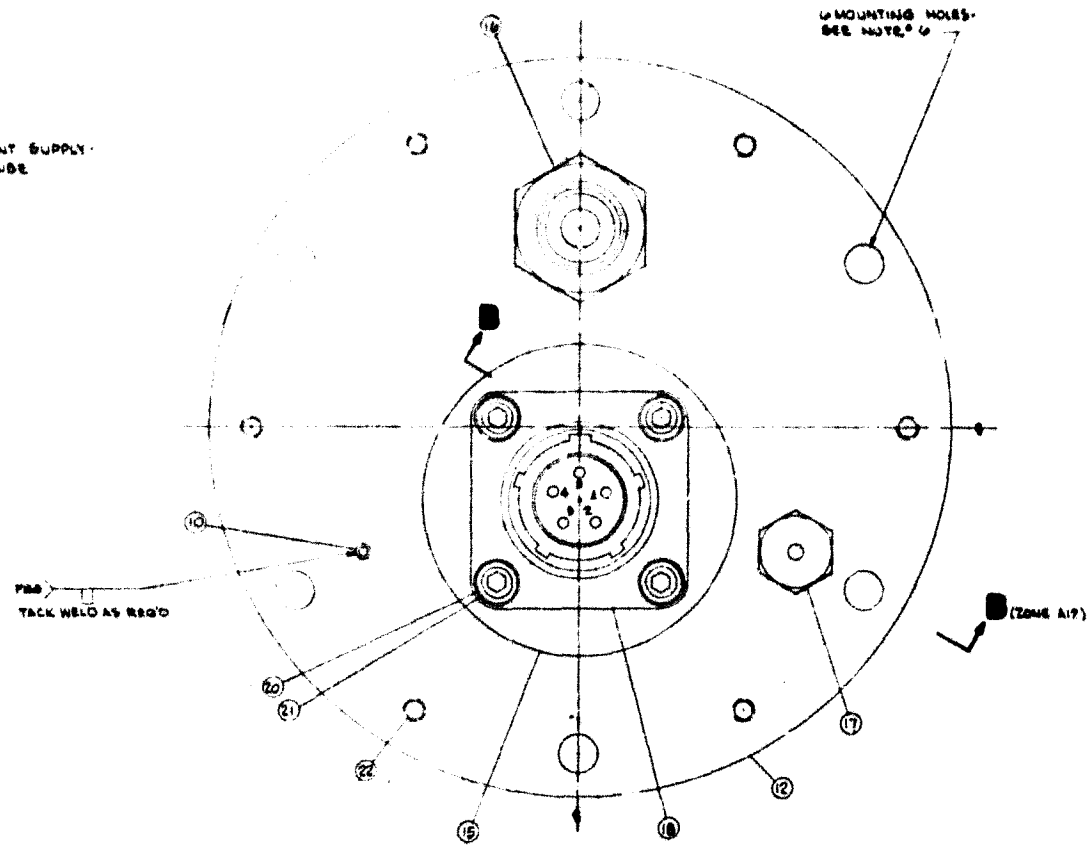


Figure 31 A TSK-2000-1C Catal

FOLDOUT FRAME 2

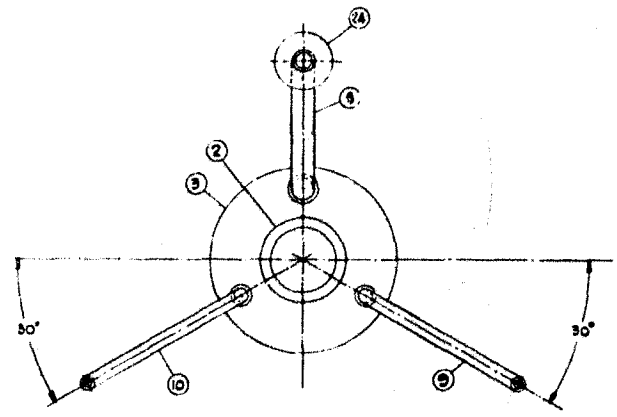




DS THRU TERMINALS AND EE NOTE #4

CAL CONNECTION DATA	
RE	TERMINAL
[illegible]	1
[illegible]	2
[illegible]	3
[illegible]	4
D	5

SENSOR LINE CONNECTION- 1/16 O.D. TUBE



SECTION A-A
ITEM #12 NOT SHOWN
(ZONE F12)

-2000-1C Catalysis Test Bed.

Performance tests were run at room temperature, 1500°F, 1700°F, and 2000°F. A significant increase in specific impulse was measured with this thruster at the lower temperature as compared to the previously measured performance of an uncatalyzed thruster. At the 1500°F operating point over 210 seconds was measured ranging up to 256 seconds at 2000°F. Typically the maximum measured at 1500°F with an uncatalyzed thruster was 195 seconds.

From the available data it was estimated that the degree of decomposition at 1500°F, 1700°F, and 2000°F was 50%, 85% and 100% respectively.

Details of the catalysis investigation and the performance testing of the catalyzed thruster have previously been reported in Summary Report Ammonia Catalysis Investigation, Contract No. NAS 5-9670 dated February 17,1967.

G. Heater Test Program

1. Background

The purpose of the heater test program was to select, in as direct a manner as possible, the materials and the design configuration most likely to provide a highly reliable heater for steady-state use at 2000°F and at low power levels. A heater development program involving an extensive study of possible materials interactions was not intended at the start of the contract period. Instead, it was intended to build upon past successful heater test experience involving metal encapsulated wire wound heaters constructed on ceramic core and insulator components and modified by the use of swaged encapsulated heater concepts; the swaged heater concept was expected to result in higher thermal conductance within the heater and a significantly lower wire element temperature. The lower metal element temperatures in turn, were expected to result in improved heater filament reliability, and the more densely swaged condition of the heater was expected to provide good support of the heater element and to reduce the possibility of metal vapor transfer within the evacuated spaces inside the metal encapsulated heater.

The heaters were designed to operate at nominal power levels of 20, 30, and 70 watts at applied DC voltages in the range of 13-20 volts. The active heating lengths were approximately 1-1/2 inches for the lower wattage heaters and about 3 inches for the 70-watt heater. While it was originally intended to restrict the diameter

of the 20-watt heater to 1/4 inch, for practical purposes all heaters were constructed to a swaged diameter of 0.370" ±0.002". These three heater configurations are shown in Figures 32, 33, and 34.

During the course of the evaluation approximately 100 heaters were prepared and processed. Initially, only a few heaters were involved in each lot, but as the materials selections were made and the design decisions were evolved, larger numbers of heaters were procured for testing and for deliverable hardware component purposes. A general description of these heaters and the numbers involved are indicated in Table VII.

Using commercially available Nichrome V ribbon element swaged heaters, the low thermal gradient between element wire and metal sheath was demonstrated in air and vacuum tests; in these tests, the limited stability of Nichrome V was indicated.

Additional tests of heaters with selected materials combinations were performed before the most promising combination was selected. Concurrently, the manufacturing process techniques were developed for the construction of heaters to the final design configurations. In addition to conducting long-duration, steady-state heater tests at 2000°F on the promising heater configuration which featured a magnesia core, platinum element wire, boron nitride fill, and an Inconel 600 sheath, parallel efforts were directed for a brief period at alternate heater materials evaluation and at the resolution

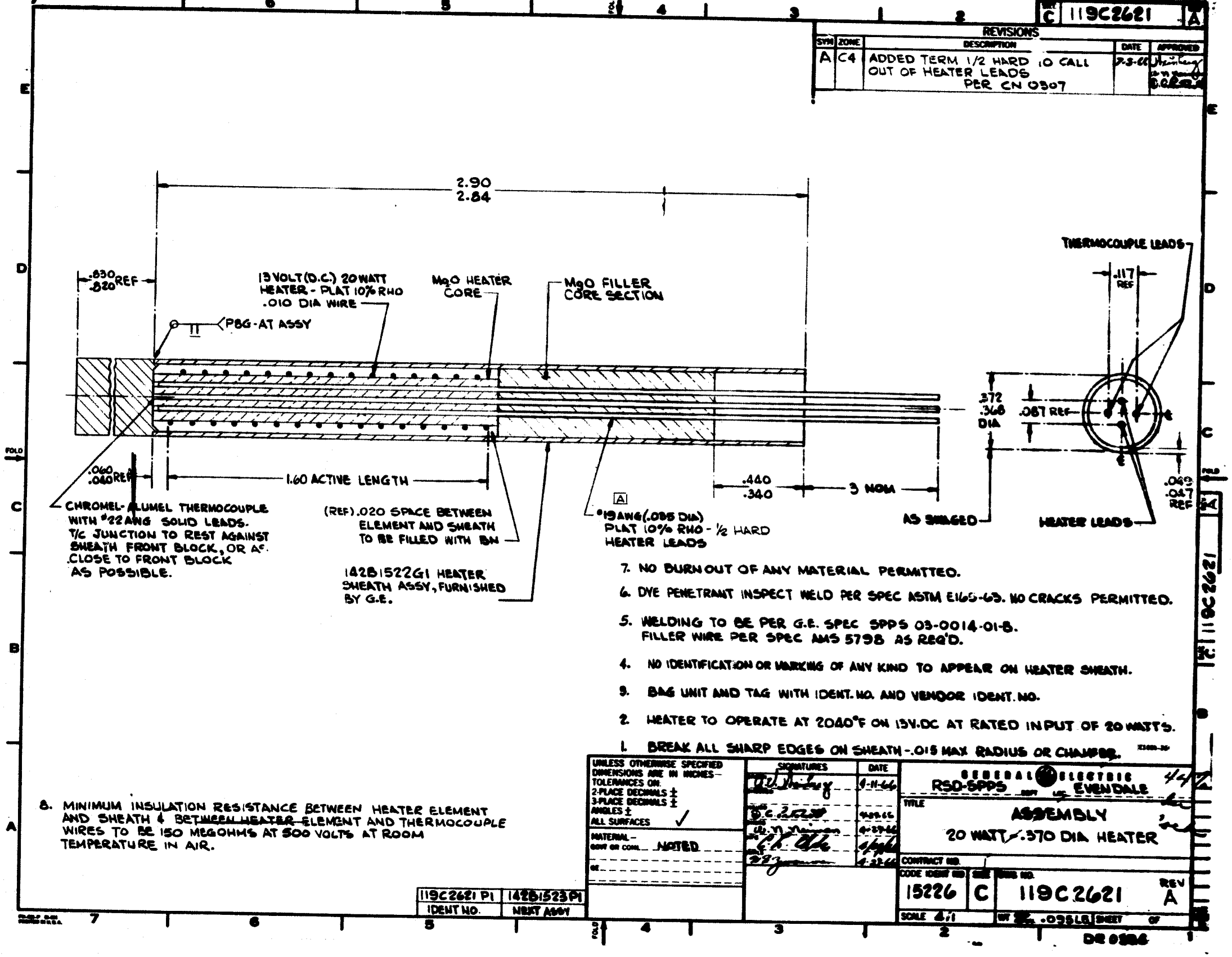
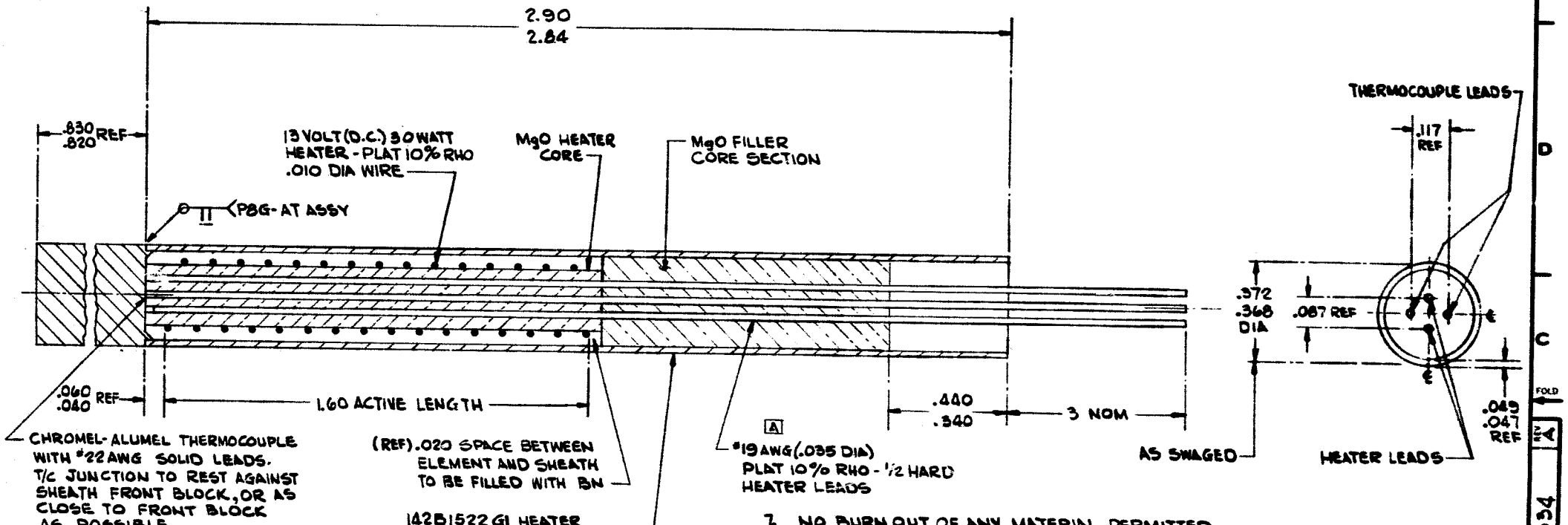


Figure 32 Outline Drawing, 20 Watt, 2000°F Heater. (119C2621)

SIZE	119C2634	REV
C		A

REVISIONS

SYM	ZONE	DESCRIPTION	DATE	APPROVED
A	C4	ADDED TERM 1/2 HARD TO CALL OUT OF HEATER LEADS PER CN 0307	7566	



7. NO BURN OUT OF ANY MATERIAL PERMITTED.
6. DYE PENETRANT INSPECT WELD PER SPEC ASTM E165-63. NO CRACKS PERMITTED.
5. WELDING TO BE PER G.E. SPEC SPPS 03-0014-01-B. FILLER WIRE PER SPEC AMS 5798 AS REQ'D
4. NO IDENTIFICATION OR MARKING OF ANY KIND TO APPEAR ON HEATER SHEATH.
3. BAG UNIT AND TAG WITH IDENT. NO. AND VENDOR IDENT. NO.
2. HEATER TO OPERATE AT 2040°F ON 13V. DC AT RATED INPUT OF 30 WATTS.
1. BREAK ALL SHARP EDGES ON SHEATH - .015 MAX RADIUS OR CHAMFER.

8. MINIMUM INSULATION RESISTANCE BETWEEN HEATER ELEMENT AND SHEATH & BETWEEN HEATER ELEMENT AND THERMOCOUPLE WIRES TO BE 150 MEG OHMS AT 500 VOLTS AT ROOM TEMPERATURE IN AIR.

119C2634P1	142B1524 P1
IDENT NO.	NEXT ASSY

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES — TOLERANCES ON: 2-PLACE DECIMALS ±, 3-PLACE DECIMALS ±, ANGLES ±, ALL SURFACES ✓
MATERIAL — GOVT OR COML NOTED; GE

SIGNATURES		DATE
ORIG CHECK'D	G.D. Shirley	4-11-66
ISSUED	DG 2-4	5-1-66
ENGRG	W.N. Norman	5-7-66
MFG	C.F. Clyde	5-9-66
MATLS	W.B. Zimmerman	5-9-66

GENERAL ELECTRIC
RSD-SPPS DEPT EVENDALE LOC.

TITLE
ASSEMBLY
30 WATT-.370 DIA HEATER

CONTRACT NO.

CODE IDENT NO.	SIZE	DWG NO.	REV
15226	C	119C2634	A

SCALE 4/1 | WT CALC ACTUAL | SHEET OF

DR 0334

Figure 33. Outline Drawing, 30 Watt, 2000°F Heater. (119C2634)

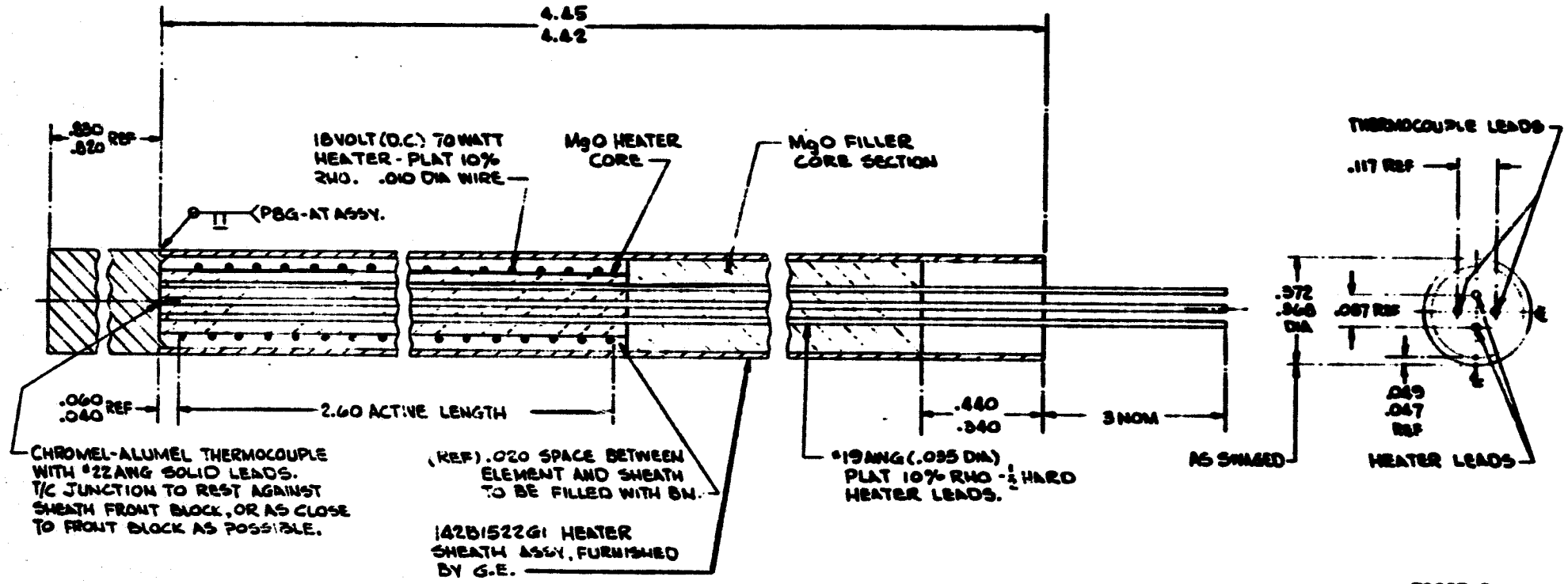


Figure 34. 70 Watt, 2000°F Heater Procurement Drawing (47C141352) Model HSK-2000-70.

FOLDOUT FRAME

TAB

HEATER D

Lot	No.	Serial No's	Power	Volts	Diam.	Length	T. C.	Sheath	Element
1	6	C1-C6	30W	28	3/8"	1 15/16"	Cr-Al	Inc. 600	Nich. V(0.016" x 0.00
2	3	For Manu-	20	13	.245"	3 1/8"	None	Inc. 600	Nich. V(.010")
3	6	facturing Evaluation	30	13	.370"	3 1/8"	Cr-Al	Inc. 600	Nich. V(.010")
4	6	Purposes Only	70	18	.370"	3 1/8"	Cr-Al	Inc. 600	Nich. V(0.10")
5	2	2A, 2B	15	15	3/8"	1 15/16"	Cr-Al	Inc. 600	100%Pt(.010")
6	2	3A, 3B	15	15	1/2"	1 15/16"	Cr-Al	Inc. 600	100%Pt(.010")
7	2	4A, 4B	15	15	3/8"	1 15/16"	Cr-Al	Inc. 600	Mo(.010")
8	2	7, 8	15	15	3/8"	1 15/16"	Cr-Al	Inc. 600	Preoxidized Nich. V (.010")
9	1	9	20	15	3/8"	3"	Cr-Al	Inc. 600	Preoxidized Nich. V(.010")
10	6	11 - 16	20	15	1/2"	2"	Cr-Al	Inc. 600	100%Pt(.010")
11	3	- ,17, -	20	15	1/2"	2 1/8"	Cr-Al	Inc. 600	Pt-10%Rh(.010")
12	2	18, 19	20	15	1/2"	2 1/8"	Cr-Al	Inc. 600	Pt-10%Rh(.010")
13	5	20 - 24	20	13	.370"	2.9"	Cr-Al	Hast. X	Pt-10%Rh(.010")
14	5	25 - 29	30	13	.370"	2.9"	Cr-Al	Hast. X	Pt-10%Rh(.010")
15	6	30 - 35	20	13	.370"	2.9"	Cr-Al	Hast. X	Pt-10%Rh(.010")
16	6	36 - 41	30	13	.370"	2.9"	Cr-Al*	Hast. X	Pt-10%Rh(.010")
17	6	42 - 47	20	13	.370"	2.9	Cr-Al	Annealed Hast. X	Pt-10%Rh(.010")
18	3	48 - 50	70	18	.370"	4.5"	Cr-Al	Inc. 600	Pt-10%Rh(.010")
19	6	51 - 53 & 57 - 59	70	18	.370"	4.5"	Cr-Al	Annealed Hast. X	Pt-10%Rh(.089")**
20	3	54 - 56	20	13	.370"	2.9"	Cr-Al	Annealed Hast. X	Thermoplatinum F.G.(.010")
21	18	60 - 77	20	13	.370"	2.9"	Cr-Al	Annealed Hast. X	Pt-10%Rh(.010")

FOLDOUT FRAME 2

TABLE VII

ATER DESCRIPTION

	Leads	Core	Fill	Spacer	Remarks
x 0.003")	Ni(0.035")	MgO	MgO-BN	Lava "A"	
	Ni(0.035")	MgO	BN	Lava "A"	
	Ni(0.035")	MgO	BN	Lava "A"	
	Ni(0.035")	MgO	BN	Lava "A"	
	Pt(0.040")	MgO	BN	Lava "A"	
	Pt(0.040")	Al_2O_3	100-200 mesh Al_2O_3	Lava "A"	
	Mo(0.035")	MgO	BN	Lava "A"	
	Ni(0.035")	MgO	MgO	Lava "A"	
	Ni(0.035")	MgO	BN	Lava "A"	
	Pt(.057")	Al_2O_3	BN	Lava "A"	
	Pt (.040")	Al_2O_3	-325m Al_2O_3, -100m Al_2O_3, -200m Al_2O_3	Lava "A"	
	Pt(.040")	Al_2O_3	-200m Al_2O_3	Lava "A"	
	Pt-10%Rh(.035)	MgO	BN	None	
	Pt-10%Rh(.035)	MgO	BN	None	
	Pt-10%Rh(.035)	MgO	BN	None	
	Pt-10%Rh(.035)	MgO	BN	None	*S/N 41-Pt vs Pt-Rh T. C.
	Pt(.040")	MgO	BN	None	
	Pt(.040")	MgO	BN	None	
**	Pt-10%Rh(1/2 Hard - .035")	MgO	BN	None	**S/N 57 has (0.010" wire)
	Pt-10%Rh(1/2 Hard - .035")	MgO	BN	None	
	Pt-10%Rh(1/2 Hard - .035")	MgO	BN	None	

of heater design and manufacturing problems. Attempts were made to construct and evaluate heaters with either alumina cores and boron nitride fill or all-alumina ceramic components; the unique heater manufacturing problems in the assembly, filling, welding, and swaging of the heaters were resolved for the final design configuration.

During the course of the work, several problems were recognized. Readily reducible oxide impurities in the ceramic components seemed to promote an oxidation instability at low oxidation potentials in Nichrome V heaters operated in vacuum.

The evaporation of elements from the sheath and thermocouple materials in the vacuum environment resulted in minor metal loss and subsurface microporosity, but the significance of this observation on system design reliability over the required operating life was not assessed.

Reactions, influenced by DC voltage fields, were observed in Lava "A" insulators used as end plugs in some of the early heaters; the phenomena were not investigated extensively since this impure material was readily eliminated in design configuration heaters. However, DC migration effects were observed in later tests in which calcium, apparently from the magnesia core material, diffused into the positive heater lead wire and into the more positive end of the heater element wire to form brittle intermetallic phases; these phases were associated with some heater failures.

A significant problem of strain age cracking occurred in the heater sheaths when the material was switched from Inconel 600, which had been used as a temporary expedient in the swaged heater construction, back to Hastelloy X; while a brief period of time was required to resolve this problem through the use of unique reannealing procedures, it did not delay the testing or delivery of hardware items.

After the steady-state operational reliability of the selected heater configuration had been demonstrated at 2000°F, thermal cycling tests from 2000°F were initiated to determine the effects of intermittent operation of the heater in its space application, should that be necessary. The ability of the platinum-10% rhodium wire wound heater to withstand such cyclic testing was poor because of the restraint of the wire element in the ceramic matrix and the low recrystallization temperature of this heater wire alloy. The thermal cyclic resistance of the heaters was improved significantly by the use of a more recrystallization-resistant platinum wire material but was still insufficient for use in a heater requiring intermittent operation.

Several heaters were successfully operated for extended periods of time. One of the earliest heaters containing a magnesia core, platinum wire, boron nitride fill, and an Inconel 600 sheath operated with very stable electrical resistance for over 6600 hours. An alumina-cored, boron-nitride-filled heater operated successfully for

2 595 hours; a heater with all-alumina ceramic components was allowed to operate for 1437 hours. In addition, two hardware prototype heaters were each operated for over 1500 hours in a highly satisfactory manner. The serviceability of these heaters under steady-state system operating conditions was successfully demonstrated, and the problems limiting their use under more demanding conditions were identified.

As a potential growth version of heated thruster devices and as a heat simulator for higher temperature radioisojet thrusters, a 3000°F radioisojet thruster was designed, and an electrical heater featuring a tungsten filament inside tantalum radiation shields was successfully tested for 500 hours at 3000°F.

A brief summary of the heater testing schedule for the more significant tests is shown in Figure 35; this schedule does not include the design, materials selection, fabrication, processing, test installation, or post-test evaluation factors which were essential to the testing.

FOLDOUT FRAME 1

Lot No	DESCRIPTION Element / Core / Fill / Sheath
1	Nich. V / MgO / MgO-BN /Inc.600
	Tests in Air
	Tests in Vacuum
5	Pt / MgO / BN / Inc. 600
6	Pt / Al_2O_3 / Al_2O_3 / Inc. 600
7	Mo / MgO / BN / Inc. 600
8	Preox. N.V/ MgO / MgO / Inc.600
10	Pt / Al_2O_3 / BN / Inc. 600
12	Pt / Al_2O_3 / Al_2O_3 / Inc. 600
13	Pt-10Rh / MgO/BN/ Hast. X
14	Pt-10Rh / MgO / BN / Hast. X
13	Pt-10Rh / MgO / BN / Hast. X
14	Pt-10Rh / MgO / BN / Hast. X
17	Pt-10Rh / MgO / BN / Hast. X
20	Thermoplat./MgO/BN/Hast. X.
—	3000°F Heater

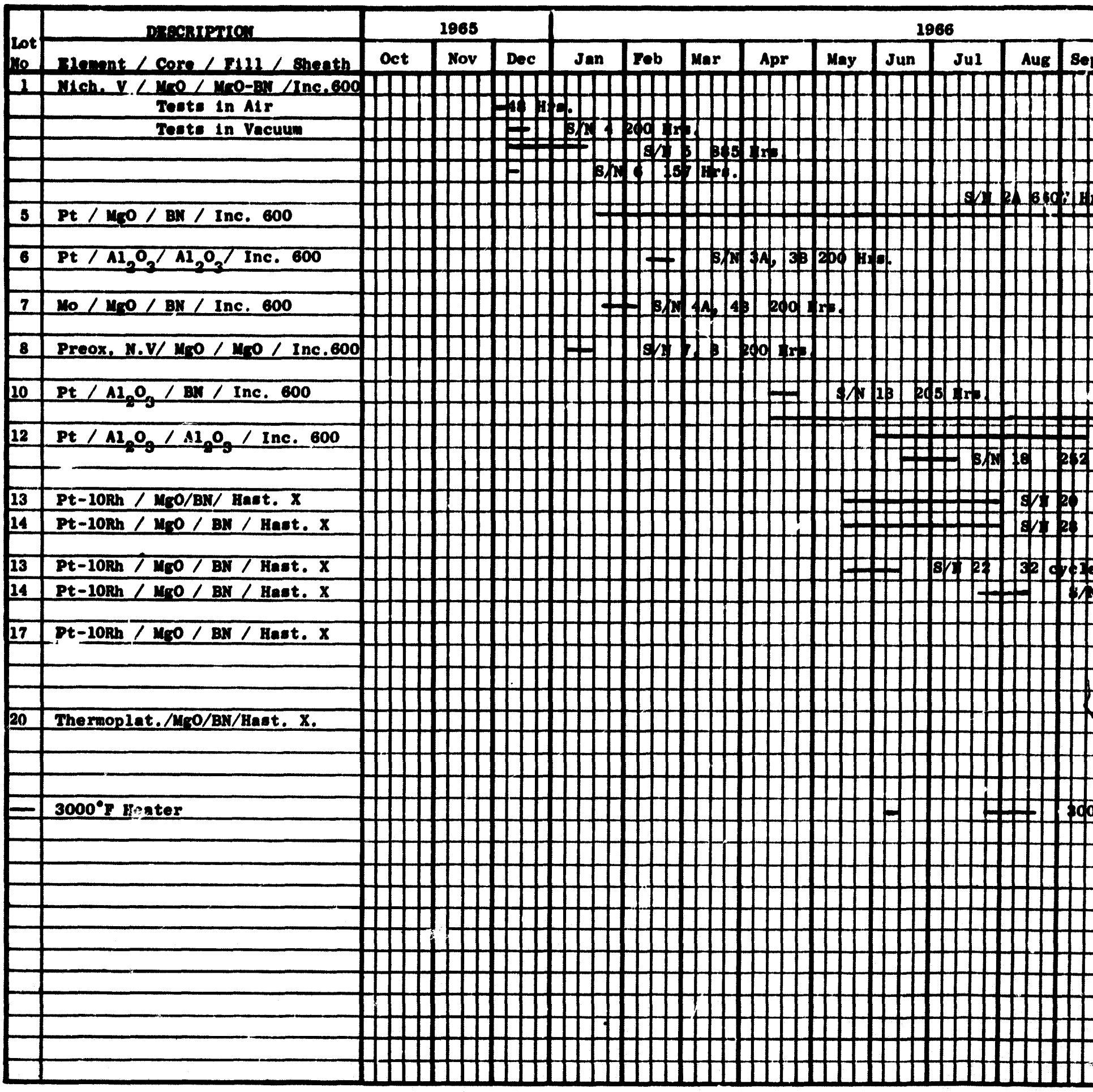
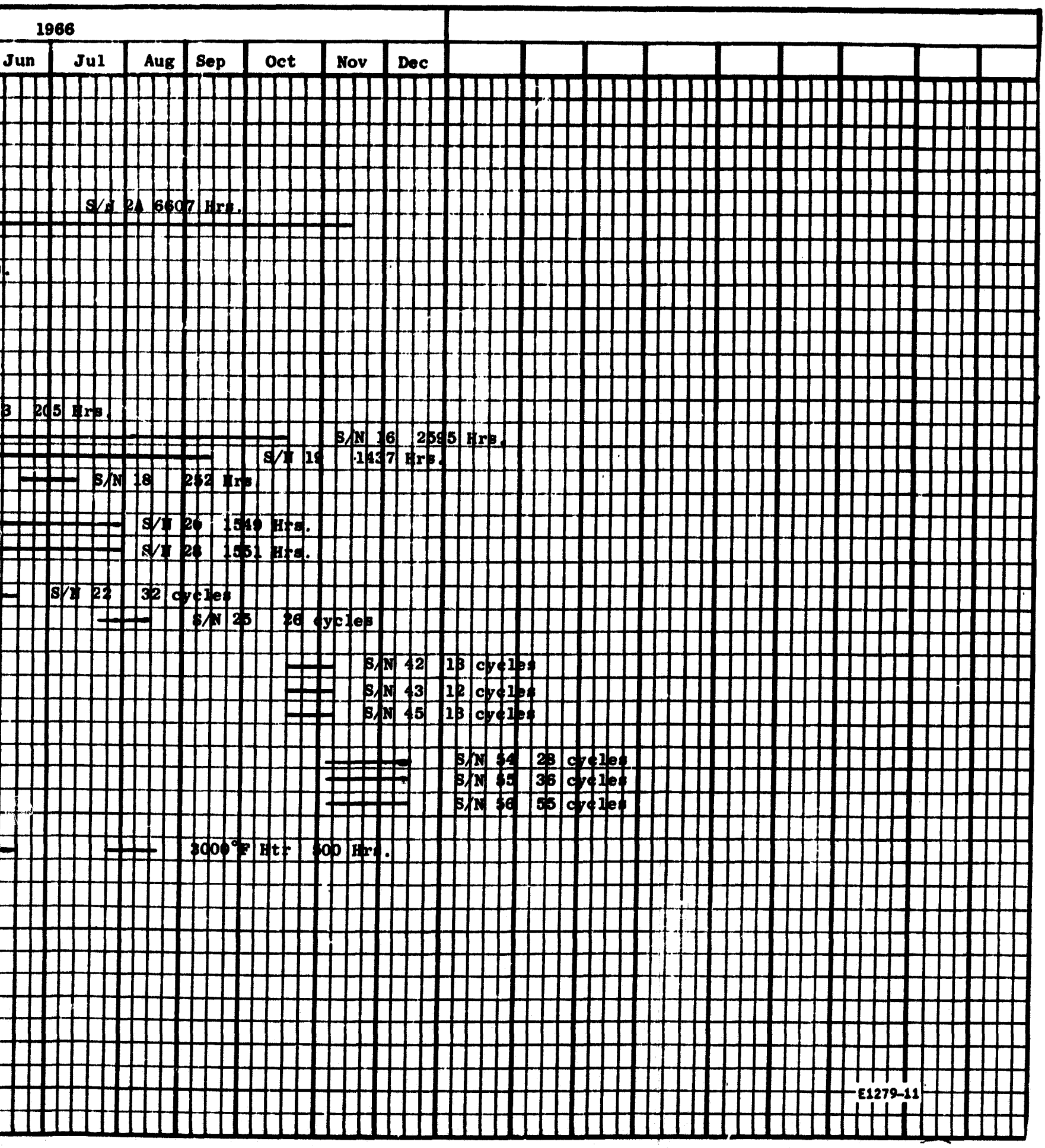


Figure 35. Schedule and Duration of Signifi

FOLDOUT FRAME 2



Duration of Significant Heater Tests.

2. Heater Test Technique and Test Data Summary

Six commercial-grade 30-watt heaters of a construction similar to that anticipated for the thruster to be developed under this program were procured and tested under extremes of environment. Two in air encased within a fiberglass insulating blanket open circuited after 48 hours having been operated at 25 watts. One heater was operated in vacuum for 157 hours with no indication of failure; another failed after 140 hours and a third failed after 648 hours. A compilation of the operating experience with these heaters appears in Table VIII.

The heaters described in Table IX were each enclosed in a heat shield representing a mock up of a thruster. Chromel Alumel junctives were located on each assembly approximately as shown on Figure 36.

A general summary of the testing experience with the heaters is shown in Table X. Specific data appear on Tables XI to XV and in curve form in Figures 37 to 41. In general the temperature differential between the interior of the heater cartridge and the sheath was lowest with S/N2B which had boron nitride fill. The highest differential was with S/N3B which had alumina fill.

S/N2A was allowed to operate until failure which occurred at 6607 hours. Examination of this heater indicated a brittle fracture of the heater lead wire outside of the compacted portion of the heater. This failure was attributed in part to the mechanical stresses imposed by the vibration of the assembly in the vacuum test facility.

TABLE VIII

Operating Experience

Heaters S/N 1 to S/N 6

Serial No.	Watt Input When Operated in		Operating Experience		°F Temp Differential, Interior to Exterior	Reason for Termination of Test
	Air	Vacuum	Hours	Exterior Surface Temp, °F		
1	25		48	1990	5 to 10	Element open-circuited
2	25		48	1960	2 to 6	Element open-circuited
3		14 max	26	75-2000		
		14 max	24	1200/1590		Still
		16	66	2000	0 to 10	operating
4		16.2 max	42	75-2000	30° max	Element
		14.85	157.5	2000	34	open-circuited
5		25.8 max	237.5	75-2030	42° max	Element
		25.6	648	2000	- -	open-circuited
6		20 max	16.35	1885	35° max	Element
		21	49.8	2000	65	open-
		25	90.8	1990	105	circuited

TABLE IX

SHAGED 2000°F HEATING BUILT UP OF SELECTED MATERIALS

Quantity tested	S/N 7 & S/N 8	S/N 9	S/N 3A & S/N 3B	S/N 3A & S/N 3B	S/N 4A & S/N 4B	S/N 11, S/N 13, S/N 16	- -	S/N 17	- -	S/N 18 & S/N 19
Quantity procured	2	1	2	2	2	-6	1	1	1	2
Approx. diameter, inches	3/8	3/8	3/8	1/2	3/8	1/2	1/2	1/2	1/2	1/2
Thermocouple	chromel-alumel	chromel-alumel	chromel-alumel	chromel-alumel	chromel-alumel	chromel-alumel	chromel-alumel	chromel-alumel	chromel-alumel	chromel-alumel
Sheath material	Inconel 600	Inconel 600	Inconel 600	Inconel 600	Inconel 600	Inconel 600	Inconel 600	Inconel 600	Inconel 600	Inconel 600
Heater element material (wire)	pre-oxidized Nichrome V	pre-oxidized Nichrome V	platinum	platinum	molybdenum	platinum	platinum-10% rhodium	platinum-10% rhodium	platinum-10% rhodium	platinum-10% rhodium
Heater element diameter, inches	0.010 (#30 AWG)	0.010 (#30 AWG)	0.010 (#30 AWG)	0.010 (#30 AWG)	0.010 (#30 AWG)	0.010 (#30 AWG)	0.010 (#30 AWG)	0.010 (#30 AWG)	0.010 (#30 AWG)	0.010 (#30 AWG)
Heater element turns/inch (approx.) (as measured on radiograph)	- -	- -	31	38	30	40	30	42	44	38
Heater active length, inches (approx.) (as measured on radiograph)	- -	- -	1½	1½	1-9/16	1-9/16	1½	1½	1½	1-9/16
Heater element lead material	nichol	nichol	platinum	platinum	molybdenum	platinum	platinum	platinum	platinum	platinum
Heater element lead diameter, inches	0.025 (#19 AWG)	0.025 (#19 AWG)	0.040 (#15 AWG)	0.040 (#15 AWG)	0.025 (#19 AWG)	0.057 (#13 AWG)	0.040 (#15 AWG)	0.040 (#15 AWG)	0.040 (#15 AWG)	0.040 (#15 AWG)
Core material	magnesium oxide	magnesium oxide	boron nitride	alumina	magnesium oxide	boron nitride	alumina	alumina	alumina	alumina
Insulation between element & sheath ("fill")	minus 100 mesh MgO	None	None	-100/-200 mesh alumina	boron nitride	in position	-200 mesh alumina	-100 mesh alumina	-200 mesh alumina	-200 mesh alumina
Cap, end opposite lead end	None	aluminum silicate	aluminum silicate	in position	None	aluminum silicate	in position	in position	in position	in position
Type of spacer disc	aluminum silicate	3	1-15/16	aluminum silicate	aluminum silicate	2	aluminum silicate	aluminum silicate	aluminum silicate	aluminum silicate
Overall length, inches	1-15/16	20	15	1-15/16	1-15/16	20	3-1/8	3-1/8	3-1/8	3-1/8
Watt rating	15	15	15	15	15	15	20	20	20	20
Voltage rating, DC	15						15	15	15	15

The numbered dots indicate the approximate locations of the thermocouple junctions.

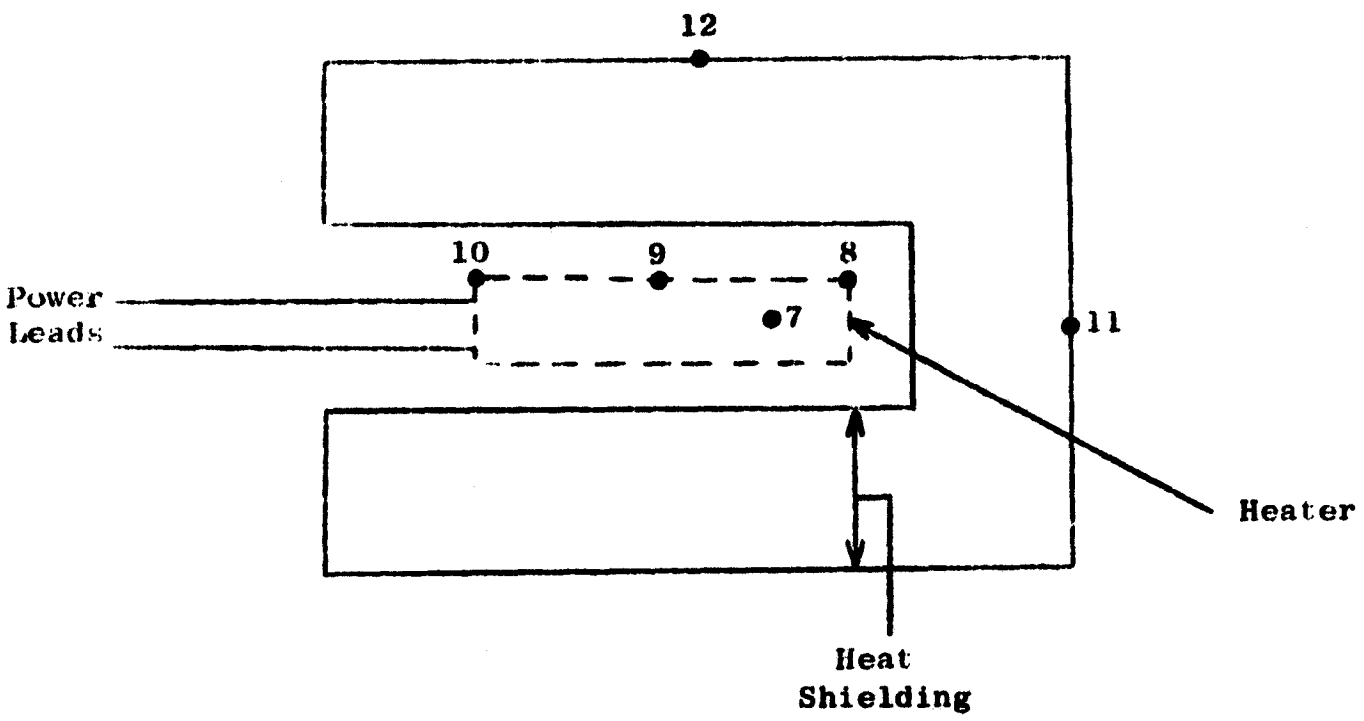


Figure 36. Locations of Thermocouple Junctions in Heater Test Assemblies

E1279-12

TABLE X.

OPERATING EXPERIENCE
HEATERS BUILT UP OF REFRACTORY MATERIALS
TESTED IN VACUUM
EACH WITH[illegible] A THERMOCOUPLE HEAT SHIELD ASSEMBLY

Serial No.	Material Buildup	Watt Input with Interior at Approximately 2000°F		Operating Experience				°F Temp Differential Interior to Exterior	Element Resistance, Ohms @ Room Temperature		Reason for Termination of Test
		Heaters with Operable Interior Thermocouple	Heaters with Inoperable Interior Thermocouple	Hours	Interior Temp, °F (Approx)	Hours	Cartridge Surface Temp, °F		At Start of Test	At End of Test	
7	Pre-Oxidized Nichrome V Element Wire, Magnesia Core, -100 Mesh Magnesia Fill	13.12 at 2018° (18.9 V, 0.695 Amp)	--	97.1	75-2000	--	--	30° at 2018°	24.35	24.65	Test discontinued and heaters opened up for examination.
				131.6	2000						
				176.7	2000/2100						
8		13.05 at 2000° (18.26 V, 0.715 Amp)	--	22	75-2000	--	--	38° at 2000°	24.77	24.78	
				208.3	2000						
9	Pre-Oxidized Nichrome V Element Wire, Magnesia Core, Boron Nitride Fill	18.75 at 2020° (20.75 V, 0.905 Amp)	--	201	2009 to 2020	--	--	20° at 2020°	20.0	20.1	Same as above
2A	Pt Element Wire Magnesia Core Boron Nitride Fill	24.2 at 2009° (12.72 V, 1.90 Amp) (at 651.8 Hrs)	--	21	75-2000	--	--	49° at 2009° (at 651.8 Hrs)	1.52	--	Test Terminated 11/9/66
				6607	2000						
2B		16.4 at 1960° (10.6 V, 1.55 Amp)	--	27	75-2000	--	--	20° at 1960°	1.61	Lead broke off upon removal from heat shield	Test discontinued and heaters opened up for inspection.
				200	2000						
3A	Pt Element Wire, Alumina Core, -100/-200 Mesh Alumina Fill	17.62 at 2023° (15.8 V, 1.18 Amp)	--	1.5	75-2000	--	--	126° at 2023°	3.135	9.70	Same as above
				14	2000						
				182.5'	2200						
3B		19.25 at 2000°F (16.9 V, 1.14 Amp)	--	2	75-2000	--	--	99° at 2000°	3.175	7.39	Same as above
				196.5	2000						
4A	Mo Element Wire, Magnesia Core, Boron Nitride Fill	17.2 at 2018° (10.9 V, 1.58 Amp)	--	29	75-2000	--	--	47° at 2000°	1.29	1.35	Same as above
				287	2000						
4B		17.7 at 2011° (11.35 V, 1.56 Amp)	--	166	75-1540	--	--	37° at 2011°	1.34	1.32	Same as above
				205	2000						
11	Pt Element Wire, Alumina Core, Boron Nitride Fill	--	With Cartridge Surface Temp[illegible]°, 23[illegible] Watts, (17.0 V, 1.35 Amp)	--	--	2	75-2050	--	2.88	2.89	Same as above
						203	1840-2050				
13		--	With Cartridge Surface Temp. at 1952°, 23.1 Watts (15.6 V, 1.48 Amp)	--	--	2	75-1982	--	2.51	2.52	Same as above
						203	1878-1982				
16		--	With Cartridge Surface Temp. at 1958°, 23.42 Watts (16.5 V, 1.42 Amp)	--	--	2	75-2012	--	2.79	A*	Test Discontinued 9/13/66
						2595.7	1920-2000				
17	Pt-10% Rh Element Wire, Alumina Core, -100 Mesh Alumina Fill	17.6 at 1995° (16.32 V, 1.08 Amp)	--	24	1177-1879	--	--	49° at 1995°	5.81	After 154 hrs at temp. between 1177 and 2057°F, 5.19 ohms	Test discontinued and heater opened up for inspection.
				134	1996-2083					At end of test, 7.19 ohms	
				48	1004-1942						
18	Pt-10% Rh Element Wire, Alumina Core, -200 Mesh Alumina Fill	--	With Cartridge Surface Temp. at 1999°, 25.1 Watts, (17.3 V, 1.44 Amp)	--	--	3.2	75-2012	--	2.89	After 170.6 hrs at temp. between 1951 and 2012°F, 5.36 ohms	Same as above
						252.7	1962-2012			At end of test, 6.82 ohms	
19	Same as Above	14.6 at 2009°F (14.6 V, 1.26 Amp)	--	4	75-2000	--	--	(at 600.1 hrs)	4.501	6.394	Test Discontinued 9/13/66
				1439.7	2009-2064						

A* 3.02 (After 379.5 hrs) 3.20 (After 1151.7 hrs) 3.935 (After 2595.7 hrs)

TABLE XI

Heater S/N 7 Test Data

Pre-Oxidized Nichrome Element Wire

Magnesia Core

100 Mesh Magnesia Fill

Elapsed Time From 2000°F Start, Hrs (Approx.)	Calculated Data		Temperatures, °F		Differential Between T/C Jctns. #1 & #2, °F
	Input Power, Watts	Resistance, Ohms	Interior, T/C Jctn. #1	Cartridge Surface, T/C Jctn. #2	
0	12.22	26.80	1970	1938	32
59.1	12.08	27.20	1978	1930	48
63.2	12.12	27.00	1960	1935	25
70.6	12.92	27.15	2010	1975	25
86.7	13.12	27.20	2018	1990	28
93.5	13.12	27.20	2018	1988	30
95.0	12.12	27.00	1990	1940	50
110.2	12.12	27.00	1985	1940	45
Power increased and thermocouple held at 2100°F					
132.8	13.90	27.60	2090	2035	45
153.6	13.82	27.40	2092	2040	52
181.2	14.04	27.30	2080	2035	45
197.2	14.04	27.30	2080	2040	40
206.5	14.18	27.30	2075	2030	45
222.2	14.18	27.30	2080	2025	55
247.0	14.15	27.45	2067	2023	44
254.5	14.15	27.45	2067	2023	44
272.5	13.99	27.80	2068	2025	43
279.0	14.15	27.40	2070	2026	44
295.0	14.15	27.40	2065	2021	44
302.2	14.15	27.40	2062	2019	43
310.0	14.15	27.40	2062	2020	42
Test discontinued					

TABLE XII

Heater S/N 8 Test Data

Pre-Oxidized Nichrome Element Wire

Magnesia Core

100 Mesh Magnesia Fill

Elapsed Time From 2000°F Start, Hrs (Approx.)	Calculated Data		Temperatures, °F		Differential Between T/C Jctns. #12 & #13, °F
	Input Power, Watts	Resistance, Ohms	Interior, T/C Jctn. #12	Cartridge Surface, T/C Jctn. #13	
0	13.30	25.3	2025	1990	35
1.55	12.42	25.4	1975	1940	35
18.20	12.50	25.6	1965	1935	30
20.00	12.85	26.5	1965	1950	35
20.90	13.05	25.5	2000	1965	35
22.00	13.05	25.5	1990	1958	32
22.25	12.65	25.6	Power reset as indicated		
44.00	12.50	25.7	1995	1945	50
46.50	12.50	25.7	1988	1939	49
70.00	12.35	25.9	1980	1930	50
70.10	12.60	25.7	Power reset as indicated		
82.40	12.38	25.6	1975	1930	35
92.50	12.90	25.6	1995	1945	50
94.60	12.68	25.9	1990	1945	45
95.70	12.60	25.7	1990	1940	50
156.20	13.00	25.8	2010	1960	50
159.20	13.00	25.8	2020	1968	52
166.00	13.15	26.0	2020	1965	50
182.00	13.15	26.0	2020	1970	50
187.00	13.40	25.8	2025	1972	53
189.00	13.40	25.8	2020	1970	40
207.00	13.30	25.7	2005	1955	50
			Test discontinued		

TABLE XIII

Heater S/N 2B Test Data

100% Platinum Heater Wire

Boron Nitride Fill

Elapsed Time From 2000°F Start, Hrs (Approx.)	Calculated Data		Temperatures, °F		Differential Between T/C Jctns. #12 & #13, °F
	Input Power, Watts	Resistance, Ohms	Interior, T/C Jctn. #12	Cartridge Surface, T/C Jctn. #13	
0	15.95	6.90	2008	2005	3
1.76	16.75	6.70	2000	2000	0
21.70	16.10	6.70	1975	1970	5
21.72	17.65	6.71	Power reset as indicated		
23.10	17.20	6.71	2000	1995	5
27.20	16.40	6.84	1996	1985	11
43.80	15.98	6.91	1980	1965	15
87.50	16.40	6.84	1980	1965	15
96.90	16.40	6.84	1975	1960	15
112.20	16.40	6.84	1980	1960	20
135.50	16.00	6.96	1969	1952	17
144.00	16.10	6.97	1969	1952	17
161.00	16.20	6.94	1968	1950	18
169.00	16.10	6.97	1957	1938	19
185.00	16.41	6.83	1968	1949	19
192.50	16.42	6.83	1970	1950	20
200.00	16.42	6.83	1970	1950	20
			Test discontinued		

TABLE XIV

Heater S/N 3A Test Data
100% Platinum Heater Wire
Alumina Core
100/200 Mesh Alumina Fill

Elapsed Time From 2000°F Start, Hrs (Approx.)	Calculated Data		Temperatures, °F		Differential Between T/C Jctns. #1 and #2 °F
	Input Power Watts	Resistance, Ohms	Interior, T/C Jctn. #1	Cartridge Surface, T/C Jctn. #2	
0	17.68	13.40	2023	1897	126
0.5	18.90	13.55	2047	1939	108
0.75	18.18	13.75	Power reduced as indicated		
1.00	18.18	13.75	2033	1939	94
3.78	18.70	13.88	2033	1953	80
23.00	17.30	14.02	1967	1897	70
24.00	24.20	14.55	Power increased to bring T/C #1 to 2200°F		
25.67	23.50	15.00	2188	2100	88
26.50	23.00	15.20	2202	2091	111
33.50	24.40	15.40	2228	2100	128
33.60	23.24	15.40	Power reduced as indicated		
48.90	22.60	15.48	2173	2043	135
56.90	2285	15.62	2178	2043	135
63.40	22.45	15.62	2163	2028	135
72.40	22.55	15.68	2154	2033	121
88.90	22.25	15.70	2144	2014	130
96.65	24.10	16.20	2228	2076	152
112.65	24.40	16.50	2228	2076	152
163.15	22.00	17.20	2161	2016	145
169.15	22.90	17.30	2188	2043	145
185.48	22.20	17.40	2142	2005	137
193.23	22.80	17.25	2163	2052	149
201.23	23.10	17.55	2188	2033	145
			Test discontinued		

TABLE XV

Heater S/N 3B Test Data
100% Platinum Element Wire
Alumina Core
100/200 Mesh Alumina Fill

Elapsed Time From 2000°F Start, Hrs (Approx.)	Calculated Data		Temperatures, °F		Differential Between T/C Jctns. #1 and #2 °F
	Input Power Watts	Resistance Ohms	Interior, T/C Jctn. #7	Cartridge Surface, T/C Jctn. #8	
0	17.60	12.60	2080	- -	- -
3.78	19.95	13.62	2033	1933	100
23.00	20.00	14.00	2014	1939	75
25.67	20.00	14.10	2005	1920	85
26.80	20.00	14.08	2009	1925	84
48.90	19.85	14.28	2005	1915	90
56.90	19.90	14.30	1995	1906	89
63.40	19.88	14.29	1995	1896	99
72.40	19.90	14.30	1995	1901	94
88.90	19.73	14.42	1986	1887	99
96.65	19.75	14.45	1990	1886	104
111.65	19.25	14.80	2000	1901	99
163.15	19.22	14.75	1990	1886	104
169.15	19.25	14.80	1990	1886	104
185.48	19.20	14.80	1964	1873	91
193.23	19.25	14.80	1967	1873	94
201.23	19.10	15.00	1971	1883	88
		Test discontinued			

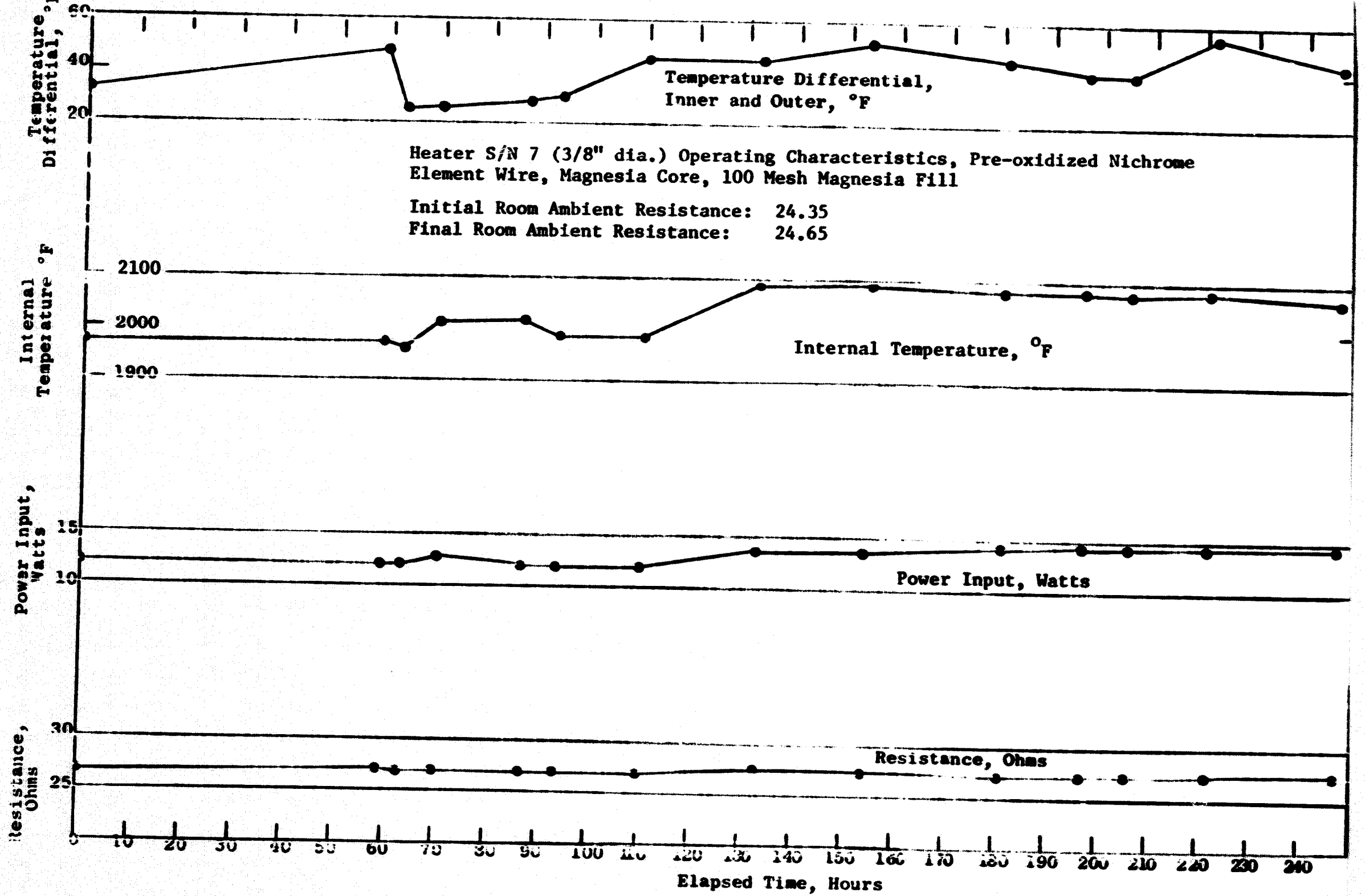


Figure 37. Heater S/N 7 Operating Characteristics

E1279-13

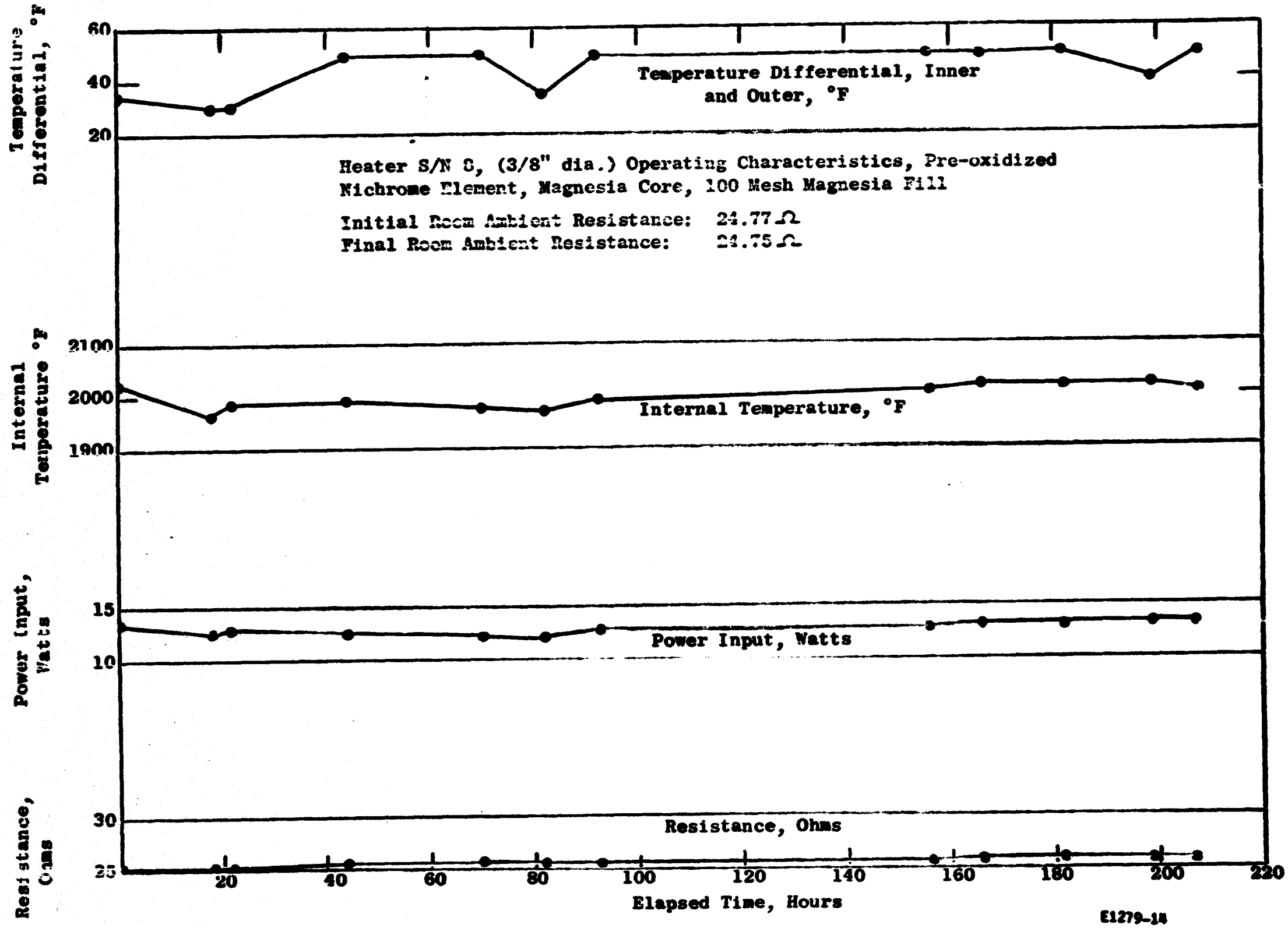


Figure 38. Heater S/N 8 Operating Characteristics

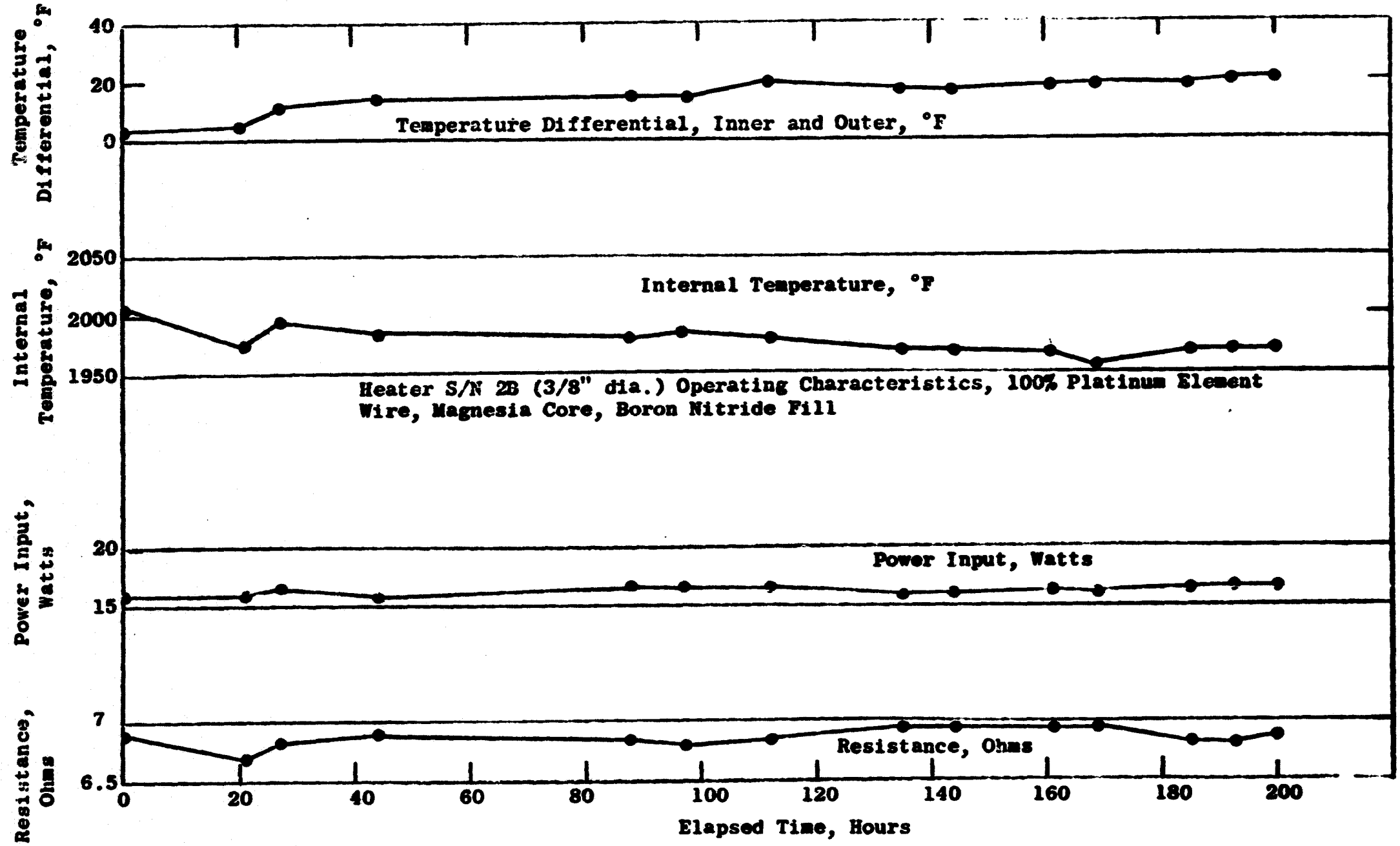


Figure 39. Heater S/N 2B Operating Characteristics

E1279-15

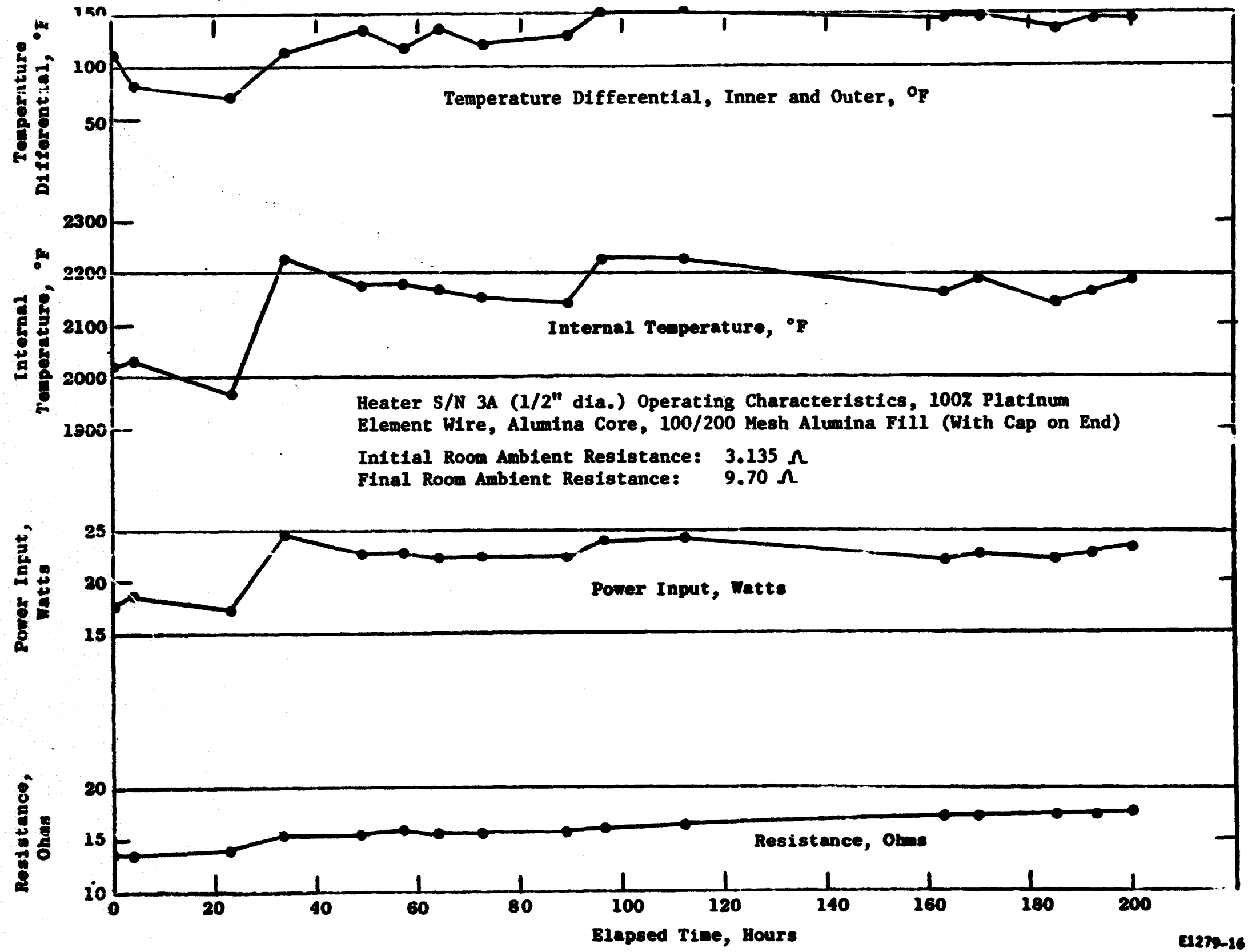


Figure 40. Heater S/N 3A Operating Characteristics

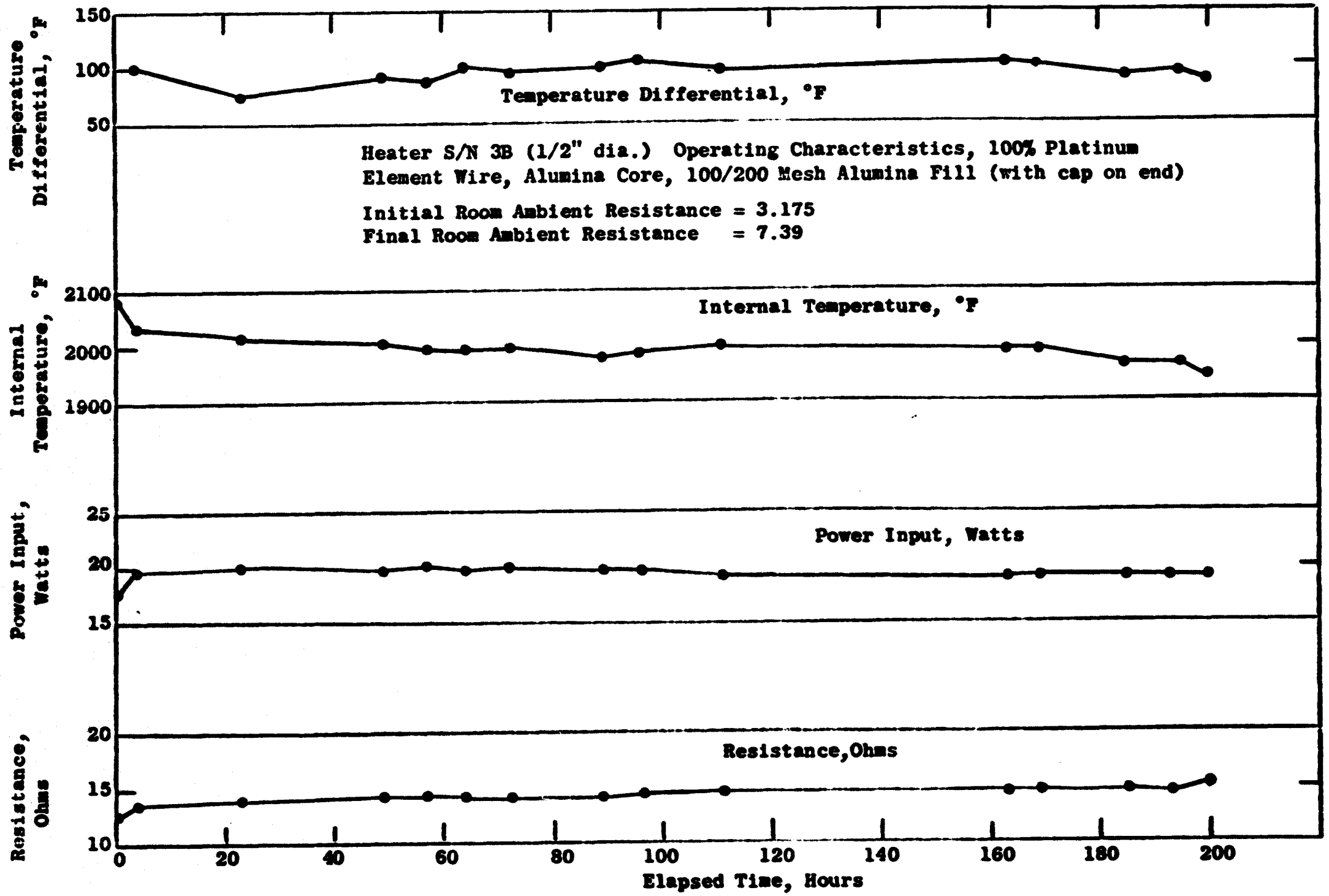


Figure 41. Heater S/N 3B Operating Characteristics

E1279-17

Heaters S/N 16 and S/N 19 were allowed to remain on test considerably longer than all but S/N 2A. At the end of 1439 hours the power to S/N 19 was turned off. After 2595 hours the power to S/N 16 was turned off. The test data obtained during these periods is tabulated in Tables XVI and XVII respectively.

The relative change in hot resistance for several heaters after testing for extended periods is given in Table XVIII. From this table the Mgo core, BN fill, Pt element heater exhibits the smallest change on a % per hour basis. Moreover, it can be argued that the major change in resistance occurs early in the life of the heater, therefore, a longer test would necessarily have the effect of reducing the average change.

The final configuration heaters were fabricated of 10 mil Pt-10% Rh element wire wound on a magnesia core with boron nitride fill between the heater and the sheath. Two of these heaters S/N 20 and S/N 28 were installed in the heat shielding packages and instrumented as shown in Figure 42. The test assemblies were then placed in vacuum test facility which was evacuated to a pressure of 5×10^{-6} torr. Applied voltage and current were monitored along with heater internal temperature and heater sheath temperature. The data obtained during these tests are given in Tables XIX and XX. Operating characteristics are supplied in curve form in Figure 43 and Figure 44.

Power was supplied during these tests through a regulated D.C. power supply. Voltage and current readings were obtained on cali-

TABLE XVI
S/N 19 Heater Test Data
(Continuation of Test)
Platinum 10% Rhodium Element Wire
Alumina Core
-200 Mesh Alumina Fill

Elapsed Time From 2000°F Start, Hours (Approx.)	Electrical Data				Temperatures, °F		Differential Between T/C Junctions #21 & #23 °F
	Measured		Calculated				
	Applied DC Voltage, Volts*	DC Current, Amperes	Input Power, Watts	Resistance, Ohms	Interior T/C Junction #21	Cartridge Surface T/C Junction #23	
8/9/66							
600.1	14.6	1.26	18.40	11.59	2009	1844	165
624.1	14.8	1.26	18.65	11.75	2027	1856	171
648.6	14.9	1.27	18.92	11.72	2040	1866	164
672.1	14.9	1.29	19.20	11.52	2056	1880	176
744.9	14.9	1.27	18.92	11.72	2027	1854	173
769.4	14.9	1.27	18.92	11.72	2031	1857	174
792.0	15.0	1.28	19.20	11.72	2037	1862	175
816.0	14.9	1.27	18.92	11.72	2043	1865	178
840.0	14.9	1.28	19.05	11.65	2026	1851	175
912.0	14.9	1.28	19.05	11.65	2015	1841	174
936.0	14.9	1.28	19.05	11.65	2046	1869	177
960.0	15.1	1.29	19.50	11.70	2053	1874	179
984.0	15.1	1.29	19.50	11.70	2045	1869	176
1008.0	15.0	1.29	19.50	11.70	2054	1874	180
1080.0	14.8	1.27	18.80	11.65	2005	1833	172
1104.0	15.0	1.28	19.20	11.72	2037	1856	181
1128.0	14.9	1.28	19.05	11.65	2029	1850	179
1152.0	14.9	1.28	19.05	11.65	2020	1841	179
1176.0	14.9	1.28	19.05	11.65	2025	1845	180
9/6/66							180
1272.5	15.2	1.29	19.60	11.80	2049	1869	180
			Test being continued				

Initial room ambient resistance = 4.501 ohms.

Environmental pressure variation during test period from 600.1 to 1272.5 hours = 6.4×10^{-6} to 4.8×10^{-6} mm Hg.

* Measured at power terminals outside vacuum tank.

TABLE XVI (Concluded)
S/N 19 HEATER TEST DATA
(COMPLETION OF TEST)
PLATINUM 10% RHODIUM ELEMENT WIRE
ALUMINA CORE
MINUS 200 MESH ALUMINA FILL

Elapsed Time From 2000°F Start, Hours (Approx.)	Electrical Data				Temperatures, °F		Differential Between T/C Junctions #21 & #23 °F
	Measured		Calculated		Interior T/C Junction #21	Cartridge Surface T/C Junction #23	
	Applied DC Voltage, Volts*	DC Current, Amperes	Input Power, Watts	Resistance, Ohms			
9/6/66							
1272.5	15.2	1.29	19.60	11.80	2049	1869	180
1292.5	15.2	1.30	19.75	11.70	2046	1866	180
1318.5	14.8	1.27	18.80	11.65	2007	1836	171
1342.5	14.8	1.27	18.80	11.65	2004	1884	120
1415.5	14.8	1.27	18.80	11.65	1994	1825	179
1439.7	14.8	1.27	18.80	11.65	2000	1829	171

9/13/66 Power Off, Test Discontinued

Initial room ambient resistance: 4.501 ohms.

Final room ambient resistance: 6.394 ohms.

Environmental pressure variation during test period extending from 1272.5 hours to 1439.7 hours: 4.9×10^{-6} to 4.2×10^{-6} mm Hg.

* Measured at power terminals outside vacuum tank.

TABLE XVII
S/N 2A Heater Test Data
(Continuation of Test)
Platinum Element Wire
Magnesia Core
Boron Nitride Fill

Elapsed Time From 2000°F Start, Hours (Approx.)	Electrical Data				Temperatures, °F		Differential Between T/C Junctions # 1 & # 2 °F
	Measured		Calculated				
	Applied DC Voltage, Volts*	DC Current, Amperes	Input Power, Watts	Resistance, Ohms	Interior T/C Junction # 1	Cartridge Surface T/C Junction # 2	
8/9/66							
4421.5	12.55	1.89	23.80	6.60	2004	1895	109
4445.5	12.56	1.90	23.85	6.60	2002	1895	107
4469.8	12.60	1.90	23.95	6.63	2007	1894	113
4493.4	12.55	1.90	23.82	6.60	2005	1892	113
4565.4	12.68	1.90	24.05	6.66	2009	1894	115
4590.0	12.63	1.90	24.00	6.65	2010	1895	115
4612.8	12.62	1.90	24.00	6.64	2005	1890	115
4636.8	12.62	1.90	24.00	6.64	2012	1898	114
4660.8	12.61	1.90	23.95	6.63	2001	1892	109
4732.8	12.62	1.90	24.00	6.64	2002	1887	115
4756.8	12.62	1.90	24.00	6.64	2014	1896	118
4780.8	12.63	1.90	24.00	6.65	2008	1889	119
4804.8	12.63	1.90	24.00	6.65	2008	1890	118
4828.8	12.63	1.90	24.00	6.65	2012	1894	118
4900.8	12.00	1.90	22.80	6.32	1982	1864	118
4925.0	12.00	1.90	22.80	6.32	2006	1886	120
4949.0	12.62	1.90	24.00	6.64	2007	1893	114
4973.0	12.57	1.90	23.82	6.61	2014	1893	121
4997.0	12.62	1.90	24.00	6.64	2014	1893	121
9/6/66							
5093.5	12.62	1.90	24.00	6.64	2017	1892	125
			Test being continued				

Initial room ambient resistance: 1.52 ohms
Environmental pressure variation during test period extending from 4421.5 hours to 5066.5 hours: 9.8×10^{-5} to 5.6×10^{-6} mm Hg

* Measured at power terminals outside vacuum tank.

TABLE XVII (Continued)
S/N 2A HEATER TEST DATA
(CONTINUATION OF TEST)
PLATINUM ELEMENT WIRE
MAGNESIA CORE
BORON NITRIDE FILL

Elapsed Time From 2000°F Start, Hours (Approx.)	Electrical Data				Temperatures, °F		Differential Between T/C Junctions #1 & #2 °F
	Measured		Calculated		Interior T/C Junction #1	Cartridge Surface T/C Junction #2	
	Applied DC Voltage, Volts*	DC Current, Amperes	Input Power, Watts	Resistance, Ohms			
9/6/66							
5093.5	12.62	1.90	24.00	6.64	2017	1892	125
5115.5	12.59	1.90	23.90	6.63	2034	1889	145
5141.5	12.55	1.90	23.80	6.62	2027	1896	-
5165.5	12.55	1.90	23.80	6.62	2020	1894	126
5238.5	12.55	1.90	23.80	6.62	2007	1883	124
5261.5	12.58	1.90	23.80	6.62	2016	1893	123
5285.0	12.56	1.90	23.82	6.61	2014	1885	129
5309.0	12.56	1.90	23.82	6.61	2004	1879	125
5334.0	12.56	1.90	23.82	6.61	2020	1891	129
5406.0	12.59	1.91	24.00	6.59	2009	1875	134
5433.0	12.58	1.89	23.75	6.66	2020	1884	136
5453.0	12.59	1.89	23.75	6.66	2020	1884	136
5477.8	12.59	1.89	23.75	6.66	2023	1887	133
5574.6	12.59	1.89	23.75	6.66	2015	1880	135
5597.6	12.59	1.89	23.75	6.66	2021	1886	135
5621.6	12.57	1.90	23.82	6.61	2015	1882	133
5669.6	12.59	1.89	23.75	6.66	2024	1888	136
5741.6	12.57	1.89	23.75	6.65	2020	1885	135
5765,6	12.59	1.89	23.75	6.65	2023	1888	135
5790.1	12.56	1.89	23.70	6.64	2022	1886	134
10/6/66							
5814.1	12.55	1.89	23.70	6.63	2020	1883	133

Test being continued

Initial room ambient resistance: 1.52 ohms.
Environmental pressure variation during test period extending from 5093.5 hours to 5814.1 hours: 813×10^{-6} to 4.7×10^{-6} mm Hg.

* Measured at power terminals outside vacuum tank.

(Tests being continued)

TABLE XVII (Concluded)
S/N 2A HEATER TEST DATA
(CONTINUATION OF TEST)
PLATINUM ELEMENT WIRE
MAGNESIA CORE
BORON NITRIDE FILL

Elapsed Time From 2000°F Start, Hours (Approx.)	Electrical Data				Temperature, °F		Differential Between T/C Junctions #1 & #2 °F
	Measured		Calculated				
	Applied DC Voltage, Volts*	DC Current, Amperes	Input Power, Watts	Resistance, Ohms	Interior T/C Junction #1	Cartridge Surface T/C Junction #2	
10/6/66							
5814.1	12.55	1.89	23.70	6.63	2020	1883	133
5838.1	12.58	1.90	23.90	6.63	2025	1889	136
5910.1	12.59	1.89	23.80	6.66	2019	1886	133
5958.1	12.59	1.89	23.80	6.66	2016	1883	133
5982.1	12.63	1.88	23.80	6.73	2017	1884	133
6006.1	12.63	1.89	23.90	6.69	2015	1883	132
6102.1	12.68	1.89	23.90	6.71	2005	1873	132
6126.1	12.61	1.89	23.90	6.69	2016	1885	131
6150.1	12.63	1.89	23.90	6.69	2001	1875	126
6174.1	12.53	1.89	23.90	6.64	2009	1876	123
6246.1	12.55	1.89	23.70	6.63	1990	1861	129
6272.1	12.55	1.89	23.70	5.63	2005	1877	128
6295.1	12.49	1.89	23.60	6.63	1993	1887	106
6319.1	12.50	1.89	23.60	6.63	2004	1872	132
6345.1	12.50	1.89	23.60	6.63	1992	1864	128
6368.6	12.50	1.89	23.60	6.63	2000	1872	128
10/31/66							
6417.1	12.48	1.89	23.60	6.61	1988	1854	134

(TEST BEING CONTINUED)

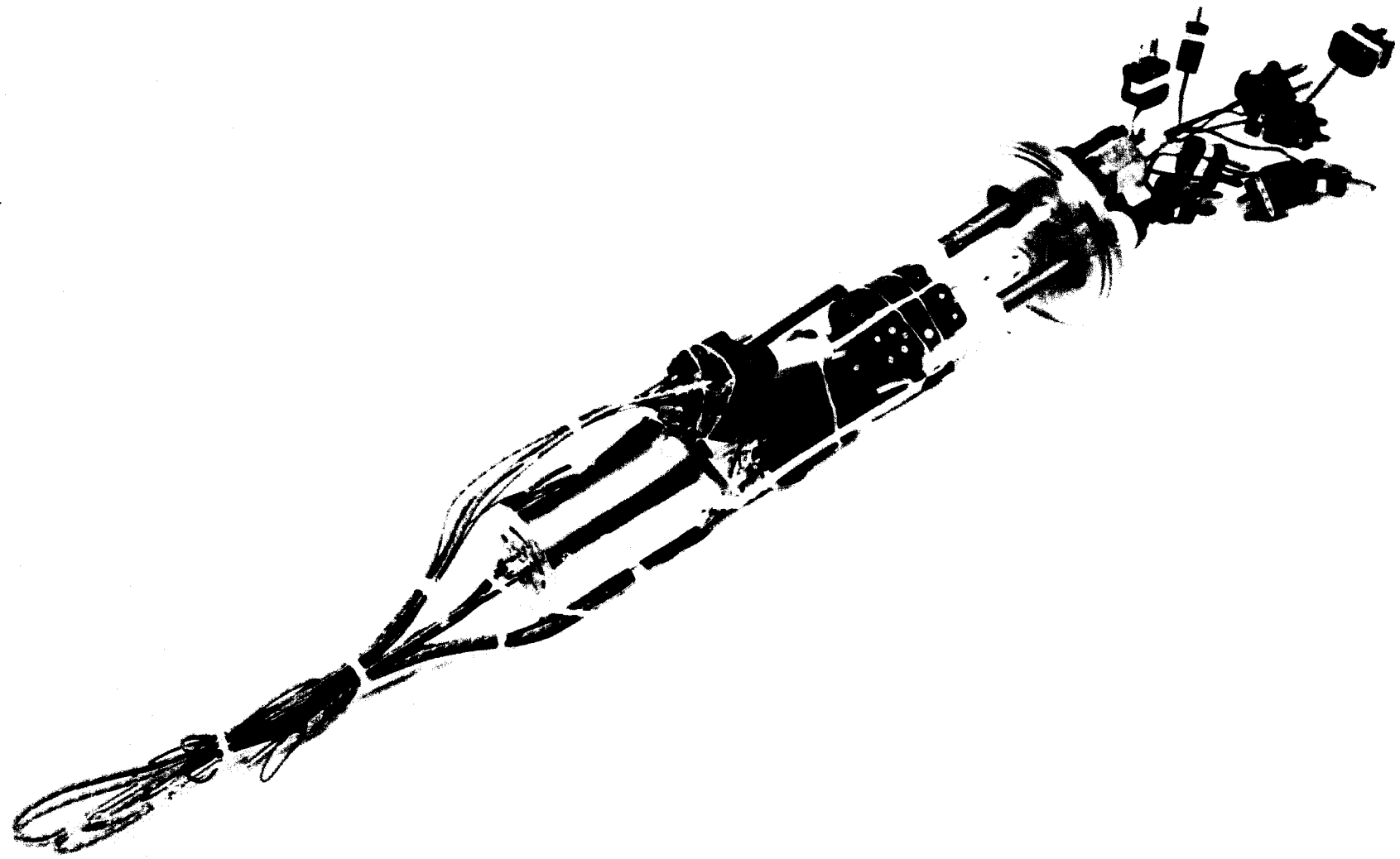
Initial room ambient resistance: 1.52 ohms
Environmental pressure variation during test period extending from 5814.1 hours to 6417.1 hours: 6.7×10^{-5} to 4.8×10^{-6} mm Hg

* Measured at power terminals outside vacuum tank.

TABLE XVIII

RELATIVE CHANGE IN HOT RESISTANCE FOR SEVERAL HEATERS AFTER TESTING FOR EXTENDED PERIODS OF TIME

Heater No.	Materials	Test Duration-Hours	Resistance Change-%/Hour
S/N 2A (On Test)	MgO Core, BN Fill, Pt Element, Cr-Al, T.C., Inconel Sheath	5814	1.28×10^{-4}
S/N 20 (20W)	MgO Core, BN Fill, Pt-10% Rh Element, Cr-Al T.C., Hastelloy X Sheath	1549	16.3×10^{-4}
S/N 28 (30W)	MgO Core, BN Fill, Pt-10% Rh Element, Cr-Al T.C., Hastelloy X Sheath	1551	2.2×10^{-4}
S/N 16	Al_2O_3 Core, BN Fill, Pt Element Cr-Al T.C., Inconel Sheath	2599	23.1×10^{-4}
S/N 19	Al_2O_3 Core, Al_2O_3 Fill Pt-10% Rh Element, Cr-Al T.C., Inconel Sheath	1440	31.3×10^{-4}



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Figure 42. Typical Assembly of Heater in Heat Shield Package Preparatory to Insertion into Vacuum Test Chamber. (C65070737)

TABLE XIX

Model HSK-2000-20
20 WATT HEATER S/N 20 TEST DATA
PLATINUM 10% RHODIUM HEATER ELEMENT WIRE
MAGNESIA CORE
BORON NITRIDE FILL

Elapsed Time From 2000°F Start, Hours (Approx.)	Electrical Data				Temperatures, °F		Differential Between T/C Junctions #12 & #13 °F
	Measured		Calculated		Interior T/C Junction #12	Cartridge Surface T/C Junction #14	
	Applied DC Voltage, Volts*	DC Current, Amperes	Input Power, Watts	Resistance, Ohms			
5/10/66							
0	11.3	1.40	15.83	8.08	1890	1888	2
15.8	10.0	1.24	12.40	8.08	1936	1927	9
24.2	10.5	1.27	13.35	8.27	1989	1979	10
39.9	10.5	1.27	13.35	8.27	1985	1977	8
68.8	10.5	1.27	13.35	8.27	1980	1972	8
136.5	10.6	1.27	13.47	8.35	1969	1964	5
160.0	11.0	1.30	14.30	8.46	2008	2003	5
182.1	11.0	1.30	14.30	8.46	2005	2000	5
212.3	11.0	1.30	14.30	8.46	1998	1994	4
236.4	11.0	1.30	14.30	8.46	1992	1990	2
332.2	11.0	1.30	14.30	8.46	1980	1978	2
356.2	10.9	1.30	14.20	8.36	1970	1964	6
380.3	10.9	1.30	14.20	8.36	1972	1968	4
404.4	11.0	1.30	14.30	8.46	1977	1972	5
500.3	10.8	1.30	14.02	8.31	1960	1955	5
524.6	11.2	1.32	14.65	8.40	2000	1998	2
548.2	11.3	1.32	14.70	8.46	2005	2000	5
6/6/66							
644.3	11.3	1.33	14.80	8.40	2009	2002	7
Test being continued							

Initial room ambient resistance = 3.03 ohms

Environmental pressure variation during test = 5×10^{-6} to 1.5×10^{-7} mm Hg

* Measured at power terminals outside vacuum tank.

TABLE XIX (Cont'd)

Model HSK-2000-20
20 Watt Heater; S/N 20 Test Data
Platinum 10% Rhodium Heater Element Wire
Magnesia Core
Boron Nitride Fill

Elapsed Time From 2000°F Start, Hours (Approx.)	Electrical Data				Temperatures, °F		Differential Between T/C Junctions #12 & #14 °F
	Measured		Calculated				
	Applied DC Voltage, Volts*	DC Current, Amperes	Input Power, Watts	Resistance, Ohms	Interior T/C Junction #12	Cartridge Surface T/C Junction #14	
6/6/66							
644.3	11.3	1.33	14.80	8.40	2009	2002	7
	Test shut down and heater removed for physical examination.						
668.2	11.0	1.28	14.08	8.59	1978	1971	7
692.0	11.0	1.28	14.08	8.59	1973	1969	4
	Test shut down to allow some other heater to be placed in facility.						
716.1	10.8	1.24	13.40	8.71	1957	1953	4
740.5	11.3	1.28	14.49	8.83	1994	1989	5
764.0	10.8	1.24	13.40	8.71	1934	1929	5
836.2	10.8	1.24	13.40	8.71	1920	1917	3
	Liquid nitrogen accidently turned off at diffusion pump.						
860.3	11.1	1.25	13.88	8.89	1949	1944	5
884.2	11.3	1.27	14.38	8.90	1965	1960	5
908.2	11.5	1.28	14.73	8.98	1984	1981	3
932.8	11.5	1.28	14.73	8.98	1986	1982	4
1029.1	11.2	1.25	14.00	8.96	1930	1928	2
	11.5	1.28	14.73	(Input power to heater increased.)			
1052.4	11.6	1.28	14.85	9.06	1979	1979	0
1078.0	11.5	1.27	14.60	9.05	1968	1967	1
	11.80	1.30	15.35	(Input power to heater increased.)			
1102.9	11.80	1.29	15.22	9.15	2000	1998	2
7/11/66			Test being continued.				

Initial room ambient resistance: 3.03 ohms

Environmental pressure variation during this portion of test: 1.9×10^{-6} to 8.3×10^{-8} mm Hg.

* Measured at power terminals outside vacuum tank.

TABLE XIX (Cont'd)

Model HSK-2000-20,
20 Watt Heater S/N 20 Test Data
(Continuation of Test)
Platinum 10% Rhodium Heater Element Wire
Magnesia Core
Boron Nitride Fill

Elapsed Time From 2000°F Start, Hours (Approx.)	Electrical Data				Temperatures, °F		Differential Between T/C Junctions #12 & #14 °F
	Measured		Calculated		Interior T/C Junction #12	Cartridge Surface T/C Junction #14	
	Applied DC Voltage, Volts*	DC Current, Amperes	Input Power, Watts	Resistance, Ohms			
7/11/66							
1102.9	11.80	1.29	15.22	9.15	2000	1998	2
1175.4	11.60	1.26	14.62	9.22	1960	1958	2
	11.75	1.28	15.05	9.20	Increased input power		
1198.2	11.80	1.27	15.00	9.30	1984	1982	2
1225.4	11.80	1.26	14.89	9.36	1975	1973	2
1245.5	11.60	1.25	14.50	9.28	1969	1966	3
1269.6	11.60	1.25	14.50	9.28	1959	1958	1
	Lost liquid nitrogen to vacuum facility for 25 minutes.						
1292.7	12.20	1.39	16.98	8.77	2018	2010	8
	Lost liquid nitrogen to test facility, Test shut down, then started up again.						
1316.8	11.80	1.23	14.52	9.60	1969	1959	10
1388.8	12.30	1.24	15.26	9.91	2008	1994	14
1412.6	12.30	1.25	15.49	9.83	2011	1998	13
1435.8	12.30	1.24	15.28	9.92	2006	1995	11
1459.2	12.30	1.23	15.12	10.00	2010	1998	12
1483.4	12.10	1.23	14.90	9.82	1986	1973	13
1549.6	12.20	1.24	15.12	9.83	2000	1989	11
8/1/66			Test concluded				

Initial room ambient resistance: 3.03 ohms
Final room ambient resistance: 4.00 ohms

Environmental pressure variation during test period from 1102.9 hours to 1549.6 hours: 4.5×10^{-6} to 8.2×10^{-8} mm Hg

* Measured at power terminals outside vacuum tank.

TABLE XX

MODEL HSK-2000-30
30 WATT HEATER S/N 28 TEST DATA
PLATINUM 10% RHODIUM ELEMENT WIRE
MAGNESIA CORE
BORON NITRIDE FILL

Elapsed Time From 2000°F Start, Hours (Approx.)	Electrical Data				Temperatures, °F		Differential Between T/C Junctions #23 & #25 °F
	Measured		Calculated				
	Applied DC Voltage, Volts*	DC Current, Amperes	Input Power, Watts	Resistance, Ohms	Interior T/C Junction #23	Cartridge Surface T/C Junction #25	
5/10/66							
0	10.0	1.83	18.30	5.46	1955	1945	10
16.2	9.0	1.60	14.40	5.62	1997	1984	13
24.2	9.0	1.59	14.30	5.66	1998	1981	7
40.0	9.0	1.59	14.30	5.66	1989	1973	16
70.5	9.0	1.59	14.30	5.66	1981	1962	19
136.6	9.0	1.59	14.30	5.66	1965	1945	20
159.9	9.3	1.60	14.88	5.82	2000	1978	22
182.0	9.3	1.60	14.88	5.82	1996	1976	20
212.3	9.3	1.60	14.88	5.82	1991	1973	18
236.4	9.3	1.60	14.88	5.82	1986	1969	17
332.2	9.3	1.60	14.88	5.82	1978	1960	18
356.2	9.3	1.60	14.88	5.82	1968	1950	18
378.8	9.3	1.60	14.88	5.82	1970	1952	18
404.2	9.5	1.62	15.30	5.86	1997	1982	15
500.2	9.4	1.63	15.30	5.77	1990	1972	18
524.0	9.4	1.63	15.30	5.77	1989	1970	19
548.2	9.4	1.63	15.30	5.77	1989	1971	18
572.1	9.5	1.62	15.40	5.86	1989	1970	19
6/6/66							
644.2	9.5	1.62	15.40	5.86	1988	1970	18
			Test being continued				

Initial room ambient resistance = 2.13 ohms

Environmental pressure variation during test = 5.0×10^{-6} to 1.5×10^{-7} mm Hg

* Measured at power terminals outside vacuum tank.

TABLE XX (Cont'd)

Model HSK-2000-30
30 Watt Heater S/N 28 Test Data
Platinum 10% Rhodium Heater Element Wire
Magnesia Core
Boron Nitride Fill

Elapsed Time From 2000°F Start, Hours (Approx.)	Electrical Data				Temperatures, °F		Differential Between T/C Junctions #23 & #25 °F
	Measured		Calculated				
	Applied DC Voltage, Volts*	DC Current, Amperes	Input Power, Watts	Resistance, Ohms	Interior T/C Junction #23	Cartridge Surface T/C Junction #25	
6/6/66							
644.2	9.5	1.62	15.40	5.86	1988	1970	18
	Test shut down to allow some other heater to be removed from facility.						
668.0	9.3	1.60	14.90	5.81	1970	1950	20
691.8	9.3	1.60	14.90	5.81	1965	1946	19
	Test shut down to allow some other heater to be placed in facility.						
715.8	9.3	1.58	14.70	5.88	1966	1951	15
740.0	9.3	1.58	14.70	5.88	1968	1954	14
763.5	9.3	1.58	14.70	5.88	1960	1945	15
835.6	9.3	1.58	14.70	5.88	1957	1945	12
	Liquid nitrogen accidentally turned off at diffusion pump.						
859.8	9.5	1.60	15.20	5.94	1991	1975	16
883.4	9.5	1.60	15.20	5.94	1987	1968	19
908.0	9.5	1.60	15.20	5.94	1988	1972	16
932.3	9.5	1.60	15.20	5.94	1985	1969	16
1028.5	9.5	1.60	15.20	5.94	1973	1955	18
1051.9	9.5	1.60	15.20	5.94	1973	1957	16
	9.8	1.64	16.08	(Input power to heater increased.)			
1075.9	9.6	1.61	15.48	5.96	1988	1970	18
1102.5	9.6	1.61	15.48	5.96	1979	1962	17
7/11/66	Test being continued.						

Initial room ambient resistance: 2.13 ohms.

Environmental pressure during this portion of test: 1.9×10^{-6} to 8.3×10^{-8} mm Hg.

* Measured at power terminals outside vacuum tank.

TABLE XX (Cont'd)

Model HSK-2000-30
30 Watt Heater, S/N 28 Test Data
(Continuation of Test)
Platinum 10% Rhodium Heater Element Wire
Magnesia Core
Boron Nitride Fill

Elapsed Time From 2000°F Start, Hours (Approx.)	Electrical Data				Temperatures, °F		Differential Between T/C Junctions #23 & #25 °F
	Measured		Calculated				
	Applied DC Voltage, Volts	DC Current, Amperes	Input Power, Watts	Resistance, Ohms	Interior T/C Junction #23	Cartridge Surface T/C Junction #25	
7/11/66							
1102.5	9.6	1.61	15.48	5.96	1979	1962	17
1175.3	9.6	1.61	15.48	5.96	1976	1960	16
	9.8	1.63	15.99	6.00	Increased input power		
1196.4	9.8	1.63	15.99	6.00	2000	1986	14
1223.6	9.8	1.63	15.99	6.00	2007	1990	17
1244.1	9.8	1.63	15.99	6.00	2010	1991	19
1268.0	9.9	1.61	15.92	6.14	2009	1991	18
	Lost liquid nitrogen to vacuum facility for 25 minutes. Test shut down, then started up again.						
1291.3	10.0	1.65	16.50	6.06	2015	2000	15
	Lost liquid nitrogen to test facility. Test shut down, then started up again.						
1315.4	9.8	1.62	15.88	6.05	1985	1967	18
1387.4	10.0	1.63	16.30	6.13	2007	1990	17
1412.7	10.0	1.63	16.30	6.13	2010	1995	15
1436.1	10.1	1.64	16.56	6.16	2011	1996	15
1460.5	10.1	1.62	16.38	6.24	2018	1998	20
1484.8	10.0	1.61	16.10	6.21	2004	1986	18
1551.0	10.0	1.62	16.20	6.16	2000	1983	17
			Test concluded				

Initial room ambient resistance: 2.13 ohms
Final room ambient resistance: 2.80 ohms

Environmental pressure variation during test period from 1102.5 hours to 1551.0 hours: 4.5×10^{-6} to 8.2×10^{-8} mm Hg

* Measured at power terminals outside vacuum tank.

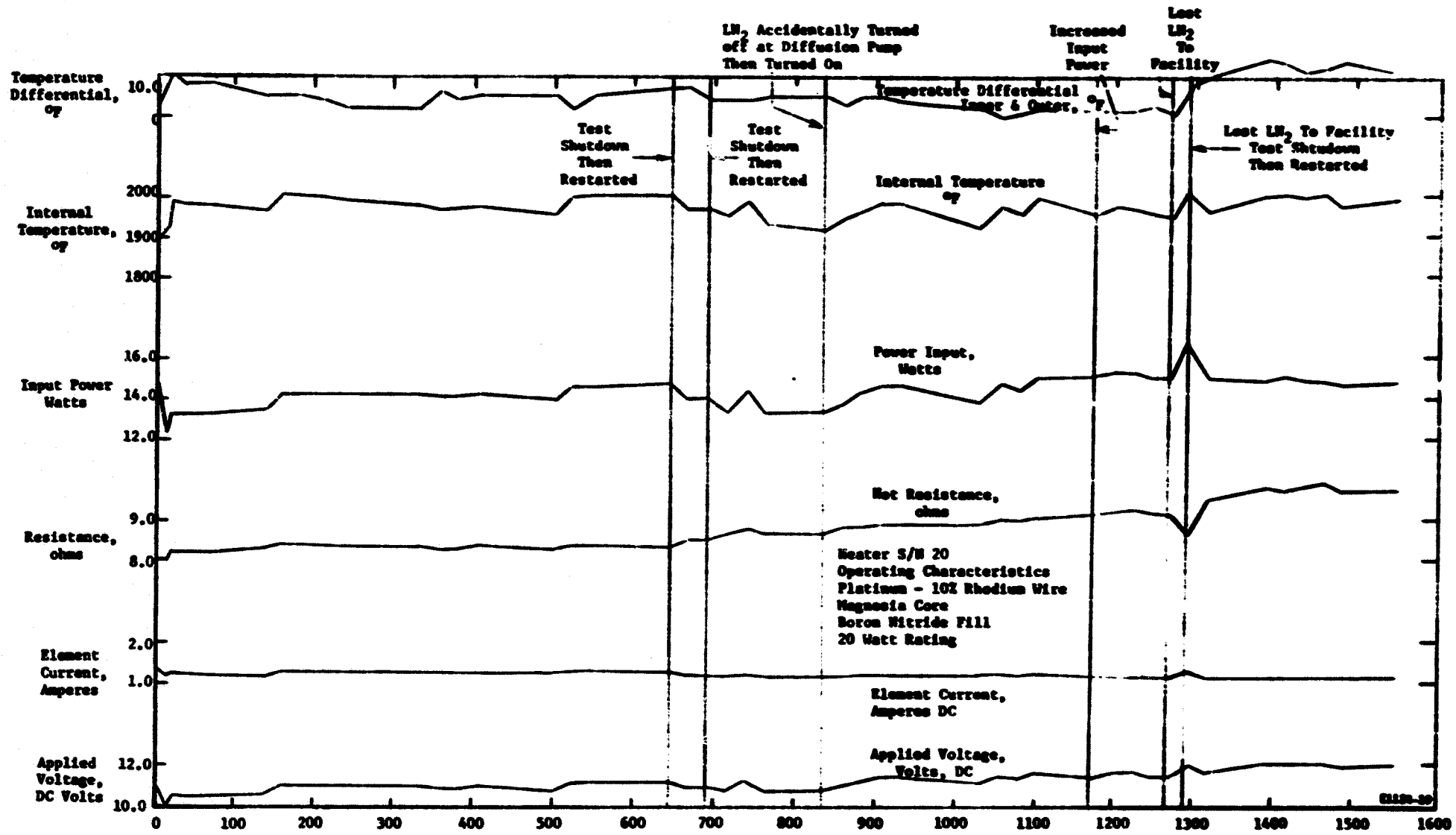


Figure 43. 1500-Hour Life Test Operating Characteristics, Heater S/N 20, Model HSK-2000-20.

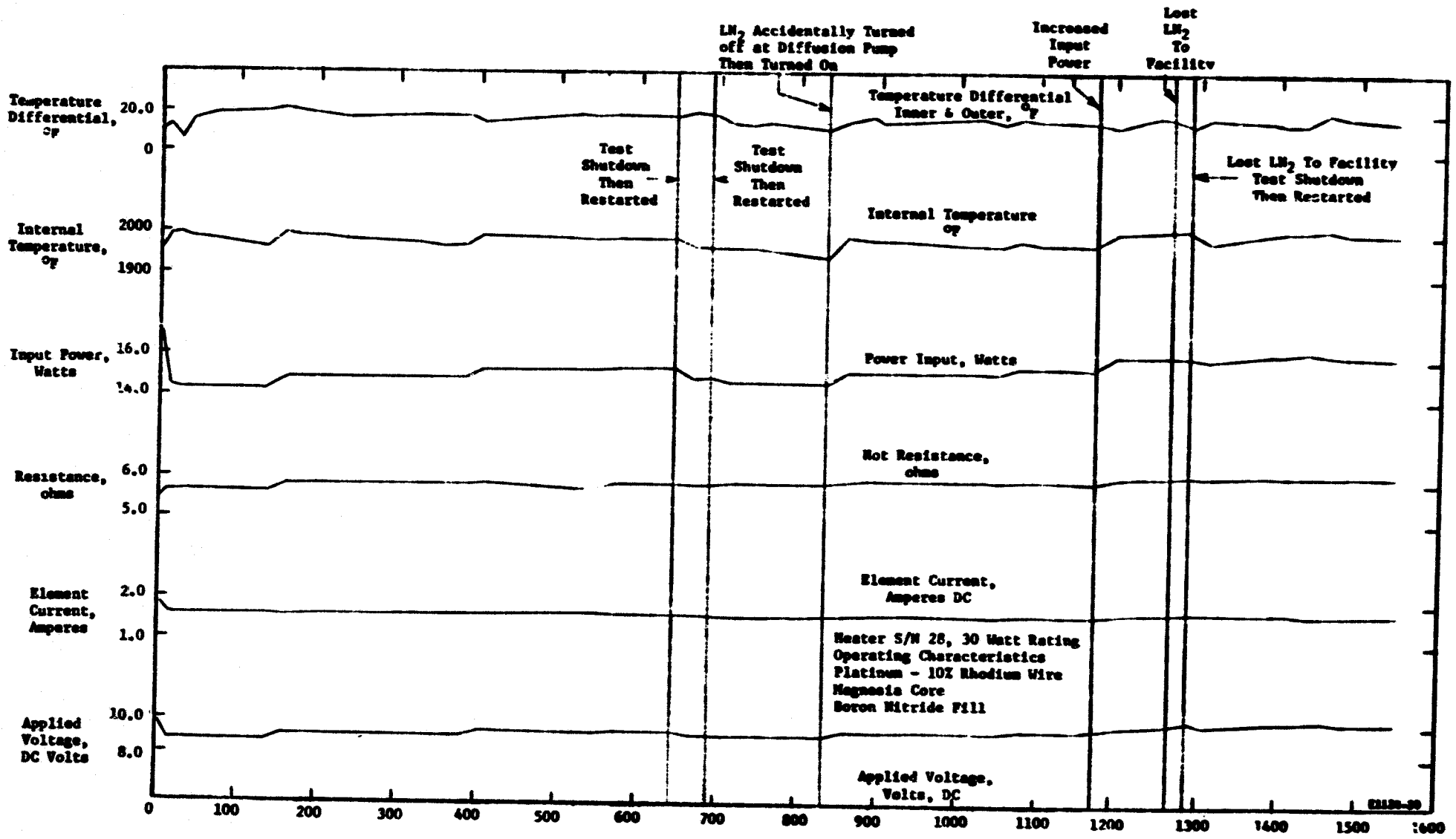


Figure 44. 1500-Hour Life Test Operating Characteristics, Heater S/N 28, Model HSK-2000-30.

brated Simpson Panel meters and temperatures measured on a Leeds & Northrop Speedomat indicator.

To determine the capability of "on" to 2000°F and "off" to room temperature of the standard 20-watt platinum-10% rhodium/ magnesium core/boron nitride fill/Hastelloy X heater a test plan was generated which provided for automatic cycling over the power supplied to the heaters.

Preliminary work had shown that with proper heat shielding a heater could be brought up to 2000°F within 4 hours without requiring excessive current. In addition it was found that 7 hours were required for the temperature to drop to 300°F after all power had been shut off. Thus a convenient time cycle was established for this most severe case giving two complete cycles per 24 hour day.

Since the ratio of hot resistance to cold resistance of the heater wire was 2.5/1 some current dropping resistance had to be inserted in series with the heater element so that the inrush current could be limited to 140% of rated current requirements. A schematic of the circuit appears in Figure 45.

The first heater, S/N22, placed on cycling tests failed after completing 32 cycles of operation. An open circuit was noted during heat up cycle but after cool down to room temperature a continuity check indicated a closed circuit. After opening it for examination a break in the wire was found. Heat-up data and cycle data for this heater are provided in Tables XXI and XXII.

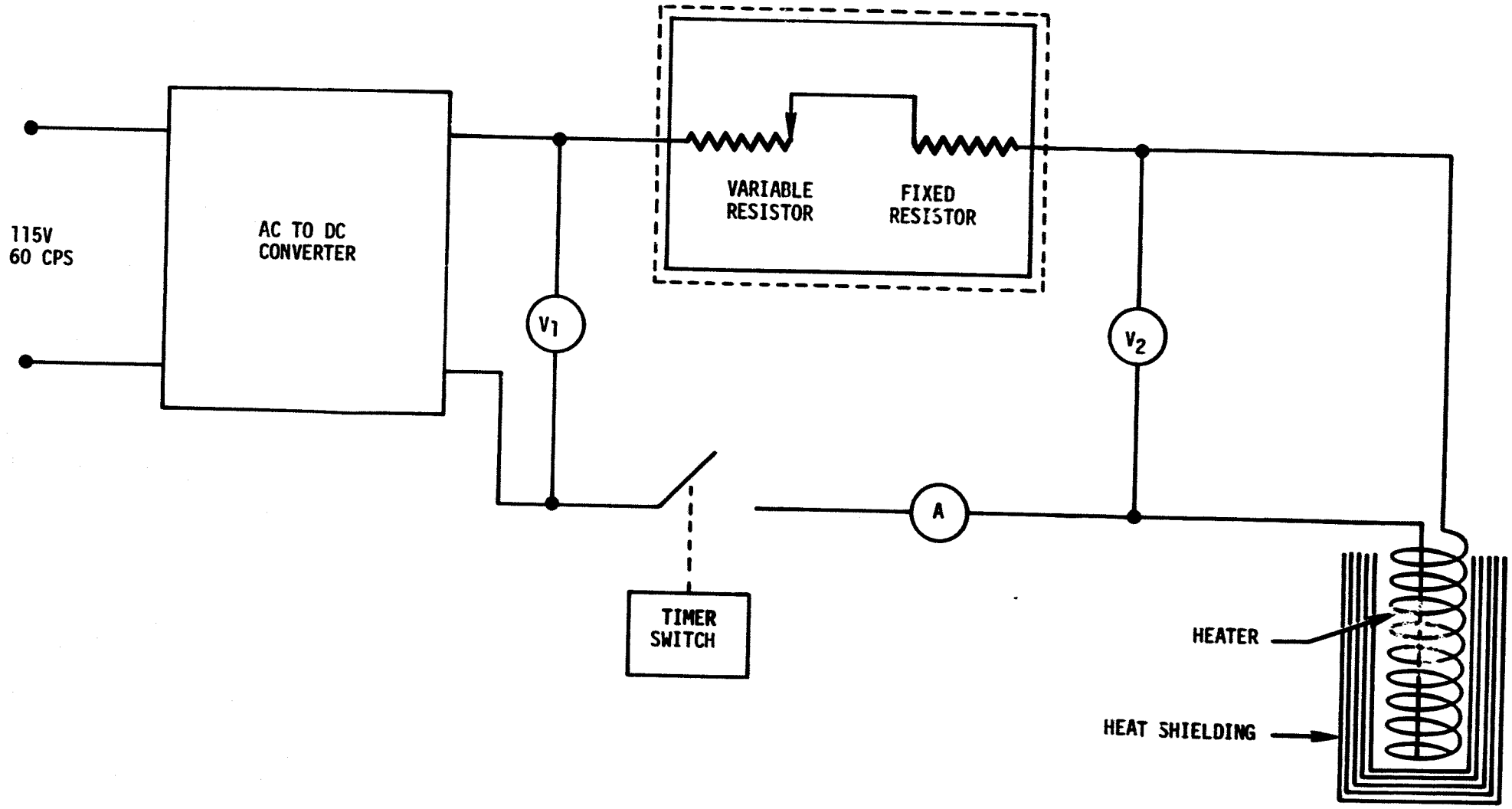


Figure 45. Heater Cycling Test Circuit Diagram.

E1279-19

TABLE XXI

HEAT-UP DATA
20 WATT HEATER S/N 22
PLATINUM-10% RHODIUM ELEMENT WIRE
MAGNESIA CORE
BORON NITRIDE FILL

Elapsed Time, Hours (Approx.)	Electrical Data				Temperatures, °F		Differential Between T/C Junctions #1 & #3 °F
	Measured		Calculated		Interior T/C Junction #1	Cartridge Surface T/C Junction #3	
	Applied DC Voltage, Volts*	DC Current, Amperes	Input Power Watts	Resistance, Ohms			
0	0	0	0	--	78	78	
0.16	9.4	1.82	17.10	5.17	970	960	10
0.46	9.9	1.62	16.02	6.10	1390	1385	5
0.71	10.1	1.55	15.65	6.52	1595	1582	13
0.91	10.3	1.50	15.45	6.87	1717	1710	7
2.0	10.4	1.45	15.10	7.18	1878	1878	--
4.0	10.6	1.42	15.02	7.47	1980	1985	-

Initial room ambient resistance = 2.88 ohms

Environmental pressure variation during test = 3.8×10^{-7} to 3.6×10^{-7} mm Hg

* Measured at power terminals outside vacuum tank.

TABLE XXII

CYCLING TEST DATA
20 WATT HEATER S/N 22
PLATINUM-10% RHODIUM ELEMENT WIRE
MAGNESIA CORE
BORON NITRIDE FILL

Elapsed Time Power Has Been Applied to Heater, Hrs	Electrical Data				Temperatures, °F		Differential Between T/C Junctions #1 & #3 °F
	Measured		Calculated		Interior T/C Junction #1	Cartridge Surface T/C Junction #3	
	Applied DC Voltage, Volts*	DC Current, Amperes	Input Power, Watts	Resistance, Ohms			
5/17/66							
0	11.00	1.55	17.10	7.10	1995	--	--
16.2	10.00	1.35	13.35	7.41	1937	1927	10
24.2	10.40	1.38	14.35	7.54	1972	1973	--
40.0	10.60	1.38	14.65	7.68	1984	1990	--
109.8	10.60	1.40	14.83	7.57	1968	1970	--
133.2	11.10	1.35	14.99	8.24	2012	2021	--
149.1	11.00	1.42	15.62	7.75	2013	2019	--
160.7	11.20	1.44	16.40	7.78	2023	2023	--
169.0	11.25	1.43	16.09	7.78	2028	2028	0
201.7	10.50	1.36	14.28	7.74	1939	1933	6
209.9	10.60	1.37	14.58	7.75	1959	1954	5
218.3	10.60	1.37	14.58	7.75	1960	1954	6
226.5	10.60	1.37	14.58	7.75	1960	1950	6
259.4	10.60	1.38	14.65	7.70	1958	1948	10
267.4	10.90	1.41	15.36	7.80	1979	1970	9
275.8	10.90	1.40	15.25	7.75	1987	1978	9
284.0	11.00	1.38	15.20	7.96	1998	1989	9
			Heater open-circuited				

Initial room ambient resistance = 2.88 ohms
Final room ambient resistance = 3.514 ohms (circuit re-established upon cooling)
Environmental pressure variation during test = 4.0×10^{-7} to 1.5×10^{-7} mm Hg

* Measured at power terminals outside vacuum tank.

Curves of both the heating and cooling characteristics of this heater appear on Figure 46.

A 30-watt heater S/N 25, was temperature cycled in a manner similar to S/N 22. Test data appear in Table XXIII. Failure occurred after 25 cycles when an open circuit appeared in the platinum-10% rhodium element wire.

Three additional heaters, S/N 42, 43, and 45, were then tested; S/N 43 failed after 11 cycles, S/N 42 after 12 cycles, and S/N 45 after 13 cycles. Test data for a typical cycling heater, S/N 45, appear in Tables XXIV, XXV, and XXVI.

The next series of cycling tests were performed with recrystallization resistant platinum wire heaters S/N 54, 55, and 56. Heat-up data for these heaters appear in Tables XXVII, XXVIII, and XXIX. Cool-down data appear in Table XXX. In addition, a cool-down cycle for heater S/N 54 is plotted in curve form on Figure 47. Heat-up data for S/N 55 and 56 are plotted in Figures 48 and 49.

Heater S/N 54 open circuited after completing 21 cycles of operation, S/N 55 after 36 cycles, and S/N 56 after 55 cycles. Actual cycle data for the three heaters appear on Table XXXI, XXXII, and XXXIII.

Details of the heater configuration tested and post-test evaluations of the heaters after removal from test are provided in the following sections.

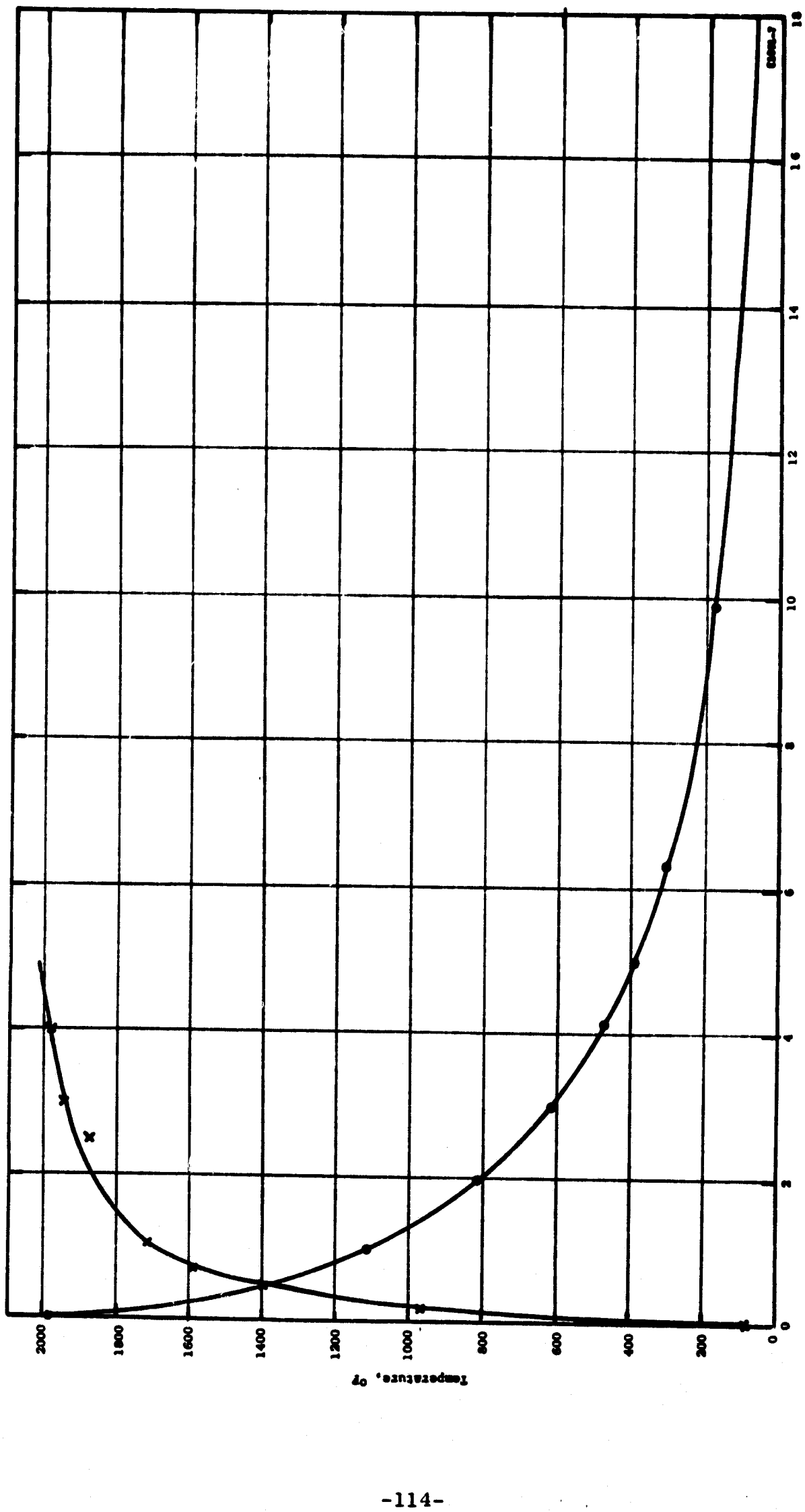


Figure 46. Heating Up and Cooling Down Characteristics of Heater S/N 22.

TABLE XXIII

Cycling Test Data
30 Watt Heater S/N 25
Platinum-10% Rhodium Element Wire
Magnesia Core
Boron Nitride Fill

Elapsed Time Power Has Been Applied to Heater, Hrs.	Electrical Data				Temperatures, °F		Differential Between T/C Junctions #1 & #4 °F**
	Measured		Calculated				
	Applied DC Voltage, Volts*	DC Current, Amperes	Input Power, Watts	Resistance, Ohms	Interior T/C Junction #1	Cartridge Surface T/C Junction #4	
6/14/66							
0	9.0	1.65			1997	2020	--
24.0	9.4	1.70			2040	2068	--
48.0	7.8	1.52			1800	1795	--
	Test interrupted and heater sheath examined for cracks.						
52.0	7.6	1.46			1808	1830	--
76.0	9.0	1.64			1990	2225	--
100.0	8.8	1.57			2003	2031	--
124.0	8.7	1.56			1989	2008	--
196.0	8.7	1.55			1977	1998	--
	Diffusion pump liquid nitrogen accidentally turned off for approximately 12 hours, but test was continued.						
220.0	8.7	1.55			1968	1987	--
244.0	8.7	1.55			1958	1987	--
268.0	8.7	1.56			1983	2000	--
292.0	8.8	1.58			1996	2115	--
7/5/66							
412.0	No readings made.						
7/5/66							
	Open circuit occurred and test discontinued.						

Initial room ambient resistance = 2.285 ohms.
Room ambient resistance after power had been applied for 48 hours = 2.210 ohms.
Final room ambient resistance = 2.3 ohms (circuit re-established upon cooling).
Environmental pressure variation during test - 5.0×10^{-7} to 2.0×10^{-7} mm Hg.

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* Measured at power terminals outside vacuum tank.
** Value unobtainable because of improper temperature indication of T/C #1.

TABLE XXIV
HEAT-UP DATA
20 WATT HEATER, S/N 45
PLATINUM -10% RHODIUM ELEMENT WIRE
MAGNESIA CORE
BORON NITRIDE FILL

Elapsed Time, Hours (Approx)	Electrical Data				Temp °F Internal Thermo-Couple Junction **
	Measured		Calculated		
	Applied DC Voltage, Volts*	DC Current, Amperes	Input Power, Watts	Resis-tance, Ohms	
0	6.4	2.0	12.80	3.20	70
0.08	6.7	1.60	10.70	4.19	398
0.41	6.9	1.28	8.32	5.38	899
0.50	8.9	1.60	14.20	(Increased power)	
0.58	8.9	1.50	10.33	5.94	1121
0.91	9.3	1.39	12.90	6.69	1407
1.00	10.2	1.50	15.30	(Increased power)	
1.08	10.3	1.49	15.35	6.91	1504
1.09	10.4	1.39	14.45	7.49	1772
2.00	10.9	1.48	16.10	(Increased power)	
2.08	10.8	1.42	15.32	7.60	1812
3.08	11.2	1.40	15.68	8.00	1918
4.00	11.2	1.39	15.58	8.05	1953
-	11.4	1.41	16.08	(Increased power)	
4.08	11.4	1.42	16.20	8.04	1965
4.41	11.4	1.42	16.20	8.04	1972
5.32	11.6	1.42	16.48	8.16	2003
		(TEST DISCONTINUED)			

Initial room ambient resistance = 3.17 ohms
Environmental pressure variation during test: 6.5×10^{-5} to 3.6×10^{-5} mm Hg

* Measured at power terminals outside vacuum tank.

** Calibration data on internal heater thermocouple junction indicates a reading of 10°F high at 2000°F.

TABLE XXV

COOL-DOWN DATA
20 WATT HEATER S/N 45
PLATINUM -10% RHODIUM ELEMENT WIRE
MAGNESIA CORE
BORON NITRIDE FILL

ELAPSED TIME, HOURS (APPROX)	TEMP °F INTERNAL THERMO-COUPLE JUNCTION *
0	1980
0.32	1485
1.32	1001
2.41	797
3.50	608
4.58	480
5.50	402
7.32	300

* Calibration data on internal heater thermocouple junction indicates a reading of 10% high of 2000°F.

TABLE XXVI

CYCLING TEST DATA
20 WATT HEATER S/N 45
PLATINUM-10% RHODIUM ELEMENT WIRE
MAGNESIA CORE
BORON NITRIDE FILL

Reading	Electrical Data					Internal Heater Thermo-Couple Junction Temp oF	Number of Cycles Completed	Remarks
	Measured			Calculated				
	DC Voltage		DC	Heater Element				
	Applied To Circuit V1 Volts	Applied To Heater Element V2 Volts*	Current Through Heater Element A Amperes	Input Power Watts	Resis-Tance Ohms			
Initial	-	6.4	2.0	12.80	-	-	1	Initial Calibration
Final	-	11.6	1.42	16.48	8.16	2003		Heat Up & Cool Down
Initial	-	9.4	1.76	16.55	-	-	2	
Final	-	11.2	1.39	15.60	8.06	1932		
Initial	24.96	10.6	1.35	14.32	-	-	1	
Final	-	11.2	1.39	15.58	8.06	1931		
Initial	24.8	7.2	2.10	15.15	-	-	1	
Final	-	11.7	1.47	17.22	7.96	1992		
Initial	41.0	5.8	1.72	9.96	-	-	1	
Final	-	11.6	1.42	16.50	8.19	1992		
Initial	37.8	5.9	1.80	10.62	-	-	1	
Final	-	11.6	1.45	16.82	8.00	1985		
Initial	37.7	6.0	1.78	10.70	-	-	2	
Final	-	11.7	1.43	16.70	8.19	1995		
Initial	37.6	6.8	1.71	11.62	-	-	2	
Final	-	11.7	1.44	16.85	8.12	1998		
Initial	-	-	-	-	-	-	2	
Final	-	-	-	-	-	-		
Initial	37.8	6.6	1.72	11.35	-		-	Heater Failed on
Final	-	-	-	-	-			Warm up at 1005°F

Definition: Initial: Reading made as timer relay energized heater circuit

Final: Reading made approximately 15 minutes before timer relay de-energized circuit

13 Cycles of Operation before Failures

*Measured at power terminal outside vacuum tank

Note: Initial vacuum ambient resistors of heater element = 3.17 ohms

Environmental pressure variation during test: 6.5×10^{-5} to 6.3×10^{-6} MMHg

TABLE XXVII

HEAT-UP DATA
20 WATT HEATER S/N 54
THERMOPLATINUM FG ELEMENT WIRE
MAGNESIA CORE
BORON NITRIDE FILL

Elapsed Time, Hours (Approx.)	Reading Ident. No.	Electrical Data				Internal Thermo-Couple Junction Temp, °F
		Measured		Calculated		
		Applied DC Voltage, Volts*	DC Amperes, Amps	Input Power, Watts	Resis-tance, Ohms	
0	1	0	0	-	-	65
	2	0.6	0.25	-	-	65
	3	0.6	0.25	0.150	-	70
1.0	1	0.6	0.24	0.144	2.5	100
	2	1.3	0.50	-	-	101
	3	1.3	0.50	-	-	115
1.5	1	1.3	0.46	0.597	2.83	170
	2	2.3	0.75	-	-	175
	3	2.3	0.74	-	-	203
2.0	1	2.3	0.65	1.50	3.54	320
	2	3.8	1.00	-	-	330
	3	3.9	0.94	-	-	396
2.5	1	4.0	0.80	3.20	5.00	569
	2	5.0	1.00	-	-	582
	3	5.1	0.96	-	-	634
3.0	1	5.1	0.87	4.44	5.86	790
	2	7.1	1.20	-	-	800
	3	7.1	1.14	-	-	885
3.5	1	7.2	1.01	7.25	7.14	1102
	2	8.7	1.20	-	-	1110
	3	8.8	1.16	-	-	1170
4.0	1	8.8	1.10	9.69	8.00	1314
	2	11.4	1.40	-	-	1330
	3	11.5	1.35	-	-	1425
4.5	1	11.5	1.24	14.28	9.28	1642
	2	14.1	1.50	-	-	1660
	3	14.2	1.45	-	-	1760
5.0	1	14.3	1.37	19.60	10.42	1938
	2	15.1	1.45	-	-	1945
	3	15.1	1.42	-	-	1994

TABLE XXVII (Cont'd)

HEAT-UP DATA
20 WATT HEATER S/N 54
THERMOPLATINUM FG ELEMENT WIRE
MAGNESIA CORE
BORON NITRIDE FILL

Elapsed Time, Hours (Approx.)	Reading Ident. No.	Electrical Data				Internal Thermo-Couple Junction Temp, °F
		Measured		Calculated		
		Applied DC Voltage, Volts*	DC Amperes, Amps	Input Power, Watts	Resis-tance, Ohms	
5.25	1	13.6	1.25	(Power Decreased)		-
5.3	1	13.6	1.26	17.10	10.80	2008
	2	(No Power Change)			-	-
	3	-	-	-	-	-
6.0	1	13.6	1.26	17.10	10.80	2008
	2	(No Power Change)			-	-
	3	-	-	-	-	-
6.3	1	13.6	1.26	17.10	10.80	2010
	2	(No Power Change)			-	-
	3	-	-	-	-	-
7.0	1	13.6	1.26	17.10	10.80	2010
	2	(No Power Change)			-	-
	3	-	-	-	-	-
7.3	1	13.6	1.26 End of Test	17.10	10.80	2010

Initial room ambient resistance = 2.33 ohms

Environmental pressure: 10^{-6} mmHg range

*Measured at power terminals outside vacuum tank

Reading Identification No. Key

1. Before power was adjusted
2. Directly after power was adjusted
3. Five minutes after power was adjusted

TABLE XXVIII

HEAT-UP DATA
20 WATT HEATER S/N 55
THERMOPLATINUM FG ELEMENT WIRE
MAGNESIA CORE
BORON NITRIDE FILL

Elapsed Time, Hours (Approx.)	Reading Ident. No.	Electrical Data				Internal Thermo-Couple Junction Temp, °F
		Measured		Calculated		
		Applied DC Voltage, Volts*	DC Amperes, Amps	Input Power, Watts	Resis-tance, Ohms	
0	1	0	0	-	-	65
	2	0.7	0.25	-	-	65
	3	0.6	0.25	0.150	-	70
1.0	1	0.6	0.24	-	-	104
	2	1.4	0.50	-	-	105
	3	1.4	0.50	-	-	119
1.5	1	-	-	-	-	-
	2	2.2	0.75	-	-	190
	3	2.3	0.75	-	-	210
2.0	1	2.6	0.70			354
	2	3.8	1.00	-	-	364
	3	3.9	1.00	-	-	399
2.5	1	4.5	0.90			626
	2	5.0	1.00	-	-	645
	3	5.1	1.00	-	-	686
3.0	1	5.5	0.92			854
	2	7.0	1.20			860
	3	7.1	1.18			900
3.5	1	7.6	1.10			1155
	2	8.5	1.20	-	-	1162
	3	8.6	1.19	-	-	1190
4.0	1	8.8	1.15			1338
	2	11.0	1.40	-	-	1350
	3	11.2	1.40	-	-	1410
4.5	1	11.7	1.30			1680
	2	13.6	1.50	-	-	1690
	3	13.9	1.50	-	-	1748
5.0	1	14.3	1.45			1963
	2	15.0	1.50	-	-	1970
	3	15.0	1.50	-	-	1996

TABLE XXVIII (Cont'd)

HEAT-UP DATA
20 WATT HEATER S/N 55
THERMOPLATINUM FG ELEMENT WIRE
MAGNESIA CORE
BORON NITRIDE FILL

Elapsed Time, Hours (Approx.)	Reading Ident. No.	Electrical Data				Internal Thermo-Couple Junction Temp, °F
		Measured		Calculated		
		Applied DC Voltage Volts*	DC Amperes, Amps	Input Power, Watts	Resis-tance, Ohms	
5.25	1	13.7	1.35	(Power Decreased)		-
5.3	1	13.7	1.35			2021
	2	13.3	1.30	(Power Decreased)		2020
	3	13.3	1.30			2010
6.0	1	13.3	1.30			1999
	2	(No Power Change)		-	-	
	3	-	-	-	-	
6.5	1	13.3	1.30			2000
	2	(No Power Change)		-	-	
	3	-	-	-	-	
7.0	1	13.3	1.30			2000
	2	(No Power Change)		-	-	
	3	-	-	-	-	
7.5	1	13.3	1.30			1999
			End of Test			

Initial room ambient resistance = 2.20 ohms

Environmental pressure: 10^{-6} mmHg range

*Measured at power terminals outside of vacuum tank

Reading Identification No. Key

1. Before power was adjusted
2. Directly after power was adjusted
3. Five minutes after power was adjusted

TABLE XXIX

HEAT-UP DATA
20 WATT HEATER S/N 56
THERMOPLATINUM FG ELEMENT WIRE
MAGNESIA CORE
BORON NITRIDE FILL

Elapsed Time, Hours (Approx.)	Reading Ident. No.	Electrical Data				Internal Thermo-Couple Junction Temp, °F
		Measured		Calculated		
		Applied DC Voltage, Volts*	DC Amperes, Amps	Input Power, Watts	Resis-tance, Ohms	
0	1	0	0	-	-	65
	2	0.6	0.25	-	-	65
	3	0.5	0.25	0.125	-	70
1.0	1	0.5	0.25	0.125	2.0	96
	2	1.2	0.50	-	-	100
	3	1.2	0.50	-	-	108
1.5	1	1.2	0.50	0.60	2.4	172
	2	2.0	0.75	-	-	175
	3	2.0	0.75	-	-	192
2.0	1	2.4	0.74	1.77	3.25	328
	2	3.4	1.00	-	-	333
	3	3.5	1.00	-	-	383
2.5	1	4.2	0.95	4.00	4.42	610
	2	4.5	1.00	-	-	631
	3	4.7	1.00	-	-	671
3.0	1	5.3	0.96	5.10	5.50	850
	2	6.7	1.20	-	-	860
	3	7.0	1.20	-	-	922
3.5	1	7.6	1.14	8.66	6.67	1202
	2	8.4	1.20	-	-	1212
	3	8.4	1.19	-	-	1245
4.0	1	8.7	1.16	10.10	7.50	1383
	2	10.8	1.40	-	-	1395
	3	11.0	1.39	-	-	1470
4.5	1	12.0	1.35	16.20	8.89	1752
	2	13.5	1.50	-	-	1765
	3	13.6	1.49	-	-	1820
5.0	1	14.4	1.44	20.70	10.00	2021
	2	13.9	1.40	(Power Decreased)		2025
	3	13.9	1.40	-	-	2032

TABLE XXIX (Cont'd)

HEAT-UP DATA
20 WATT HEATER S/N 56
THERMOPLATINUM FG ELEMENT WIRE
MAGNESIA CORE
BORON NITRIDE FILL

Elapsed Time, Hours (Approx.)	Reading Ident. No.	Electrical Data				Internal Thermo-Couple Junction Temp, °F
		Measured		Calculated		
		Applied DC Voltage, Volts*	DC Amperes, Amps	Input Power, Watts	Resistance, Ohms	
5.25	1	12.6	1.25	(Power Decreased)		-
5.5	1	12.6	1.26	15.90	10.00	2009
	2		(No Power Change)		-	-
	3	-	-	-	-	-
6.0	1	12.6	1.26	15.90	10.00	2002
	2		(No Power Change)		-	-
	3	-	-	-	-	-
6.5	1	12.6	1.26	15.90	10.00	2004
	2		(No Power Change)		-	-
	3	-	-	-	-	-
7.0	1	12.6	1.26	15.90	10.00	2004
	2		(No Power Change)		-	-
	3	-	-	-	-	-
7.5	1	12.6	1.26	15.90	10.00	2004
			End of Test			

Initial room ambient resistance = 2.23 ohms

Environmental pressure: 10^{-6} mmHg range

*Measured at power terminals outside of vacuum tank

Reading Identification No. Key

1. Before power was adjusted
2. Directly after power was adjusted
3. Five minutes after power was adjusted

TABLE XXX

COOL-DOWN DATA
20 WATT HEATERS, S/N 54, S/N 55 & S/N 56
THERMOPLATINUM FG ELEMENT WIRE
MAGNESIA CORE
BORON NITRIDE FILL

S/N 54

Elapsed Time, Hours (Approx)	Temp. °F Internal Thermo-Couple Junction
0	1993
0.40	1500
1.46	1000
2.20	800
3.50	600
4.41	500
5.75	400
7.80	300

S/N 55

Elapsed Time, Hours (Approx)	Temp. °F Internal Thermo-Couple Junction
0	1984
0.36	1500
1.26	1000
2.08	800
3.25	600
4.08	500
5.36	400
7.31	300

S/N 56

Elapsed Time, Hours (Approx)	Temp. °F Internal Thermo-Couple Junction
0	1983
0.40	1500
1.46	1000
2.20	800
3.50	600
4.41	500
5.75	400
7.80	300

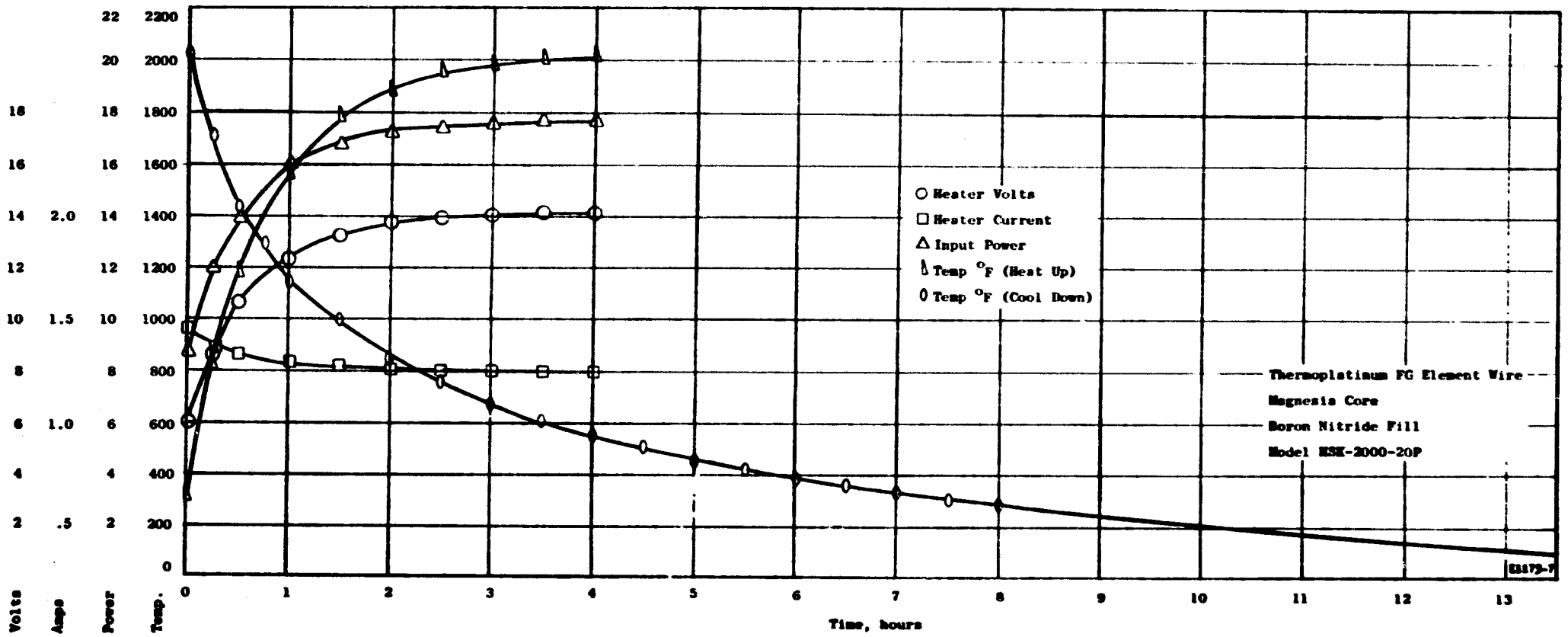


Figure 47. Typical Heat Up and Cool Down Cycle for Heater S/N 54.

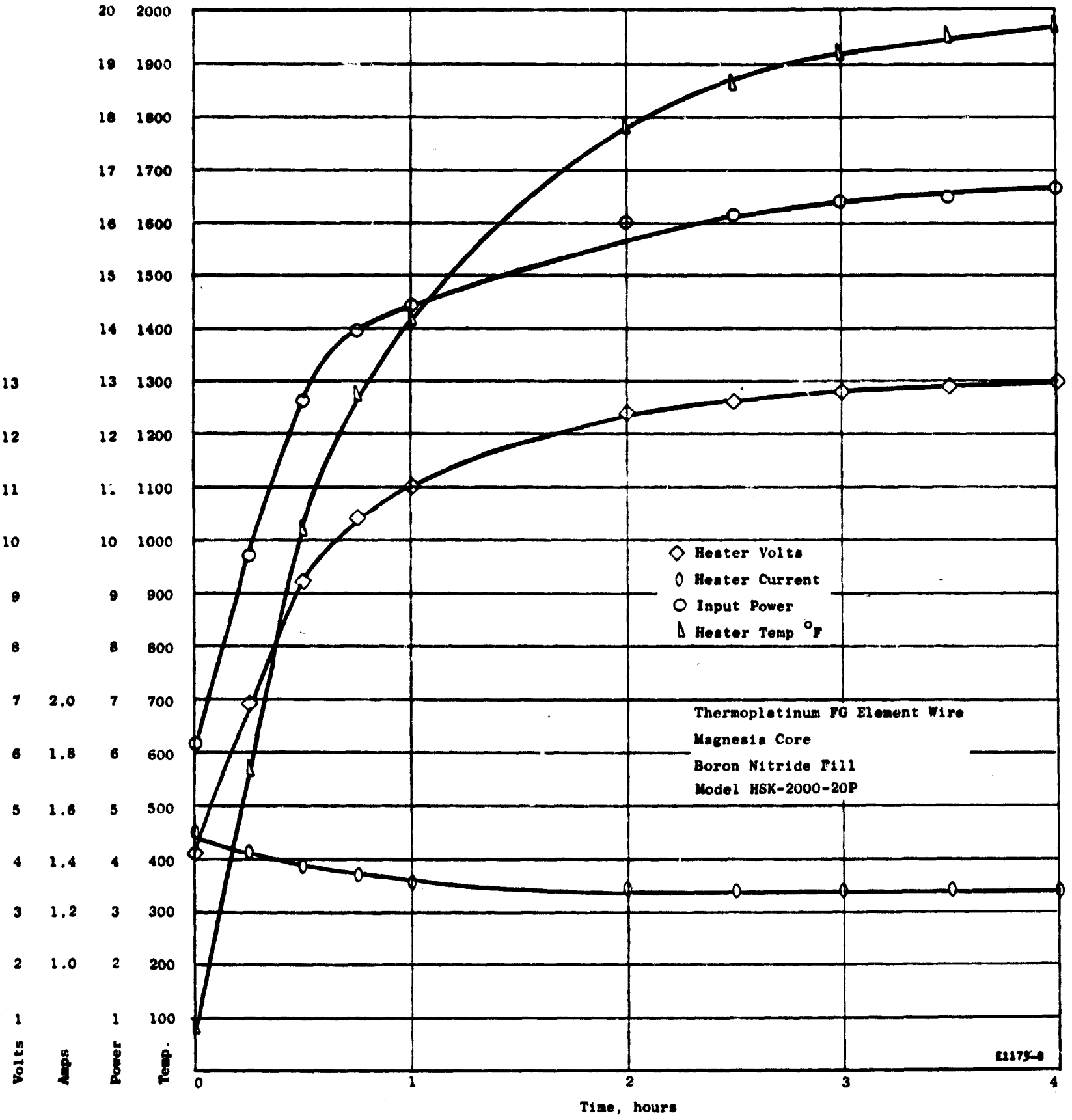


Figure 48. Typical Heat Up Cycle for Heater S/N 55.

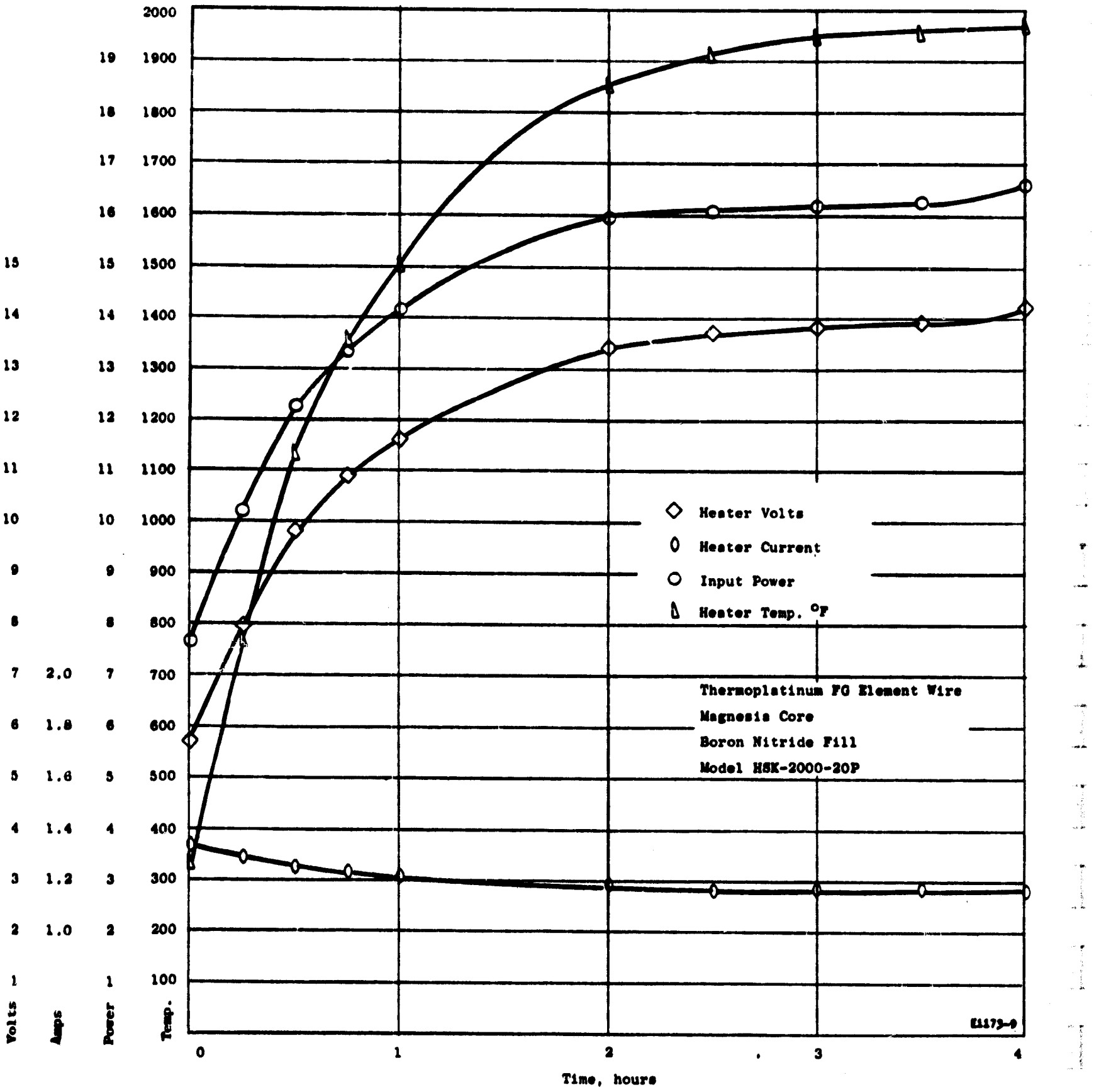


Figure 49. Typical Heat Up Cycle for Heater S/N 56.

TABLE XXXI

CYCLING TEST DATA
20 WATT HEATER S/N 54
THERMOPLATINUM FG ELEMENT WIRE
MAGNESIA CORE
BORON NITRIDE FILL

Reading (For One Observed Cycle)	Electrical Data						Number Of Cycles Completed	Remarks
	DC Voltage		DC	Heater Element		Internal		
	Applied To Circuit V1 Volts	Applied To Heater Element V2 Volts*	Current Through Heater Element "A" Amperes	Input Power, Watts	Resistance, Ohms	Thermo-Couple Junction Temp, °F		
Initial	68.4	4.4	1.50	6.6	2.93	135	1	
Final	-	13.8	1.25	17.25	10.05	2000		
Initial	68.4	7.0	1.44	10.08	4.86	482	3	Cycle Started Before Cool-Down Period Completed
Final	-	14.0	1.25	17.50	11.20	2010		
Initial	68.4	6.0	1.45	8.70	4.14	311	5	
Final	-	14.1	1.25	17.62	11.28	2013		
Initial	68.4	6.0	1.46	8.75	4.10	311	11	(Test Continued Over Weekend)
Final	-	14.5	1.24	18.00	11.70	2020		
Initial	67.3	6.1	1.44	8.79	4.22	312	15	
Final	-	14.5	1.21	17.55	12.00	2000		
Initial	67.3	6.1	1.44	8.79	4.22	305	17	
Final	-	14.6	1.21	17.68	12.05	2008		
Initial	67.4	6.1	1.44	8.79	4.22	301	19	
Final	-	14.7	1.21	17.78	12.15	1965		
Initial	67.4	6.4	1.43	9.14	4.47	303	25	(Test Continued Over Weekend)
Final	-	-	(Heater Open Circuited)			-		

Definition: Initial: Reading made as timer relay energized heater circuit

Final: Reading made approximately 15 minutes before timer relay de-energized circuit

Note: 19 certain cycles plus 2 calibration cycles = 21 cycles of operation before failure

*Measured at power terminals outside vacuum tank

Note: Initial room ambient resistance of heater element = 2.33 ohms

Environmental pressure variation during test = 10^{-6} mmHg range

TABLE XXXII

CYCLING TEST DATA
20 WATT HEATER S/N 55
THERMOPLATINUM FG ELEMENT WIRE
MAGNESIA CORE
BORON NITRIDE FILL

Reading (For One Observed Cycle)	Electrical Data: DC Voltage Applied To Circuit V1 Volts	DC Voltage Applied To Heater Element V2 Volts*	DC Current Through Heater Element "A" Amperes	Heater Input Power, Watts	Element Resistance, Ohms	Internal Thermo-Couple Junction Temp, °F	Number Of Cycles Completed	Remarks
Initial	63.0	4.0	1.42	5.66	2.82	72	1	
Final	-	12.2	1.21	14.80	10.08	1880		
Initial	63.0	4.1	1.50	6.15	2.73	80	2	
Final	-	13.0	1.28	16.62	10.15	1971		
Initial	64.0	5.6	1.50	8.40	3.73	300	4	
Final	-	12.4	1.21	15.00	10.25	1992		
Initial	63.0	5.6	1.46	8.16	3.84	281	10	(Test Continued Over Weekend)
Final	-	13.1	1.24	16.22	10.58	1985		
Initial	63.0	5.5	1.45	7.97	3.79	274	12	
Final	-	13.2	1.25	16.50	10.55	1986		
Initial	64.0	6.0	1.48	8.86	4.05	355	14	
Final	-	13.7	1.28	17.50	10.70	2008		
Initial	64.3	5.5	1.48	8.15	4.71	275	18	
Final	-	13.8	1.28	17.68	10.78	2010		
Initial	64.0	6.2	1.45	8.98	4.27	350	22	
Final	-	13.8	1.26	17.55	10.95	1972		
Initial	64.24	9.6	1.32	12.67	7.27	960	34	(Readings Not Made for Several Days)
Final	-	14.3	1.25	17.87	11.4	2000		
Initial	64.0	4.8	1.49				41	
Final	-	14.5	1.26	18.3	11.5	1982		

TABLE XXXII (Cont'd)

CYCLING TEST DATA
20 WATT HEATER S/N 55
THERMOPLATINUM FG ELEMENT WIRE
MAGNESIA CORE
BORON NITRIDE FILL

Reading (For One Observed Cycle)	Electrical Data: DC Voltage Applied To Circuit V1 Volts	DC Voltage Applied To Heater Element V2 Volts*	DC Current Through Heater Element "A" Amperes	Heater Input Power, Watts	Element Resistance, Ohms	Internal Thermo-Couple Junction Temp, °F	Number Of Cycles Completed	Remarks
Initial	64.0	7.1	1.47			428	53	
Final		14.0	1.29	18.1	10.85	1771		
Initial	66.8	6.2	1.55	9.61	4.00	220	67	
Final		14.7	1.32	19.4	11.14	1790		
Initial	68.5	6.3	1.58	9.95	3.98	250	79	
Final	70.0	16.1	1.40	24.00	11.5	1500		
Initial	74.5	7.0	1.72	12.04	4.07	280	91	
Final	-	17.6	1.48	26.05	11.89	1925		
Initial	75.0	11.8	1.63	19.23	7.23	710	99	
Final	-	18.0	1.49	26.82	12.03	1920		
Initial	75.0	7.2	1.78	12.82	4.04	110	105	
Final	-	18.2	1.48	26.94	12.29	1930		
Initial	76.0	10.5	1.67	17.54	6.28	620	117	
Final	-	18.2	1.45	26.39	12.55	1911		
Initial	79.0	16.3	1.55	25.26	10.51	1430	123	
Final	-	19.2	1.49	28.61	12.88	1960		
Initial	79.0	12.8	1.65	21.12	7.76	890	125	
Final	-	19.3	1.49	28.76	12.95	1958		
Initial	79.0	16.8	1.52	25.54	11.05	1477	131	
Final	-	19.9	1.49	29.65	13.36	1970		

TABLE XXXII (Cont'd)

CYCLING TEST DATA
20 WATT HEATER S/N 55
THERMOPLATINUM FG ELEMENT WIRE
MAGNESIA CORE
BORON NITRIDE FILL

Reading (For One Observed Cycle)	Electrical Data: DC Voltage Applied To Circuit V1 Volts	DC Voltage Applied To Heater Element V2 Volts*	DC Current Through Heater Element "A" Amperes	Heater Input Power, Watts	Element Resistance, Ohms	Internal Thermo-Couple Junction Temp, °F	Number Of Cycles Completed	Remarks
Initial	79.0	10.5	1.70	17.85	6.17	480	133	
Final		19.7	1.48	29.16	13.31	1963		
Initial	79.0	9.5	1.70	16.15	5.58	430	135	
Final		20.1	1.46	29.35	13.76	1979		
Initial	79.0	9.0	1.70	15.30	5.29	360	137	
Final		30+				1620		

Heater Open Circuited After 137th Cycle

Definition: Initial: Reading made as timer relay energized heater circuit

Final: Reading made approximately 15 minutes before timer relay de-energized circuit

Note: 14 cycles of operation plus 1 calibration cycle = 15 cycles of operation thus far

*Measured at power terminals outside vacuum tank

Note: Initial room ambient resistance of heater element = 2.20 ohms

Environmental pressure variation during test = 10^{-6} mmHg range

TABLE XXXIII

CYCLING TEST DATA
20 WATT HEATER S/N 56
THERMOPLATINUM FG ELEMENT WIRE
MAGNESIA CORE
BORON NITRIDE FILL

Reading (For One Observed Cycle)	Electrical Data: DC Voltage Applied To Circuit V1 Volts	DC Voltage Applied To Heater Element V2 Volts*	DC Current Through Heater Element "A" Amperes	Heater Input Power, Watts	Element Resistance, Ohms	Internal Thermo-Couple Junction Temp, °F	Number Of Cycles Completed	Remarks
Initial	77.2	4.0	1.46	5.83	2.74	145	1	
Final	-	13.3	1.29	17.15	10.31	2030		
Initial	73.7	6.1	1.36	8.30	4.48	484	3	
Final	-	12.3	1.22	15.00	10.02	1955		
Initial	73.8	5.2	1.38	7.16	3.77	316	5	
Final	-	12.6	1.24	15.60	10.15	1970		
Initial	75.1	5.3	1.39	7.36	3.81	312	11	(Test Continued
Final	-	13.2	1.23	16.22	10.82	1996		Over Weekend)
Initial	75.3	5.5	1.40	7.70	3.93	311	15	
Final	-	13.6	1.22	16.60	11.15	2014		
Initial	74.4	5.4	1.39	7.50	3.88	306	19	
Final	-	13.5	1.21	16.35	11.15	2001		
Initial	74.3	5.6	1.38	7.72	4.06	305	25	(Test Continued
Final	-	14.1	1.21	17.05	11.65	2010		Over Weekend)
Initial	73.8	5.5	1.39	7.65	3.95	298	27	
Final	-	14.1	1.20	16.90	11.75	2018		
Initial	74.3	5.5	1.37	7.54	4.02	300	29	
Final	-	14.4	1.20	17.30	12.00	2010		
Initial	73.5	5.7	1.34	7.64	4.25	330	31	
Final	-	14.2	1.17	16.60	12.12	1970		
Initial	74.1	5.9	1.34	7.90	4.40	330	33	
Final	-	14.0	1.17	16.39	11.92	1990		

TABLE XXXIII (Cont'd)

CYCLING TEST DATA
20 WATT HEATER S/N 56
THERMOPLATINUM FG ELEMENT WIRE
MAGNESIA CORE
BORON NITRIDE FILL

Reading (For One Observed Cycle)	Electrical Data: DC Voltage Applied To Circuit V1 Volts	DC Voltage Applied To Heater Element V2 Volts*	DC Current Through Heater Element "A" Amperes	Heater Input Power, Watts	Element Resistance, Ohms	Internal Thermo-Couple Junction Temp, °F	Number Of Cycles Completed	Remarks
Initial	74.3	5.7	1.34	7.64	4.26	295	39	(Test Continued
Final	-	14.8	1.16	17.15	12.75	1980		Over Weekend)
Initial	74.4	5.7	1.34	7.64	4.26	295	41	
Final	-	14.1	1.17	16.50	12.05	1988		
Initial	75.4	4.4	1.37	6.02	3.22	150	43	
Final	-	-	-	-	-	-		
Initial	75.5	6.3	1.35	8.50	4.66	395	47	
Final	-	14.4	1.17	16.82	12.30	1990		
Initial	75.5	7.1	1.30	9.24	5.46	564	49	
Final	-	14.4	1.17	16.8	12.30	1975		
Initial	73.7	6.2	1.31	8.12	4.73	383	53	
Final	-	14.3	1.16	16.58	12.32	1978		
Initial	75.46	6.1	1.36	8.30	4.48	318	55	
FINAL	(Heater Open Circuited on 56th Cycle)							

Definition: Initial: Reading made as timer relay energized heater circuit

Final: Reading made approximately 15 minutes before timer relay de-energized circuit

Note: 47 cycles plus 2 calibration cycles = 49 cycles of operation thus far

*Measured at power terminals outside of vacuum tank

Note: Initial room ambient resistance of heater element = 2.23 ohms

Environmental pressure variation during test = 10^{-6} mmHg range

3. Preliminary Heater Tests

As a preliminary to the selection of materials for thruster heaters, commercially available swaged Nichrome V heaters, Lot 1, Table IX, were procured and tested in air and vacuum. The purpose of these tests was to determine, quickly, the thermal gradient between the heater element and the heater sheath and to determine the expected life of commercially available heaters in vacuum at 2000°F and at power levels of 20-30 watts.

The two heaters tested in air were enclosed within a fiberglass insulating blanket so that at 2000°F on the cartridge sheath the watt input would be approximately as rated. Both heaters operated at approximately 25 watts. The temperature differential for each, as determined by measurements made on an internal thermocouple and an external one located on the cartridge sheath, was approximately 10°F; this confirmed the expected low thermal gradient and indicated that the element wire would not operate at a temperature several hundred degrees hotter than the heater sheath as had occurred in metal-encapsulated heaters containing loose wound wire on prefired ceramic core and insulator materials.

Failure of the heater element in each case occurred in 48 hours in the first turn of the element winding at the end opposite the lead end and was due to oxidation of the element wire. Also, as a result of a metallurgical examination of the failed heaters, there was found to be a chromium oxide film on the wire, being most severe

in regions adjacent to the aluminum silicate end plugs built into the heater cartridge. The oxidation may have resulted from oxygen diffusion through the aluminum silicate end plugs.

Four heaters were installed within multiple Nichrome V radiation shields in a vacuum of 10^{-6} to 10^{-7} torr and heated to a metal sheath temperature of approximately 2000°F. At a power input of 25 watts the thermal gradient was only 34 to 60°F. The life of the heaters in vacuum was better than in air; this was indicated by total test lifes of 157, 200, and 885 hours in vacuum as compared to 48 hours in air.

Testing of heater S/N4 was terminated without failure at 157 hours. In this heater, as in those which failed, an embrittling surface reaction occurred between the Nichrome V ribbon element and the fill material. In those cases where heater failure occurred, the wire was locally embrittled, and the MgO-BN fill material appeared more strongly sintered. Within the embrittling oxide core the heater wire open circuited by a localized melting; in areas away from the failure the oxide film was less, and the wire remained ductile. See Figures 50 and 51.

The reaction product was believed to be an oxide film formed by reduction of the silica impurities (approximately 3%) in the MgO fill material by the Nichrome, either by its direct contact with the ceramic grain or by metal vaporization and metal transfer to the

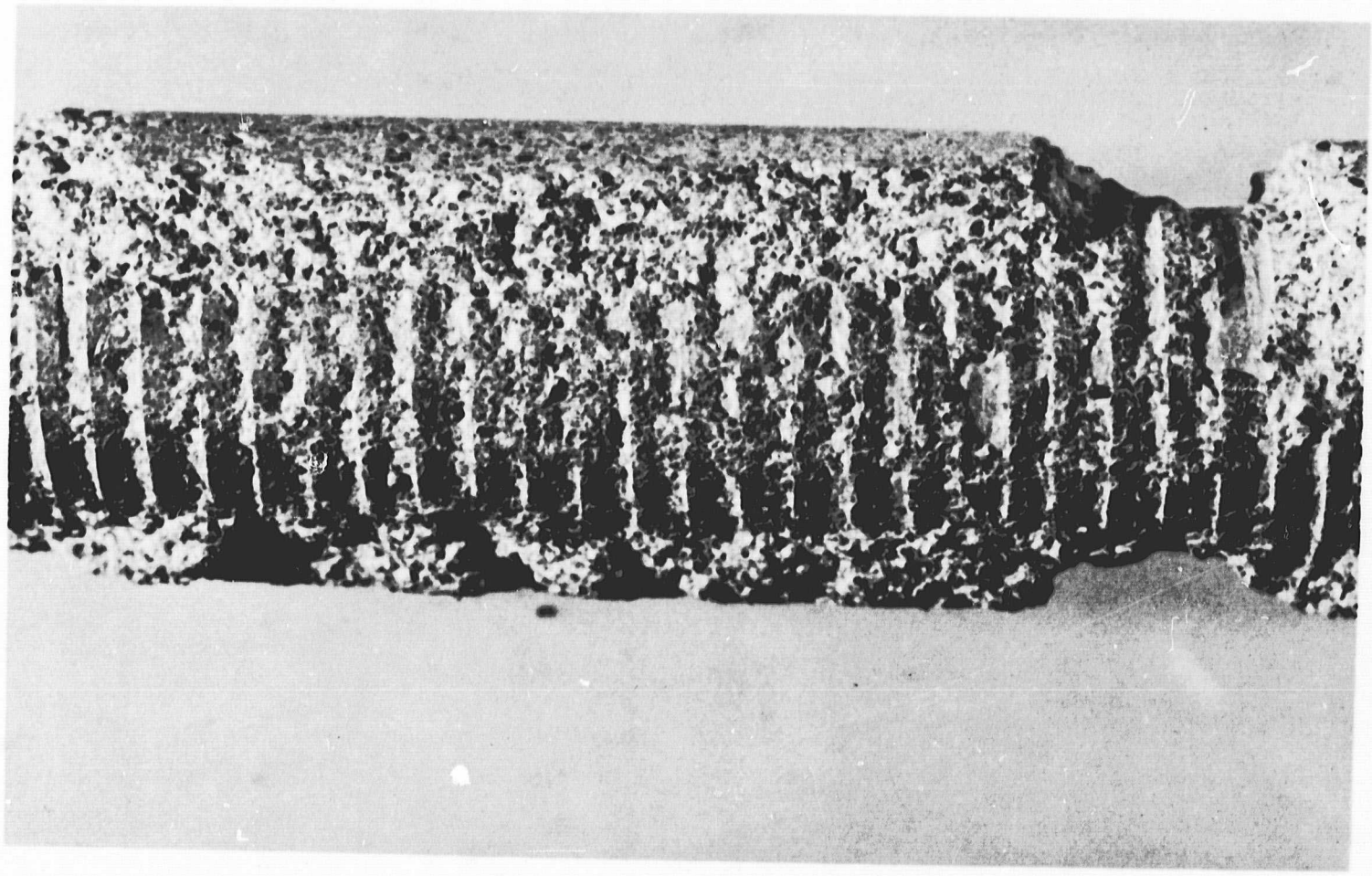


Figure 50. Failed Heater S/N 6, Failure at Right, Wire Embrittled Locally (C66011634)

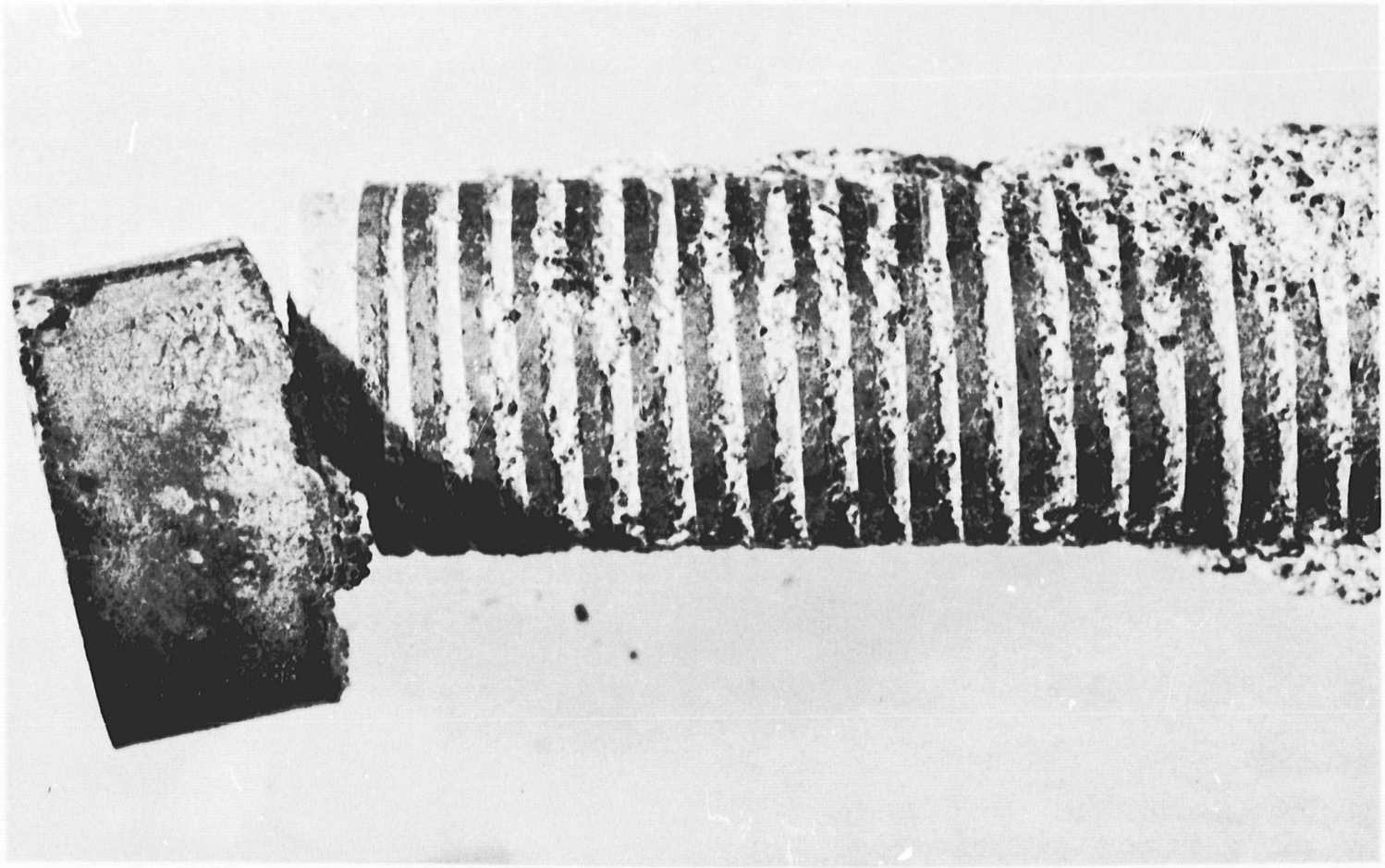


Figure 51. **Failed Heater S/N 6 Showing Region of Ductile Unaffected Wire (C66011033)**

grain. Figure 52 shows the manner in which this suggested reaction mechanism attacked the wire. Further evidences of metal vaporization from the sheath ID were deduced from the presence of a green, chromium oxide film at the interface between the sheath and the MgO-BN fill material.

In a longer-duration test of heater S/N5 for 885 hours, the good general ductility of the wire and the localized nature of failure indicated that the slightly oxidizing atmosphere, which occurred as the result of poor vacuum conditions, may have been somewhat preferred for this materials system since it tended to form an initial stable oxide film on the Nichrome V element wire that acted as a barrier to ceramic-metal reactions and to possible metal vapor transfer to the ceramic components.

The following summarizes the experience with the commercially available heaters:

1. A gross oxidation of the Nichrome V heater wire occurred under very good vacuum test conditions. It is suspected that metal vapor from the heater element may have reduced the silica impurity in the magnesia, liberating oxygen for the corrosive attack of the element wire.
2. An apparent Brinnelling of the heater wire was noted, but this appearance was more likely the result of reaction between the wire and the silica-containing MgO fill material which adhered to the wire.

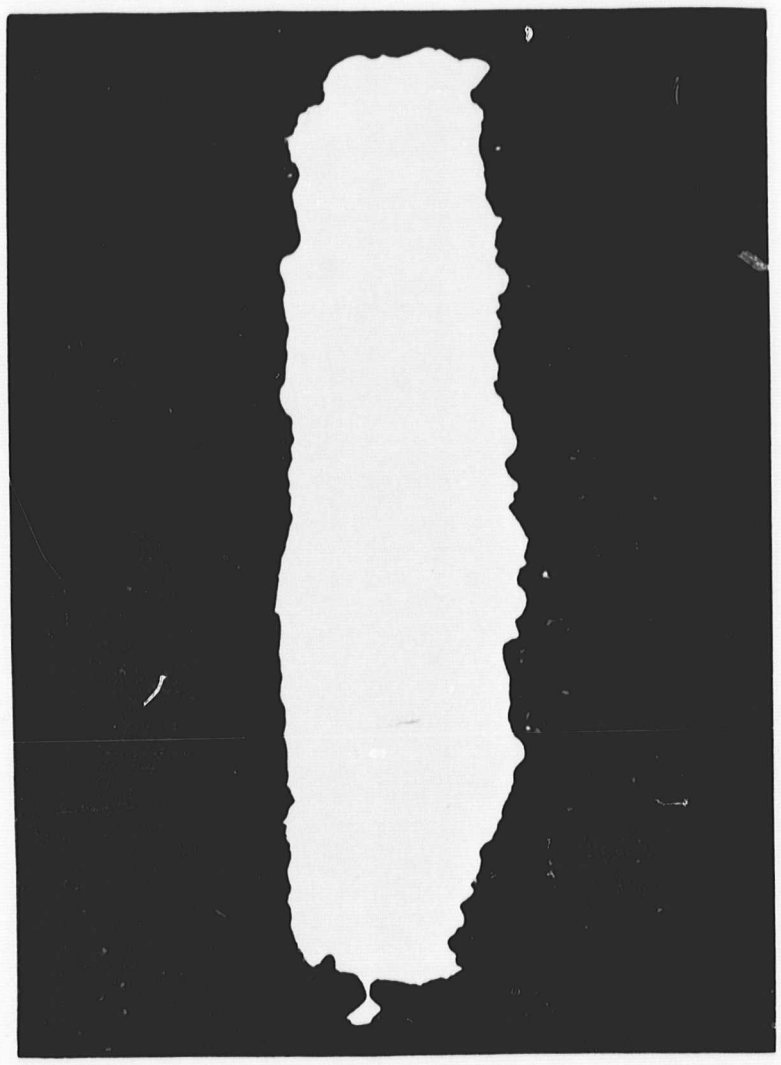


Figure 52. Cross-Section of Rectangular Nichrome V Element Wire from Early Heater, Mag. 250X After Having Been Operated at 2000°F

3. The MgO grain in the MgO-BN mixture darkened, indicating a possible reduction of the silica which it contained as an impurity.

4. The gross corrosion of the Nichrome V wire was not observed in a heater which operated in a poor vacuum. Instead, the wire failed by a local oxidation burnout, but the preoxidized film on the wire appeared to prevent the previously observed general gross corrosion of the wire.

5. Reactions between the positive power lead and the Lava "A" end plugs were observed.

4. Materials Compatibility Heater Tests

Because of the reactions reported above in commercially available swaged heaters containing Nichrome V ribbon wound on MgO cores and filled with MgO-BN mixture, several unique heaters were prepared to evaluate materials compatibility and to provide a broader base of test experience from which to choose materials for thruster component heaters. Several materials combinations were selected for trial based upon past experience but also limited to some extent by the fabrication and processing requirements for swaged heaters. These included two each of the following:

a) 1/2" diameter heaters with 0.010" diameter platinum wire on Al_2O_3 cores and filled with -100 to -200 mesh alumina (Lot No. 6).

b) 3/8" diameter heaters with molybdenum wire on MgO cores and filled with boron nitride (Lot No. 7).

c) 3/8" diameter heaters with preoxidized round 0.010" diameter Nichrome V wire on MgO cores and filled with -100 mesh MgO (Lot No. 8).

d) 3/8" diameter heaters with 0.010" diameter platinum wire on MgO cores and filled with boron nitride (Lot No.5).

All heaters were approximately 2" in length and contained Lava "A" end plugs. With the exception of the Nichrome V heaters, which had larger diameter nickel lead wires, the leads for each material were wire of the same alloy and of larger diameter (approximately 0.040 inch). A description of these and other heaters was

given in Table VII.

In the selection of materials for these heaters, it was recognized that reactions between the metal and ceramic components might occur. Although literature sources indicated the presence of metal-ceramic reactions only at much higher temperatures, the possibility of adverse reaction over long periods of time at lower temperatures was recognized. It was for these reasons that (1) the magnesia grain in the BN-MgO fill, which was employed in the commercial Nichrome V ribbon heaters, was eliminated (this MgO contained 3% SiO_2), (2) high purity alumina cores were procured even though alumina cores had several disadvantages in the manufacturing process, (3) Lava "A" aluminum silicate end plugs containing numerous impurities, which were required for manufacturing reasons, were later eliminated from the design component heaters, and (4) the MgO cores used were a relatively high purity composition which was commercially available for heater construction. The typical chemical composition and impurity levels of the various materials used, and of alternate materials not immediately available, are shown in Table XXXIV.

The vendor's commercial practices were followed in controlling the use of raw materials in heaters. Establishing a rigorous discipline involving clean rooms, separate facilities, and isolated lots of vendor materials would have imposed undue delays and costs in the program before any criteria of required control could be determined. It was expected that the materials combinations would

TABLE XXXIV

CHEMICAL ANALYSES OF CERAMIC MATERIALS FOR HEATER APPLICATION

	Al_2O_3 Fill (Norton 38 Alundum) (x)	Alumina Cores (Saxonburg St-61) (x)	#730 Al_2O_3 Core* (American Lava (y)	MgO Fill (x)	#689 MgO Core* (American Lava) (x)	BN (Carborundum HP) (x)	Lava "A"* (American Lava) (x)
Al_2O_3	99.28%	99.5% min	99.89	--	0.08		32.8%
MgO	--	0.02	0.0005	Bal	98.92		0.08
SiO_2	0.05	0.09	0.02	3.0%	0.5		56.2
Fe_2O_3	0.15	0.06	0.03	0.06	0.1		0.7
Cr_2O_3	--	0.002		--	0.001**		--
TiO_2	0.02	0.003		--	0.001		2.5
Na_2O	0.50	--	0.005	--	--		--
CaO	--	0.05	0.003	1.3	0.4		0.7
R_2O_3(total)	--	--		0.15	--		--
Water							6.6

Boron Nitride	99.5%
Chloride	0.01 max
Sulfate	0.0005 max
Ammonia	0.0005 "
Borate	0.2 "
Aluminum	0.1 "
Silicon	0.5 "
Iron	0.1 "
Magnesium	0.03 "
Calcium	0.1 "
Sodium	0.1 "
Chromium	0.1 "
Manganese	0.005 "
Titanium	0.1 "

* Typical analysis

** PbO, CuO, NiO also 0.001 or less; MnO < 0.002

(x) Used in heaters for this project

(y) Cores procured during this project

either be acceptable or that failure analysis would indicate the criteria needed for establishing more rigorous controls. The approach was to select the best availalble materials consistent with the vendor's commercial practice in order to permit the rapid evaluation of heaters for thruster component use.

Testing - The heaters described above were tested in vacuum at temperatures near 2000°F under conditions simulating the intended application. Each was enclosed within a heat shield representing a mockup of a thruster. Chromel-alumel thermocouple junctions were located on each assembly to measure temperatures within the heater, at the heater sheath surface, and on the outer surfaces of the radiation shielding. The heaters were energized to bring their internal temperatures up to the range of 2000°F. Tests on these heaters were run for a minimum of 200 hours at maximum operating temperatures near 2000°F at power levels and in heat shielding similar to that of the thruster application.

In general, the heaters filled with BN or MgO showed significantly lower thermal gradients between the heater core and the heater sheath (about 20°F) than did those heaters containing the alumina fill (as much as 100°F). The high thermal conductivity of the BN and the ability of both BN and MgO fill materials to swage to a high density were contributing factors to these low thermal gradients. On the other hand, the alumina fill materials (and the alumina cores) did not swage to such high densities, and as a result they provided a

greater barrier to heat flow and more readily allowed the diffusion of metal vapors through these ceramic components.

The hot resistance of the heater wires appeared to increase with time. The most apparent trend was in the platinum wire heaters S/N3A and 3B (Lot No. 6); in these heaters the porous alumina fill permitted the diffusion of chromium metal vapor to the platinum wire element where the chromium alloyed with the platinum to increase the wire resistance. The least apparent change in hot resistance was in the preoxidized Nichrome V wire heaters S/N7 and 8 (Lot No. 8). Because of the high swaged density of both the BN fill and the crushable MgO core of the platinum element heaters S/N2A and 2B (Lot No. 5), the hot resistance of these heaters was also stable since the element was isolated from a source of contaminating metal vapors.

Heater Evaluation - After the 200-hour test period, the heaters were cut open and examined, both under high power binoculars and in selected metallographic examination.

1. Platinum-Alumina Heaters (Lot No. 6) - Two additional heaters featuring 0.010" diameter platinum wire wound on alumina cores and filled with -100 mesh alumina powder were tested. Heater S/N3B was tested for 196 hours at 2000°F. The heater did not burn out, but its cold resistance increased approximately twofold after testing. Chromium oxide was observed along the inner surface of the swaged sheath, but the alumina fill was apparently unaffected. The coarse-

crained, -100 mesh alumina, which was used because of its flowability in filling the swaged heater, had Brinnelled the platinum wire and may have contributed in a minor way to the increase in resistance. This Brinnelling effect is shown in Figure 53. The second heater, S/N3A, was operated at a surface temperature of 2000°F for 14 hours and at 2200°F for 183 hours. A metallic film was noted on the Lava "A" plug at the cooler, exit side of the plug between the sheath and the plug; this demonstrated the vapor phase transfer of chromium and nickel from the inside surface of the sheath. The vaporization of the sheath toward the interior of the heater was further indicated by the presence of pink and red crystals of an alumina-chromium oxide solid-solution phase produced by chromium vapor reaction with the alumina. Green chromium oxide of a more intense form was noted at the inside surface of the sheath. The effects of this mass transfer resulted in alloying of the platinum with chromium from the sheath to increase the heater wire resistance by a factor of three; this was confirmed by spectrographic analysis. The ductility of the wire was not seriously reduced except in a few places where incipient melting within the wire appeared to have occurred. More severe Brinnelling of the platinum wire was noted at this higher temperature as is shown in Figure 54.

2. Molybdenum-MgO Heaters on MgO Cores (Lot No. 7) - These heaters exhibited an initial fabrication difficulty which prompted their immediate disfavor. During swaging, the high elastic modulus, high



Figure 53. Heater S/N 3B Showing Pt Wire Element, Mag. 20X, After Operation at 2000°F for 200 Hours. (C66022451)

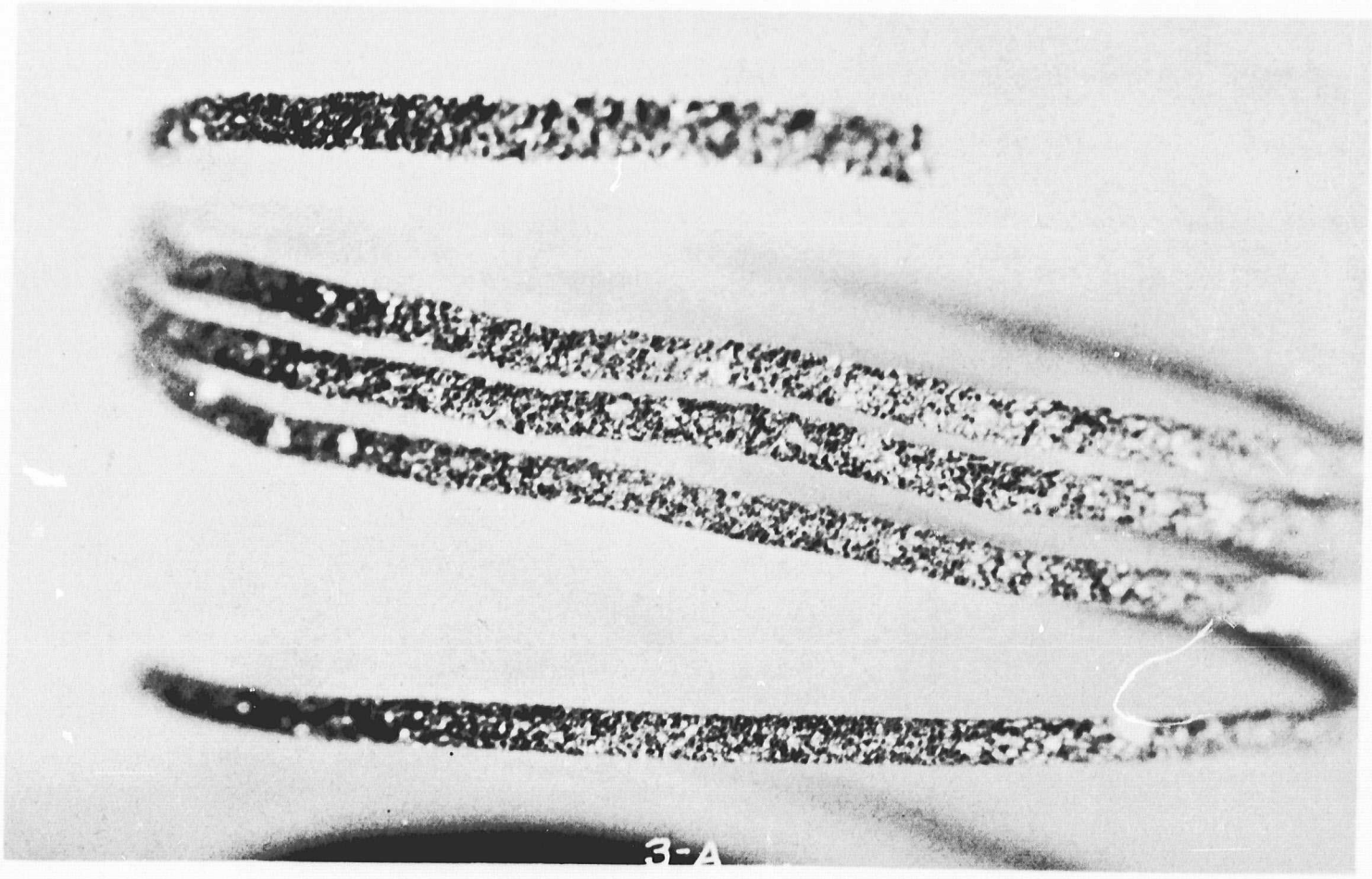


Figure 54. **Heater S/N 3A Showing Pt Wire Element Mag. 20X After 200 Hours at 2200°F. (C66022448)**

yield strength, and low ductility of the molybdenum wire prevented a uniform reduction in the diameter of the resistance wire coil; instead, the wire buckled locally as the heater was compressed in swaging. This was observed in initial X-radiographs of the heaters and is shown in Figure 55, a photograph of the heater core and molybdenum wire after testing was completed and the sheath and fill material were removed. The severity of this undesirable effect could not be predicted with accuracy; the possibility existed of developing direct electrical shorts between the molybdenum wire and the sheath. The decision not to use molybdenum wire was necessary, but regrettable, since the two heaters, S/N4A and 4B, were operated successfully for 287 and 206 hours, respectively, and evidenced only a 0.06-ohm increase in wire resistance. Also, there was no observable chemical reactions or vapor phase transfer in these heaters. Since more ductile molybdenum-rhenium alloy wire was not immediately available and it was necessary to select materials for the prototype thruster heaters at this point, no new materials compatibility heater tests on ductile molybdenum alloy wire were initiated.

3. Preoxidized Nichrome V Heaters (Lot No. 8)- Heater S/N8 was fabricated with preoxidized Nichrome V wire wound on a MgO core and surrounded with -100 mesh MgO fill material. This heater was brought to temperature in 22 hours and held for 208 hours at 2000°F. The MgO had developed a gray color in contrast to its original tan color and had developed a strongly sintered mechanical strength. The wire was ductile over its entire length, and failure had not

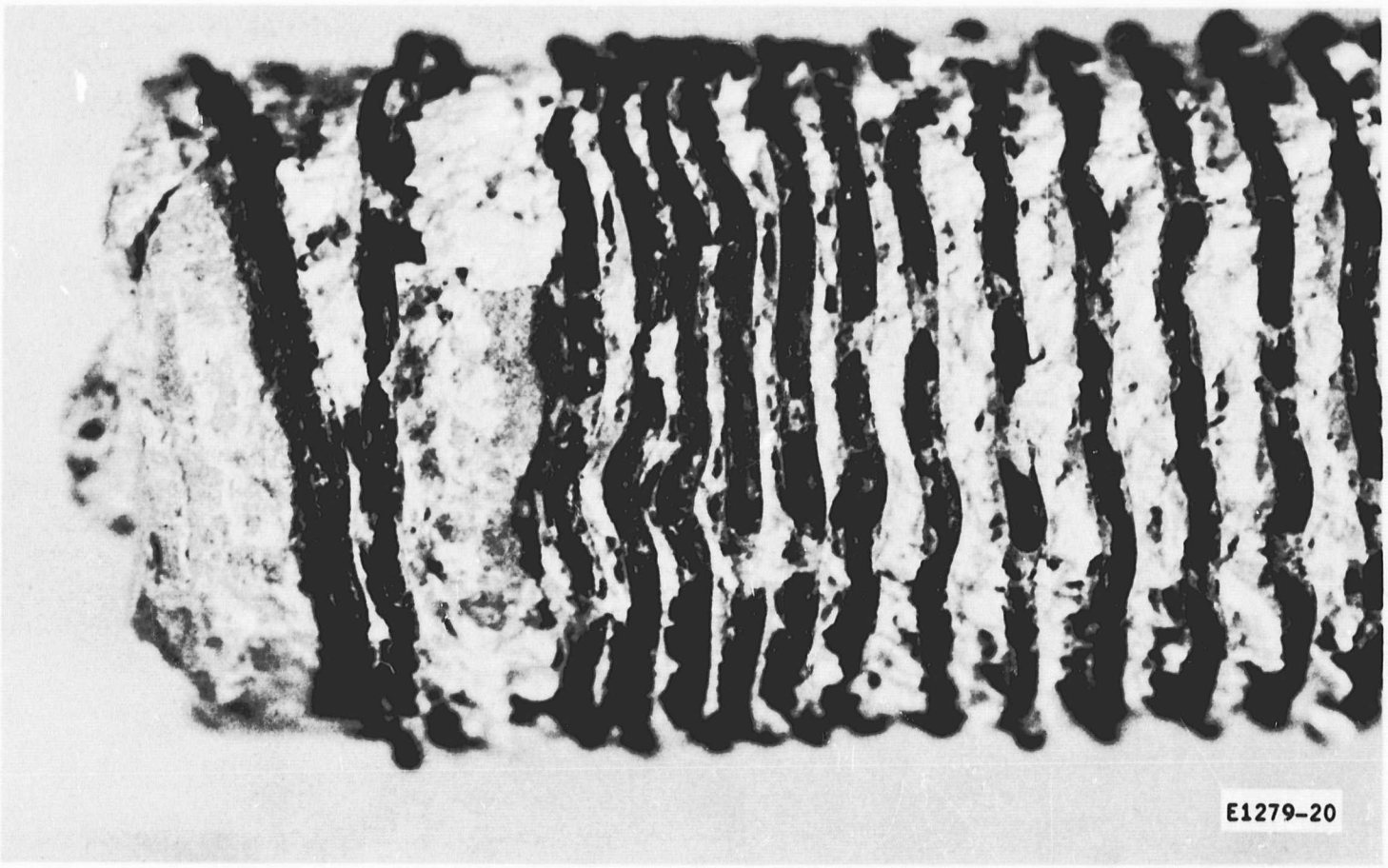


Figure 55. Molybdenum Wire Heater S/N 4B After 2000°F Test and Removal of Sheath and MgO Fill Material. Note Waviness in Wire Produced During Swaging of the Heater.

Mag: 15X (C66030824)

occurred. A reaction was noted in the Lava "A" plug at the positive power lead. A trace of green chromium oxide was observed on the MgO core underneath the first several turns of wire near the heater end opposite the power leads. The stability of the preoxidized wire in the presence of MgO was indicated by the ductility of the wire and by the lack of extensive oxidation corrosion, as indicated in Figure 56. A sample of unoxidized Nichrome V wire taken from a swaged heater is shown in Figure 57. While some surface contamination was observed in the former micrograph, it was not extensive.

A similar preoxidized Nichrome V heater, S/N7, was tested at 2000°F for 132 hours and for an additional 177 hours at 2100°F to test the effect of preoxidation in avoiding the catastrophic corrosion previously noted in unoxidized wire heaters of this type. The heater did not fail; the wire was ductile. Some chromium oxide was observed under the first three turns of wire at each end of the heater. A reaction product was noted between a thermcouple lead and the Lava "A" end plug; the usual positive power lead reaction with the Lava "A" was also observed. Because of the higher temperature and longer operating time, the preoxidized surface of the wire showed a greater degree of instability than did the previously tested heater as shown in Figure 58. Although these preoxidized heaters performed in a highly reliable manner, the trend toward oxide formation at the wire-magnesia interface and the changes in the wire oxide film were not encouraging, and this materials combination was rejected in favor of the more stable platinum-magnesia-boron nitride

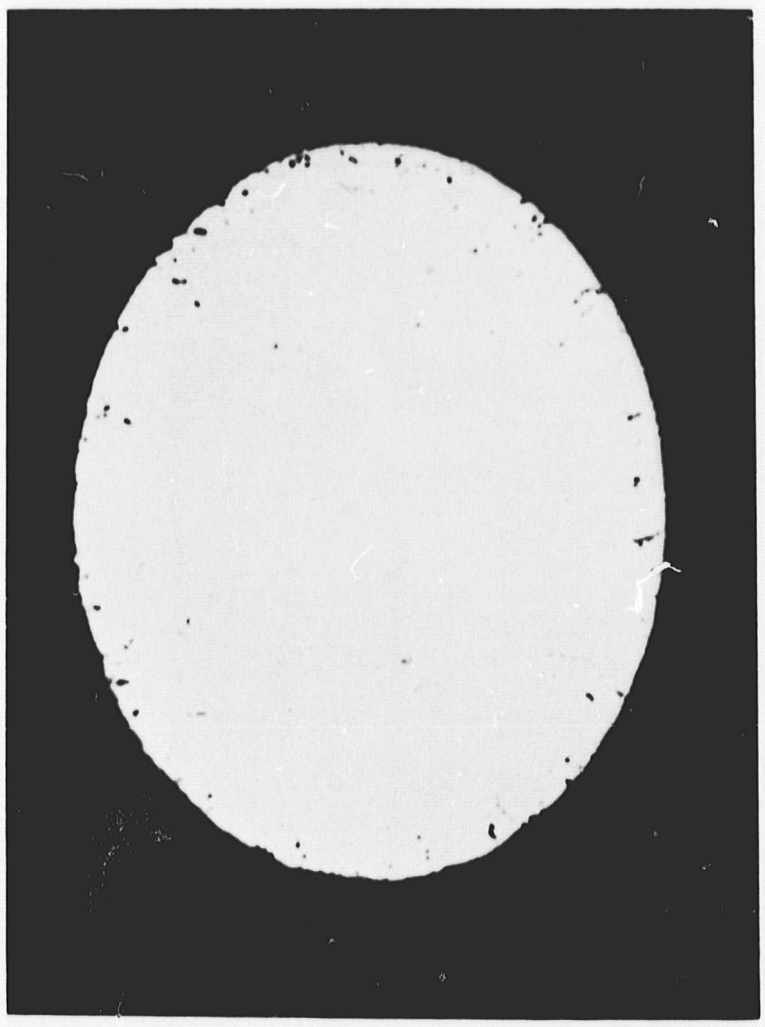


Figure 56. Cross-Section of S/N 8 Pre-Oxidized Nichrome V Wire, Mag. 250X, After 208.3 Hours at 2000°F.(B440112)

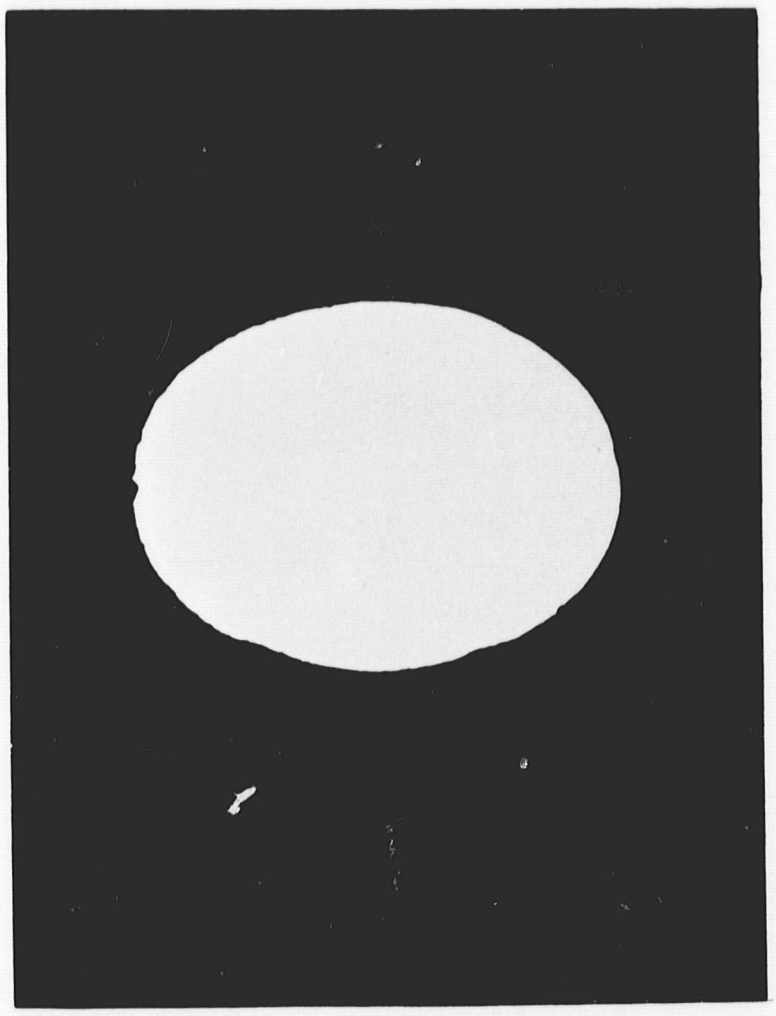


Figure 57. Nichrome V Element Wire from Unused Heater, Cross-Section Mag. 250X. (B140112)



Figure 58. Cross-Section of Pre-Oxidized Nichrome Element Wire, Mag. 250X, After 308.35 Hours at 2000-2100°F. (B510111)

materials combination.

4. Platinum-BN Heaters on MgO Cores (Lot No. 5) - A platinum wire heater, S/N2A, on a MgO core with BN fill was tested for an initial period of 200 hours without significant change in resistance. The densely compacted, high thermal conductivity BN provided a low temperature gradient between heater element and outer sheath temperature; its swaged density evidently prevented metal vapors from the sheath from penetrating to the platinum wire and changing the heater element resistivity by alloying with the platinum. A second heater of this type, S/N2B, was inspected after operating 200 hours at 2000°F without failure. The heater wire was clean, ductile, and not Brinnelled. The BN fill material was densely packed around the heater wires. The Lava "A" plug, as in all other heaters, had a reaction zone around the positive power lead.

The stability of the platinum-MgO-BN heater system was very encouraging at this point. The packed density of the fill material was significant when it was considered along with the stability of the platinum wire resistance and the low temperature drop from core to sheath. It suggested that similar improvements could be made in an all-alumina ceramic system if manufacturing difficulties could be overcome in using fine-grained alumina as the fill material. Effort along this line was continued for some time, and additional tests were conducted on all-alumina heaters and alumina core, boron nitride fill heaters; these tests are described under the section on long-

duration heater tests. The possible necessity of using some material other than nickel-base alloys (for vapor pressure reasons) was also considered. As the materials compatibility work was continued to indicate optimum combinations of materials selections, longer duration testing, described below, was undertaken to insure long-time heater reliability. Since the preliminary evidence indicated the MgO core, Pt wire, BN fill heater materials combination was most promising, this system was emphasized for prototype heaters.

In summary, the principal materials selected for prototype heaters were:

a) Hastelloy-X sheaths and end plugs;

b) MgO cores;

c) Boron nitride fill;

d) Pt-10% Rh wire elements;

e) 1/2 hard Pt-10% Rh power leads.

While some heater materials compatibility experience was achieved, the intent of this portion of the program was to concentrate upon the development of a satisfactory 2000°F heater. All the possible interrelating combinations of variables of materials purity, interactions between components, fabrication techniques, etc. were not explored in a systematic way nor were side experiments purposefully designed to effect an increased understanding of the real limits in the use of materials. Undoubtedly, some of the alternative approaches, which were set aside, could be developed to provide materials systems that

might more economically approach the usefulness of the above system which appeared most promising.

5. Manufacturing Development

The thruster configuration heaters required some modifications in manufacturing processes and heater construction methods in order to achieve the general design configuration shown in Figure 59. These heaters were developed in their desired configuration in a progressive manner, first, using commercially available materials such as Nichrome V ribbon, nickel wire power leads, and an Inconel 600 sheath. Magnesia cores and boron nitride fill were used in the preparation of these initial prototype heaters, which are shown in Figure 60. In this early heater the unheated portion of the cartridge was thermally insulated with a magnesia core which was originally less than full diameter and which was not intended to densify during swaging. An organic fiber plug, held in place at the open end of the heater by the circumferential dimple in the sheath, served to restrain the movement of ceramic materials from the sheath during swaging. This fiber plug was removed by burnout in air at 1000°F. When Pt-10% Rh wire was used in the later development heaters, movement of the Lava "A" plugs at the ends of the insulated MgO section resulted in local stretching and necking of the wire. An example of this type of localized deformation is shown in Figure 61. To prevent this problem, the low-density MgO unheated section of the cartridge was eliminated and replaced by a full-diameter MgO core which was swaged to a density approaching that of the heater core itself. In order to minimize the possible recurrence of necking of these power leads, the fully annealed

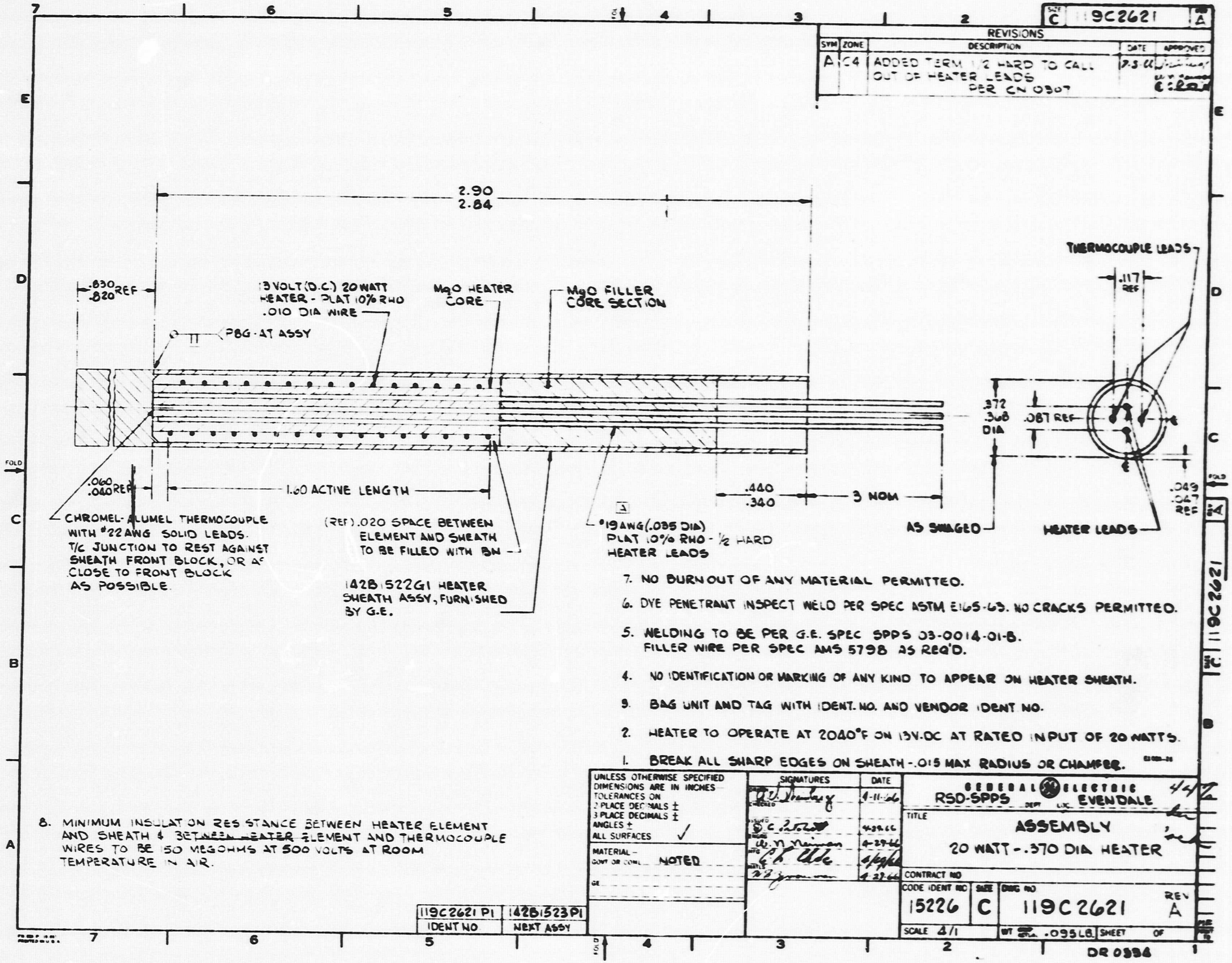


Figure 59 Outline Drawing, 20 Watt 2000°F Heater (119C2621)

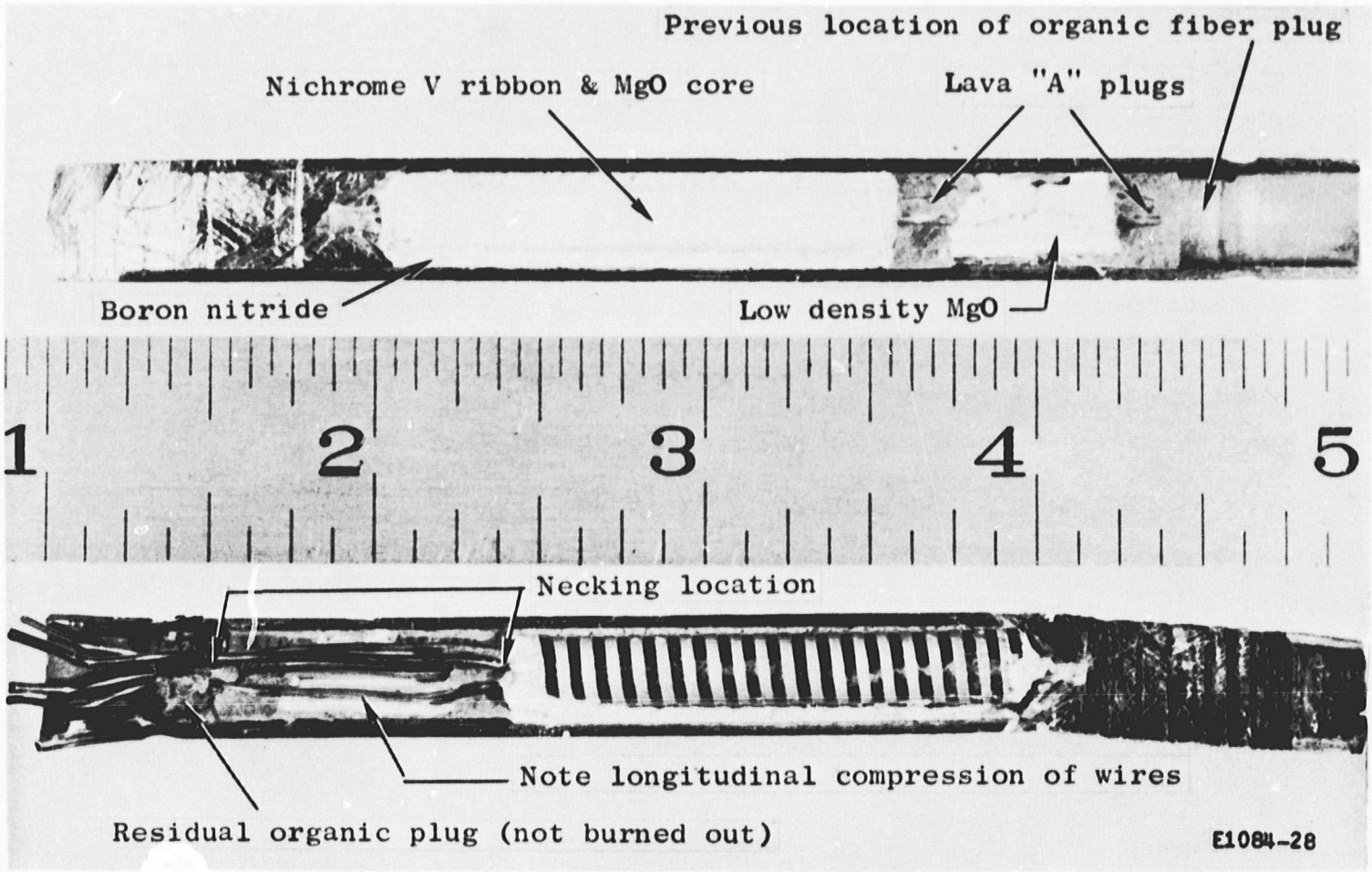
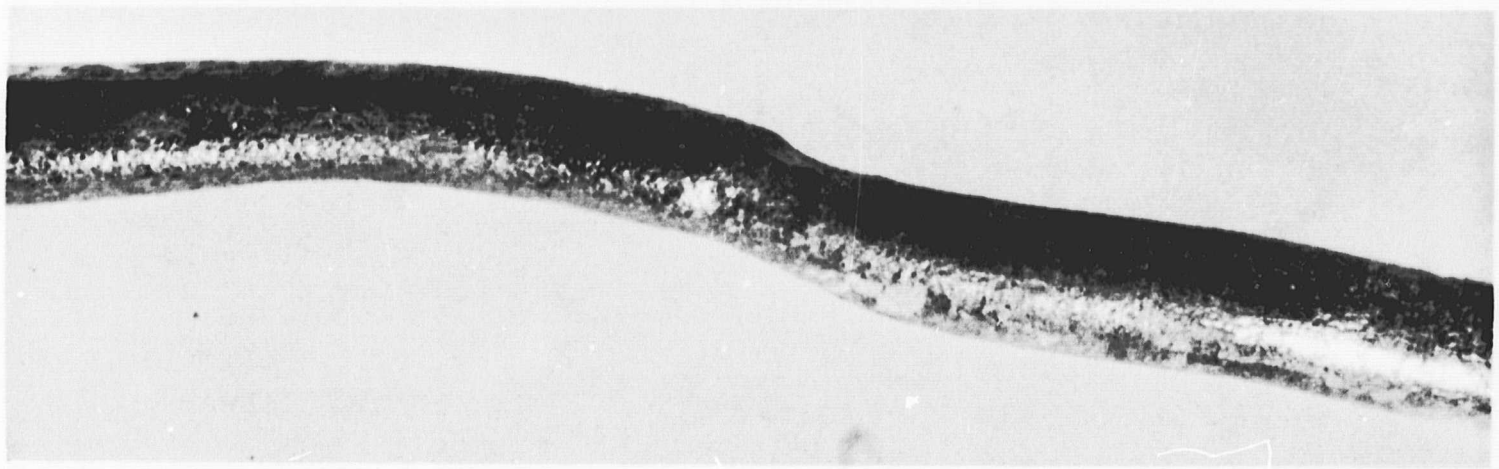


Figure 60. 30 Watt Nichrome V Heaters in Swaged Inconel 600 Sheath (C66041450)



E1084-29

Figure 61. Reduced Cross Section in Platinum-10% Rhodium Power Lead Wire Caused by Swaging Forces Within the 2000°F Thruster Configuration Heater. (C66041982)

Pt-10% Rh leads were replaced by the same material in the 1/2 hard condition. The need for the Lava "A" plugs and both the circumferential dimple and fiber plug were eliminated; the swaged MgO core insulation was terminated about 3/8 to 1/2 inch from the open end of the heater.

Axial heat losses by conduction along the length of the unheated portion of the cartridge were reduced by grinding the cartridge OD to a smaller dimension, thus reducing the wall thickness as shown in Figure 62.

During the development of these long heaters, minor cracking of the welds occurred at the joint between the sheath and the solid-metal end plug during the swaging operation. A modification in weld joint configuration produced sound welds, free from cracks after swaging.

The final thruster configuration heaters in the as-received condition are shown in Figure 63. These are made of Pt-10% Rh, 10-mil diameter element wire wound on a MgO core. The fill material between the element wire and the Hastelloy X sheath was boron nitride. The power leads were made of Pt-10% Rh wire. As received, the heaters were nominally 3/8" in diameter. The 20-watt heater was procured in accordance with G. E. Drawing 119C2621; the 30-watt heater was procured in accordance with G. E. Drawing 119C2634. Both had a Chromel-Alumel thermocouple junction located within the magnesia core near the closed end of the heater cartridge.

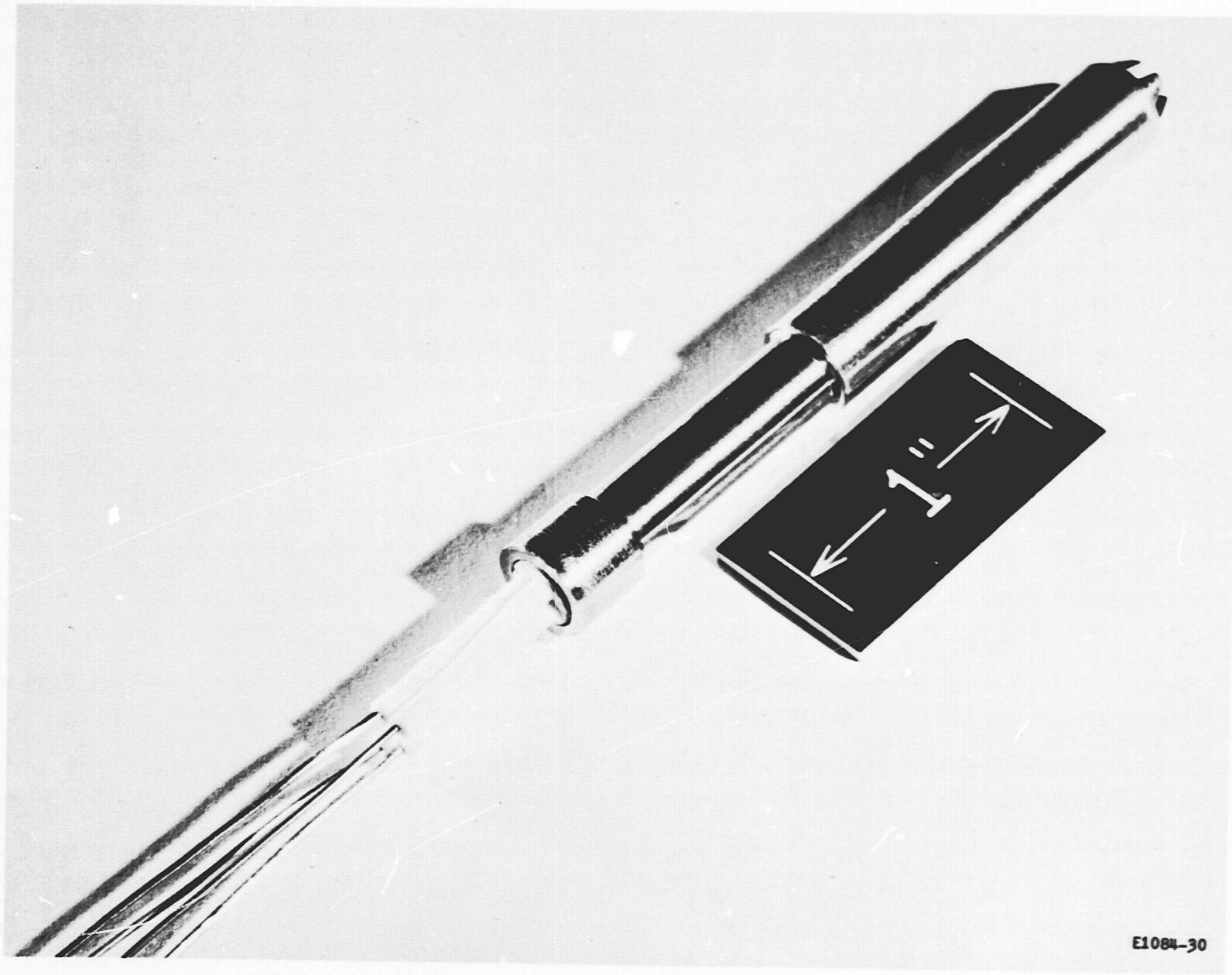


Figure 62. 20 Watt, 2000°F Heater Machined for Insertion into Thruster. (C66050538)

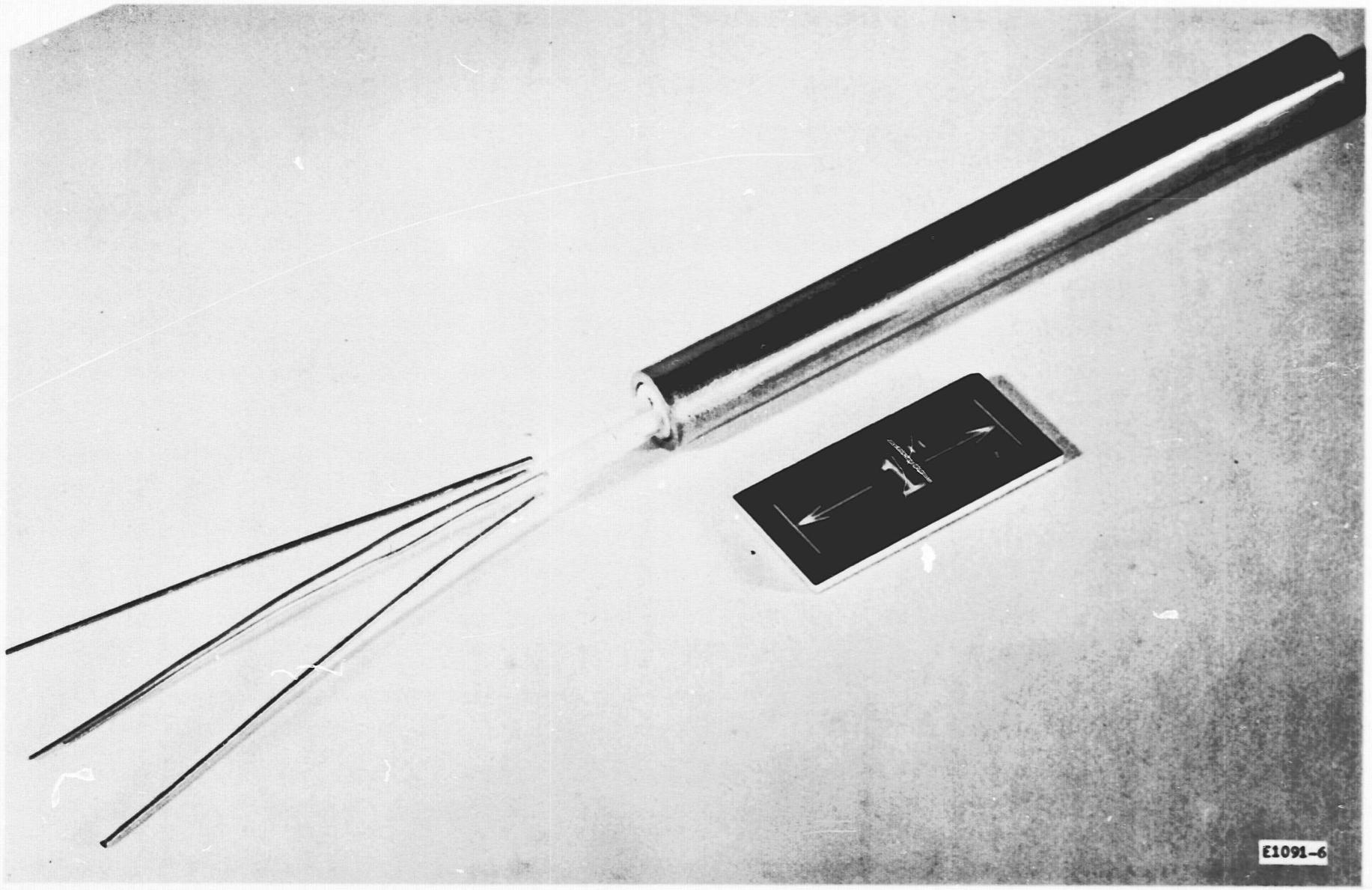


Figure 63. Thruster Configuration Heaters, Selected Materials, 20 and 30 Watt, 2000°F as Received From the Vendor. (C66050322)

Insulation resistance measurements have been made across the power leads and the various electrical insulators of selected heaters at temperatures of 2000°F. Adequate values of resistance were observed for the various ceramic insulations. Resistance measurements were made on a 1/2" diameter heater (S/N 18), featuring Pt-10% Rh wire wound on an alumina core with boron nitirde fill, and on a final configuration 30-watt, 3/8-inch-diameter heater (S/N 25), featuring Pt-10% Rh wire wound on a magnesia core and filled with boron nitirde.

The insulation resistance measurements were made using a General Radio Company Type 1650-A impedance bridge supplied by a 90-volt external DC power source. The heaters were installed within a tantalum resistance heated vacuum furnace and raised in temperature to 2000°F. Resistance measurements were made using wire leads into the vacuum furnace which were connected to appropriate parts of the heater. Care was taken to minimize the use of electrical insulators on the lead wires in the hot portion of the furnace, a condition which would have provided unwanted ceramic resistance paths in addition to the ceramic insulators in the swaged heaters themselves. The resistance data are given in Table XXXV. In most cases, the final resistance values were approached very slowly since conductance in the insulator progressively decreased as ions migrated toward the electrodes under the influence of the 90-volt applied DC potential of the resistance measuring instrument.

TABLE XXXV

INSULATION RESISTANCE OF HEATERS

Heater	Test Temp. °F	Resistance - ohms							
		Pt-10% Rh Element		Between Element & Thermocouple Wire			Between Element Wire & Case		
		50V	90V	50V	90V	500V	50V	90V	500V
S/N 25, 3/8" Dia. 30 Watt, MgO Core, BN Fill	Room	2.13	2.4	∝	∝	200K meg	∝	∝	100K meg
	1895	--	5.7	--	139K	--	--	236K	--
	2000	--	5.7	--	32.3K	--	--	24.6K	--
S/N 18, 1/2" Dia. Al_2O_3 Core, BN Fill	1760	--	--	--	5.62 meg	--	--	2.21 meg	--
	1920	--	--	--	0.91 meg	--	--	0.755 meg	--
	2010	--	--	--	0.38 meg	--	--	0.258 meg	--

Based upon an estimate of resistance leakage paths in the 1/2-inch-diameter alumina core, boron nitride fill heater, the 2000°F resistance of the alumina core was calculated from published resistivity values as 0.68 megohms and the boron nitride fill insulation was similarly calculated as 1.03 megohms. The observed values of 0.38 megohms and 0.258 megohms for the core and fill, respectively, correlate reasonably well with these calculated values.

These measured resistance values indicate the adequacy of the selected materials for the 2000°F heater application. Current leakage at the expected heater voltages should be of no serious consequences.

c. Long-Duration Tests

Following the preliminary short-time heater tests for the evaluation of various heater materials combinations and shortly after the materials decision had been made regarding prototype heaters, addition heater testing was initiated with emphasis on tests of longer duration and on continuing evaluation of alumina component heaters. These tests included:

Alumina Heater	S/N13	Pt/Al_2O_3/BN/Inconel 600	- 205 Hrs.
Alumina Heater	S/N16	Pt/Al_2O_3/BN/Inconel 600	- 2,595 Hrs.
Alumina Heater	S/N19	Pt/Al_2O_3/BN/Inconel 600	- 1,437 Hrs.
Alumina Heater	S/N18	Pt/Al_2O_3/Al_2O_3/Inc. 600	- 252 Hrs.
Prototype Heater	S/N20	Pt-10%Rh/MgO/BN/Inc. 600	- 1,549 Hrs.
Prototype Heater	S/N28	Pt-10%Rh/MgO/BN/Inc. 600	- 1,551 Hrs.
Materials Comp. Heater	S/N2A	Pt/MgO/BN/Inconel 600	- 6,607 Hrs.

Heater Evaluation - Heater S/N13, a platinum wire heater wound on an aluminum core and compacted with boron nitride fill, was evaluated after 205 hours of test operation at 2000°F. The resistance stability was good during the 205-hour test. There was a very small DC discoloration effect around the Lava "A" end plug; the wire in the heating element was still ductile, and there were no green or pink discoloration products in the BN fill or Al_2O_3 core components. An identical heater, S/N16, which ran without failure for 2 595 hours, had an increase in cold resistance of 14.8% after 1 151.7 hours of test; spectrographic examination confirmed that high

vapor pressure alloying constituents such as chromium and other impurity elements from the chromel-alumel thermocouple materials within the core penetrated the porous alumina core and alloyed with the platinum element, increasing its resistance. However, the element wire was still ductile as determined by a simple trend test.

Heater S/N 19 featured an alumina core, -200 mesh alumina fill, platinum-10% rhodium wire, and an Inconel 600 sheath. After testing for 1437 hours at temperatures to 2000°F, the heater appeared as shown in Figure 64 after it was opened. The platinum wire was still ductile. The positive lead wire was embrittled and failed in handling at the Lava "A" end plug where DC migration effects were noted.

An all-alumina heater, S/N 18, was tested for 220 hours at temperatures to 2000°F. This heater was constructed with -200 mesh alumina fill and was subjected to swaging reductions greater than usual in an effort to achieve better fill characteristics; but the resistance increase of 128% indicated, once again, the permeability of the alumina fill to metal vapors from the sheath material. Although the alumina fill in contact with the sheath had a pink coloration, there was no evidence of pink or green colorations within the remaining alumina fill as had been observed in previous alumina fill heaters. The platinum heating element wire was still ductile, but seemed to be more stiff than before test. The platinum lead wires had developed cracks and partially failed

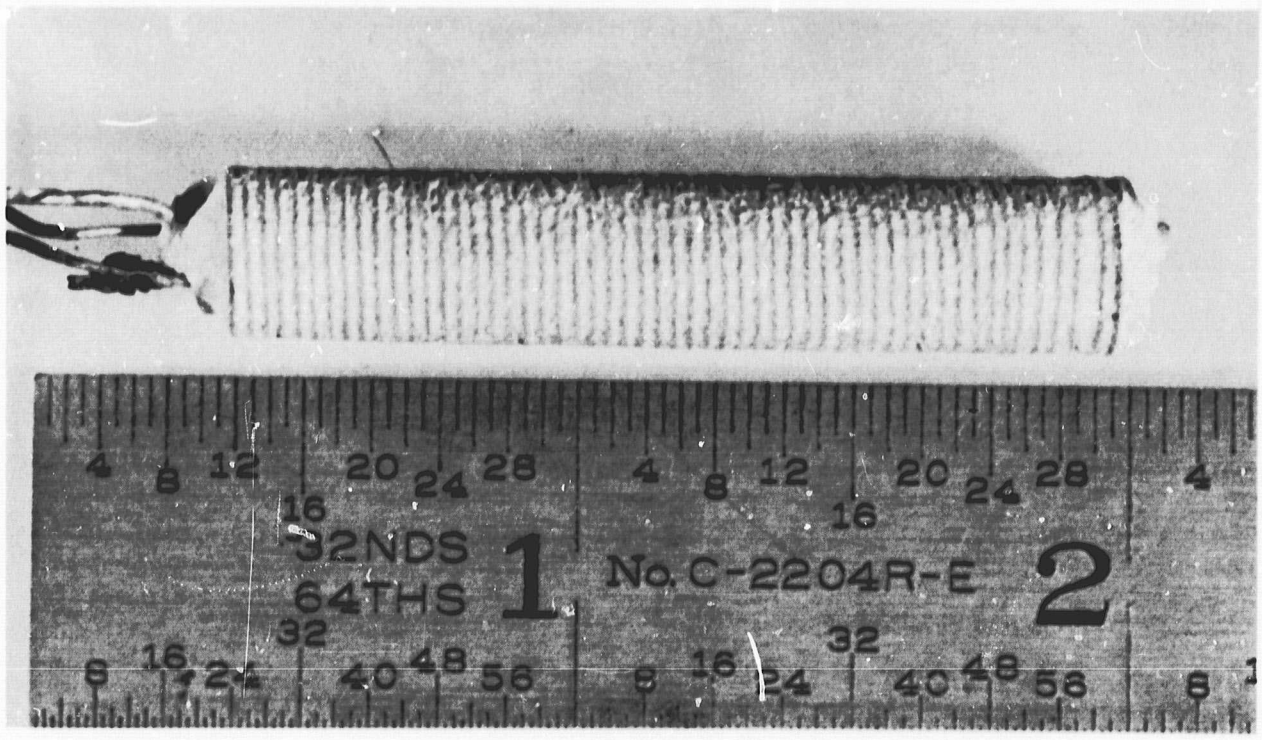


Figure 64. Heater S/N 19 Featuring Al_2O_3 Core, -200 Mesh Al_2O_3, Pt-10% Rh Wire and Inconel 600 Sheath, After 1437 Hours Testing to 2000°F.

at the outer edge of the Lava "A" end plugs as shown in Figure 65. The ceramic end plug, itself, had developed a pronounced, blackened area around the lead wires as shown in Figure 66.

A 20-watt and a 30-watt prototype heater (S/N20 and S/N28) were evaluated after about 1500 hours testing at 2000°F. The outer appearance of these heaters after testing are shown in Figure 67 and 68. They were opened carefully by means of longitudinal and circumferential cuts in the sheath, using a silicon carbide cutting wheel, and a detailed binocular inspection was made.

Heater S/N20 was (1) tested for 1549 hours at temperatures near 2000°F, (2) thermal cycled four times between room temperature and 2000°F and, (3) exposed to atmospheric pressure on three occasions while at temperature. The outer Hastelloy X sheath appeared somewhat porous, indicating the possible evaporation of some higher vapor pressure element. Minor sheath cracks (which will be discussed further below) were evident. There was no evidence of reaction between the sheath and the ceramic components. The appearance of the core is shown in Figure 69. The platinum wire was still smooth and bright at the lead wire end of the heaters, but a frost-like surface deposit was apparent in various locations, particularly at the plug end of this heater. This variation between lustrous and frost-like appearance can be seen in Figure 70. A severe surface corrosion effect was observed in the heater wire at the plug end of the heater as shown in Figure 71. The changed surface appearance of the wire, as determined by binocular inspection,

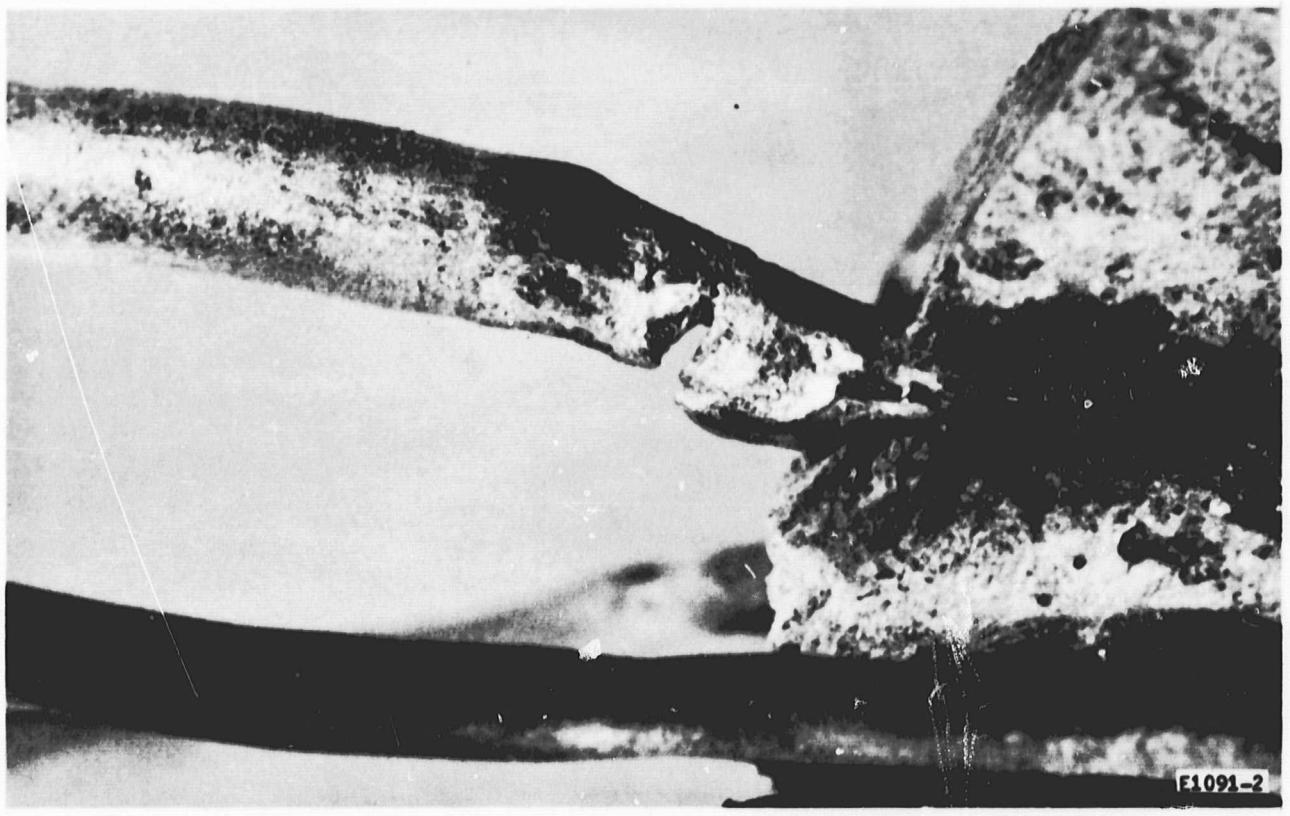


Figure 65. Platinum Lead Wire From All-Aluminum, Pt-10% Rh Heater, S/N 18 After 220 Hours of Operation at 2000°F. (C66060602)

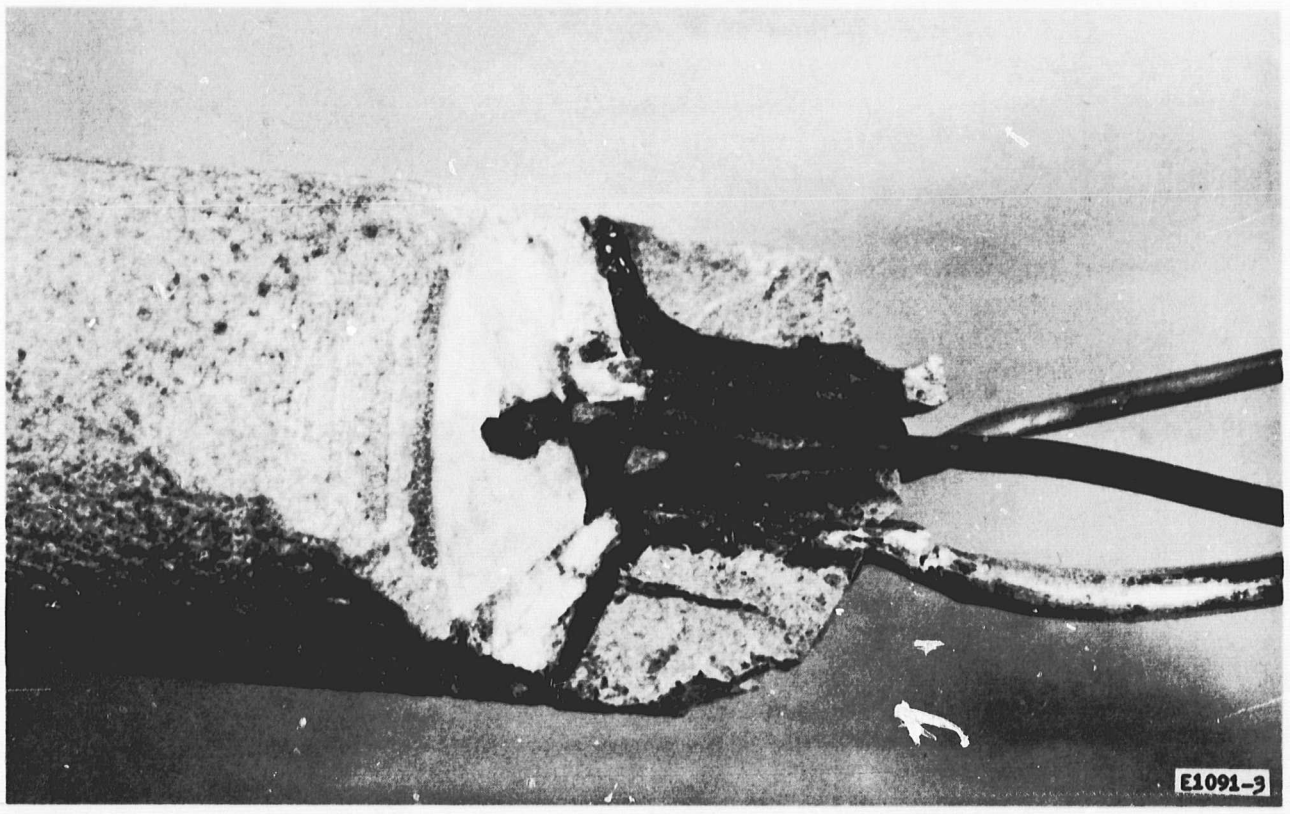


Figure 66. All Aluminum, Pt-10% Rh Heater S/N 18 with 200 Mesh Al_2O_3 Fill and Lava "A" End Plug After 220 Hours Testing at 2000°F. Note Granular Surface Appearance of Heater Wire, Blackening of Lava "A" Plug and Apparent Embrittlement of Platinum Wire. (C66060603)

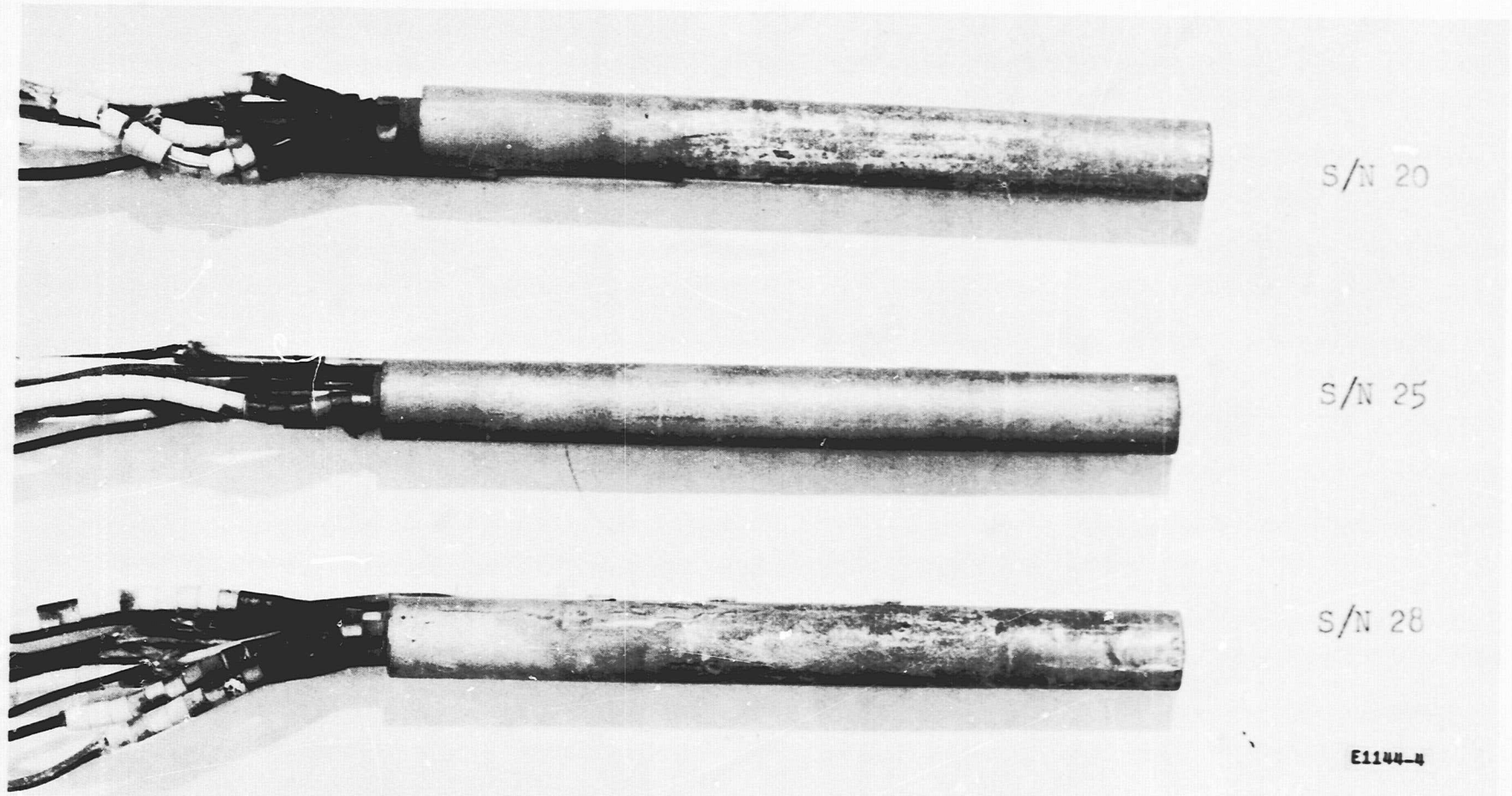


Figure 67. Heater S/N 20, S/N 25, and S/N 28 After Testing as Viewed From Instrumented Side. (C660816116)

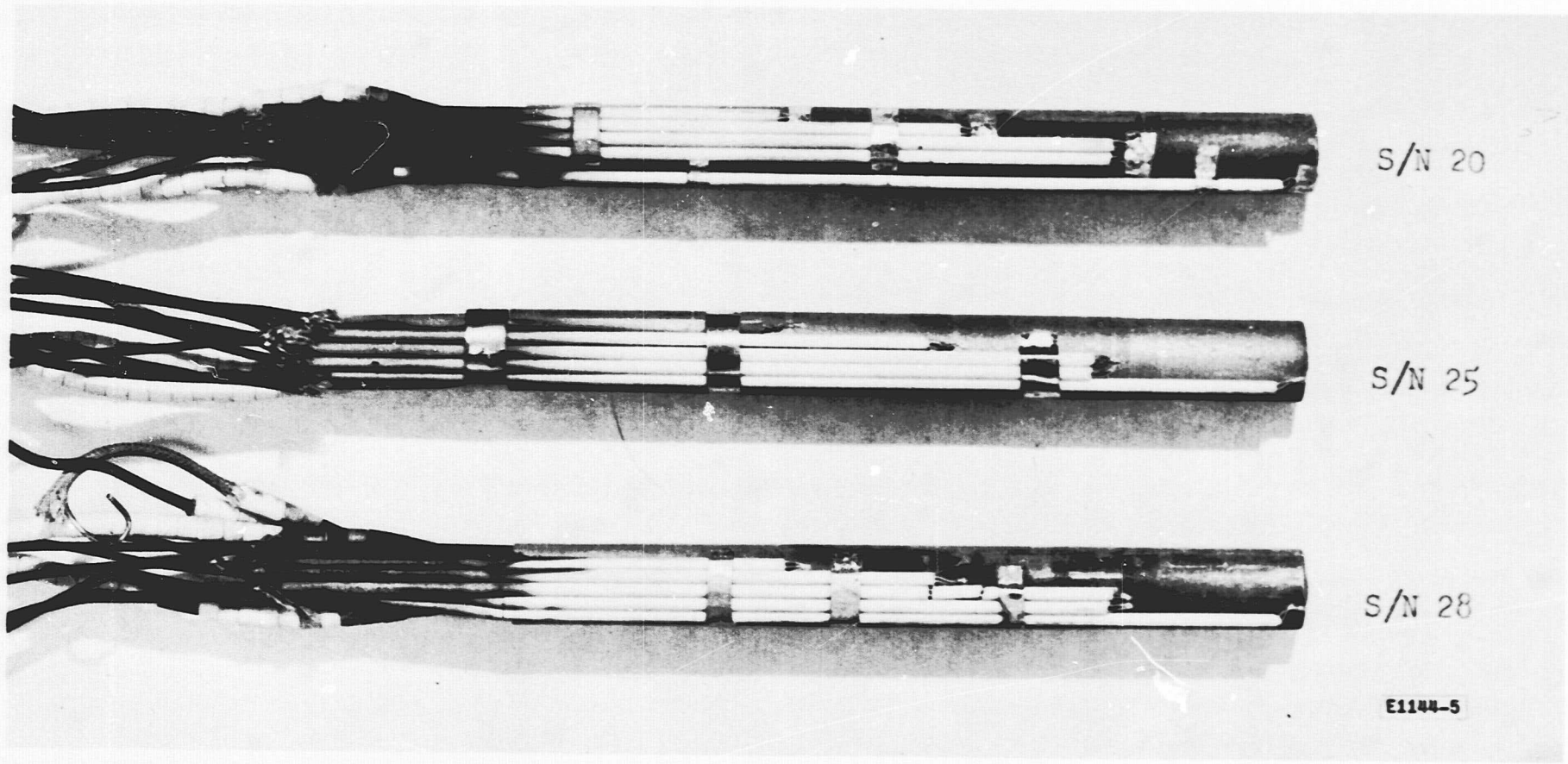


Figure 68. Heaters S/N 20, S/N 25, and S/N 28 After Testing as Viewed From Instrumented Side. (C660816117)

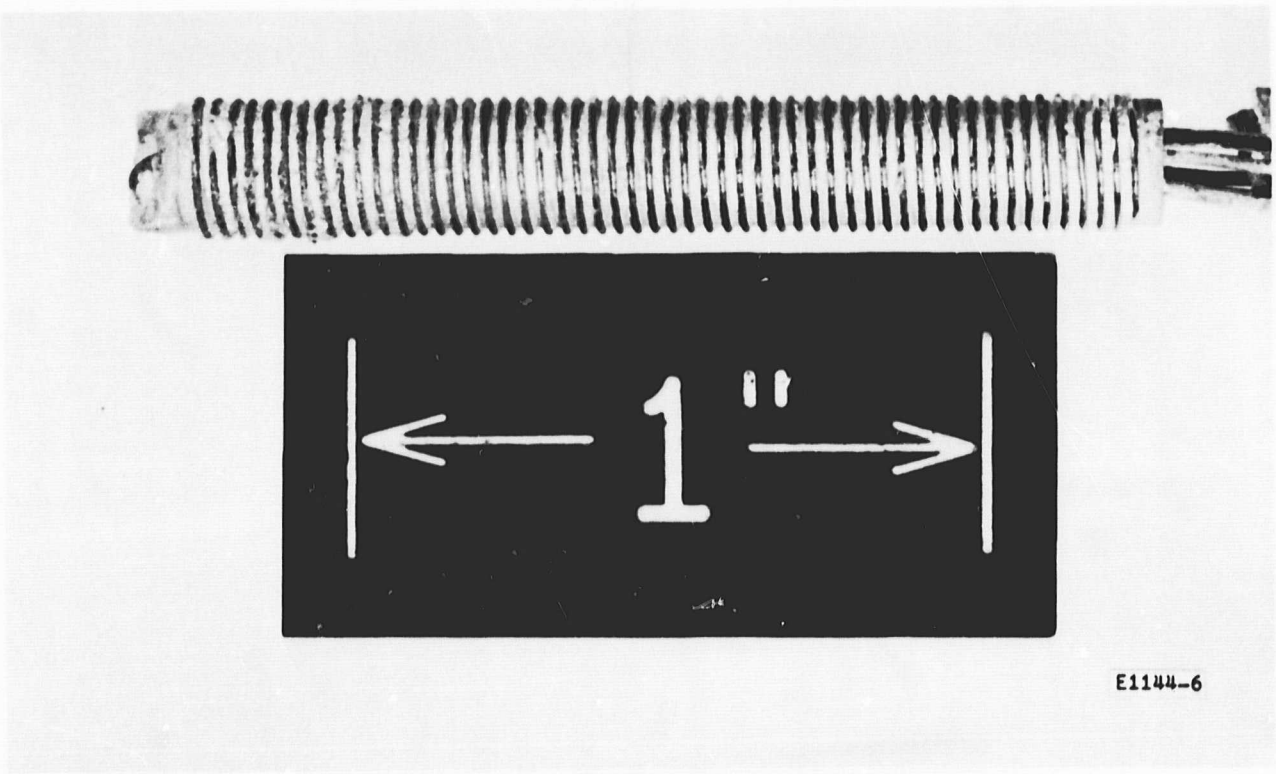


Figure 69. Core of Pt-10% Rh Wound Heater S/N 20 After Having Been Operated for 1500 Hours at 2000°F. Note Partial Deterioration of Wire at Left. (C66081928)



Figure 70. Pt-10% Rh Wire From Heater S/N 20 at Lead Wire End After Test For 1500 Hours at 2000°F. Note Grain Boundaries Traverse to Wire Length and Frost-Like Appearance of Wire in Same Location. (C66081929)

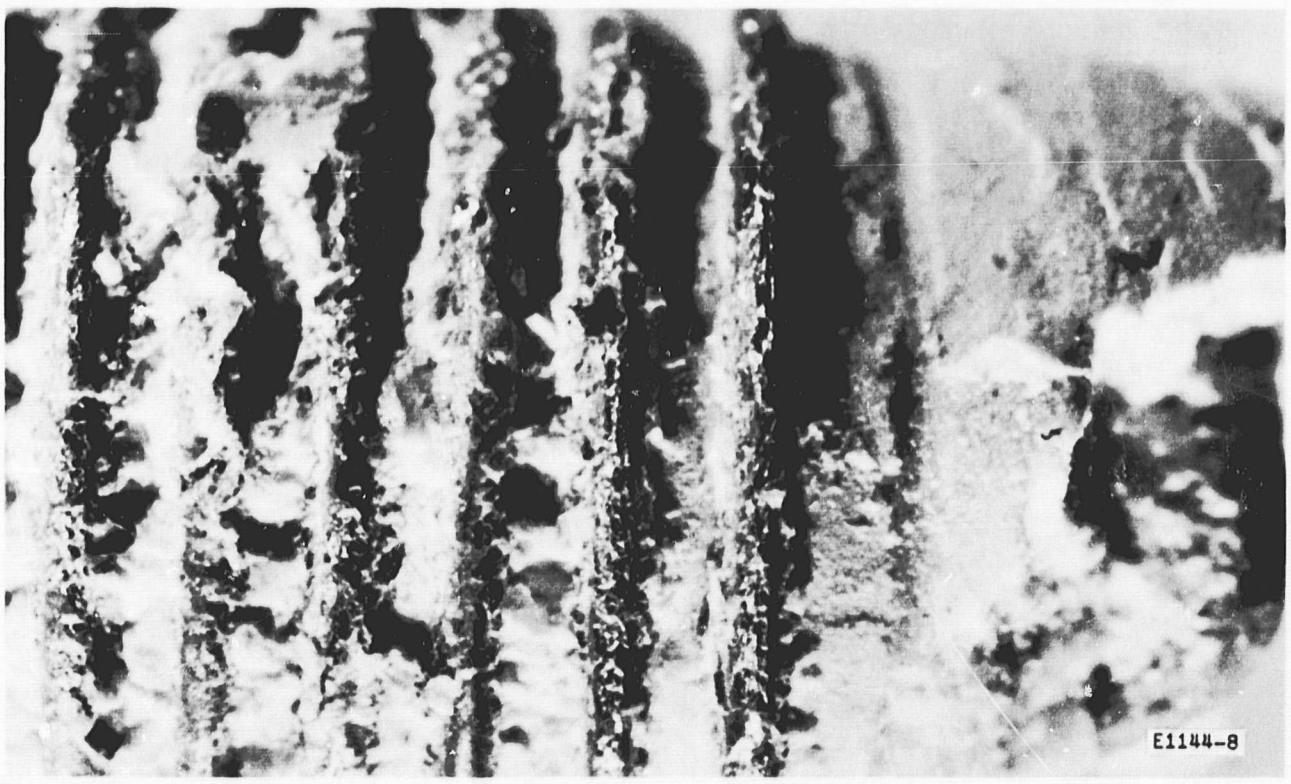


Figure 71. Pt-10% Rh Wire From Heater S/N 20 at Plug End After Test For 1500 Hours at 2000°F. Note Deteriorated Surface of Wire and Apparent Surface Melting or Corrosion. (C66081931)

and its extreme brittleness suggested either severe corrosion or localized melting.

Metallographic examination of the element wires from heater S/N 20 indicated the internal melting or vaporization of the platinum-rhodium element wire as shown in Figures 72 and 73. Both gross surface porosity and large internal pores were found in the severely frosted and embrittled area of this wire. Note that a second phase also appears in the unetched wire; this phase is the result of calcium diffusion into the positive power lead side of the heater element and is discussed under DC Migration Effects.

The results of spectrographic analyses of the element wires from heaters S/N 20 and S/N 28 are shown in Table XXXVI; the data are for wire specimens which had been scraped to remove the adherent surface deposits. Considering those elements that are more abundant in the heater systems, there appears to be a possibility of increased Ca, Cr, Ni, Mn, and Si in the element wire, as the result of (1) vapor phase transfer of these elements from the Cr-Al thermocouple or from the heater sheath alloy, or (2) migration of impurity elements from the ceramic components. An increase in magnesium and of boron in the wire may be the result of some BN of MgO impressed into the surface of the wire and not scraped off prior to spectrographic analysis. For example, the boron analyses were significantly higher in those analyses of the wire which were made without prior scraping

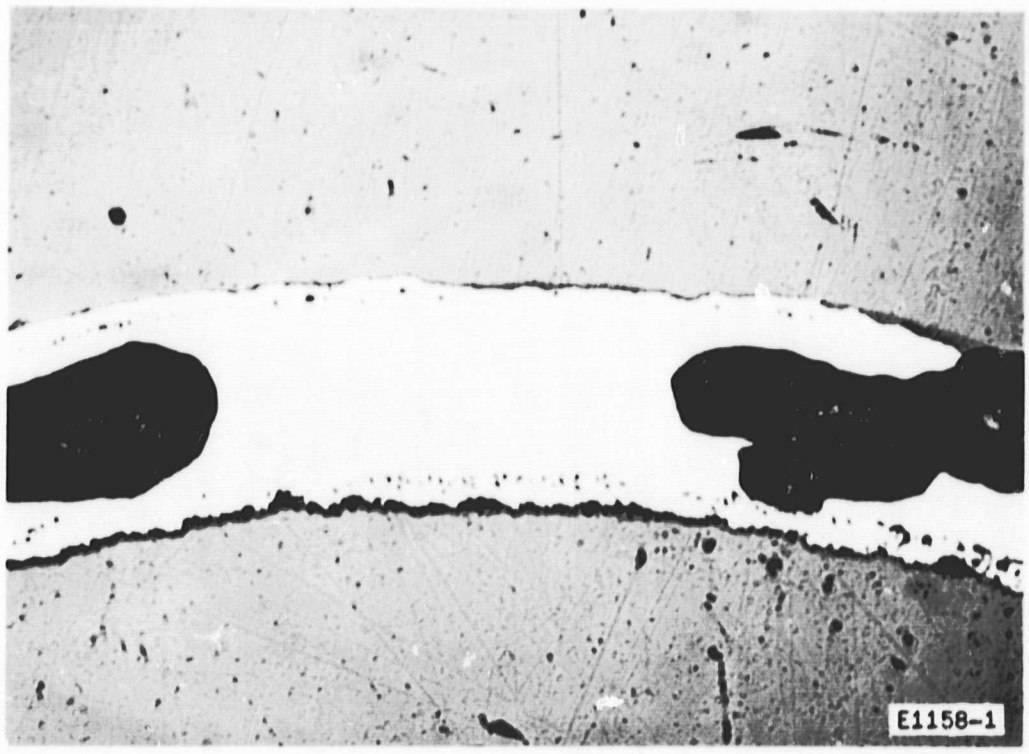


Figure 72. Pt-10% Rh Element Wire From Heater S/N 20 After 1549 Hours at 2000°F. (C380211)

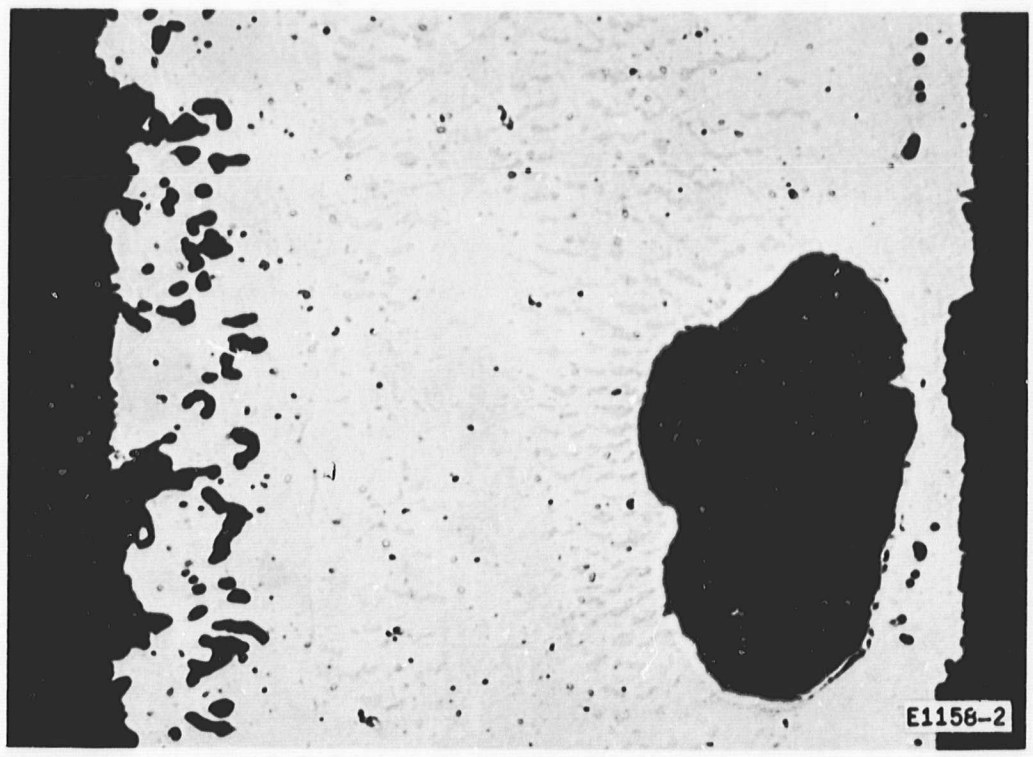


Figure 73. Pt-10% Rh Element Wire From Heater S/N 20 After 1549 Hours at 2000°F. (C380212)

TABLE XXXVI

SPECTROGRAPHIC ANALYSIS OF Pt-10% Rh ELEMENT WIRES FROM HEATERS S/N 20 and S/N 28 AFTER APPROXIMATELY 1500 HOURS AT 2000°

	Amount				Amount		
Element	S/N 20	S/N 28	Control	Element	S/N 20	S/N 28	Control
Ag	O	O	O	Mn	T	T	T-
Al	T	T	T-	Mo	O	O	O
B	T	T	T-	Na	O	O	O
Be	O	O	O	Ni	T	T	T-
Ca	T	T	O	Pb	O	O	O
Cb	O	O	O	Si	T	T	T-
Co	O	O	O	Sn	T-	T-	O
Cr	T-	T-	O	Ti	O	O	T
Cu	T	T	T	V	O	O	O
Fe	T	T	T-	Zn	O	O	O
Mg	Minor	Minor	T-	Pt	Matrix	Matrix	Matrix

of the wire surface.

Heater S/N28 was much more stable in its operating resistance characteristics during 1551 hours of testing at 2000°F. The physical appearance of the element wire from this heater was also much better than heater S/N20.

The components of heater S/N28 are shown in Figure 74. There was no apparent reaction between the Hastelloy X sheath and the BN fill, nor any evidence of the DC effect previously noted at the positive power lead. The core had cracked from a longitudinal line along its surface into one of the power lead holes; the reason for this crack is not immediately obvious, but may have resulted from some variation in the swaging process. The platinum-10% rhodium element wire was ductile but had occasional evidences of an adherent frost-like surface as seen in Figure 75. The wire was ductile throughout.

A longitudinal crack occurred in the outer surface of the Hastelloy X sheath but did not penetrate through the sheath wall; surface porosity on the Hastelloy X outer surface appeared much more severe than that observed in the 20-watt, 1500-hour tested-heater, S/N20.

In the post-test evaluation of Hastelloy X heater sheaths, the formation of a second phase was noted in the sheaths from heaters S/N20 and S/N28 which were tested for about 1500 hours at 2000°F.

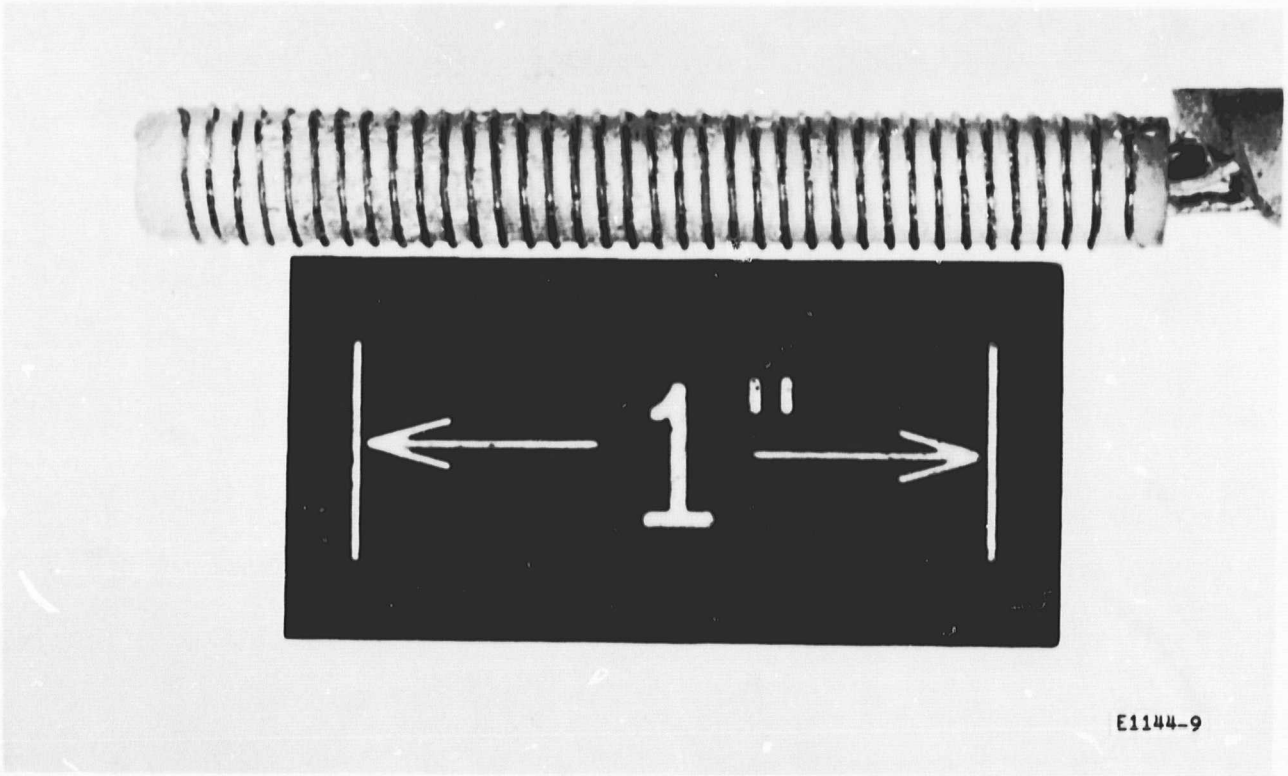


Figure 74. Core of Pt-10% Rh Wound Heater S/N 28 After Test For 1500 Hours at 2000°F. Note Occasional Arena of Frost-Like Appearance on Wire. (C66081927)



Figure 75. Pt-10% Rh Wire From Heater S/N 28 at Plug End After Test For 1500 Hours at 2000°F. Note Frost-Like Appearance of Wire in Same Locations. (C66081930)

This second phase is shown in Figure 76. Evaluation of this phase by electron microprobe indicates it contains a high percentage of molybdenum as shown in Table XXXVII. Its hardness as measured by a Tukon microhardness tester was over 700 DPH as compared to about 110 DPH for the matrix. While no serious consequences of the presence of this phase have been observed yet, the surface porosity and vaporization effects appear to be greater near this phase.

As indicated in Table XXXVIII, the carbon content of Hastelloy X sheath material is depleted from 0.08% before test to 0.01 - 0.02% after the 1500 hour tests; the oxygen content has increased slightly, the nitrogen content has decreased somewhat, and the hydrogen content has remained relatively low.

Analyses of the element wires from heaters S/N20 and S/N28 for oxygen, nitrogen, and hydrogen are given in Table XXXIX. The increased nitrogen content in the tested heaters and the presence of boron, determined spectrographically, indicate the possibility of a long-term reaction between the BN and the element wire.

While the above metallographic, macroscopic, and chemical analyses results can be used to indicate the <u>possibility</u> of various reactions and of long-term materials incompatibilities, the problem of proving that materials transfer is a reaction product rather than a surface adherent product is difficult. Of greater significance as a guiding criterion to long-life reliability is (1) the resistance

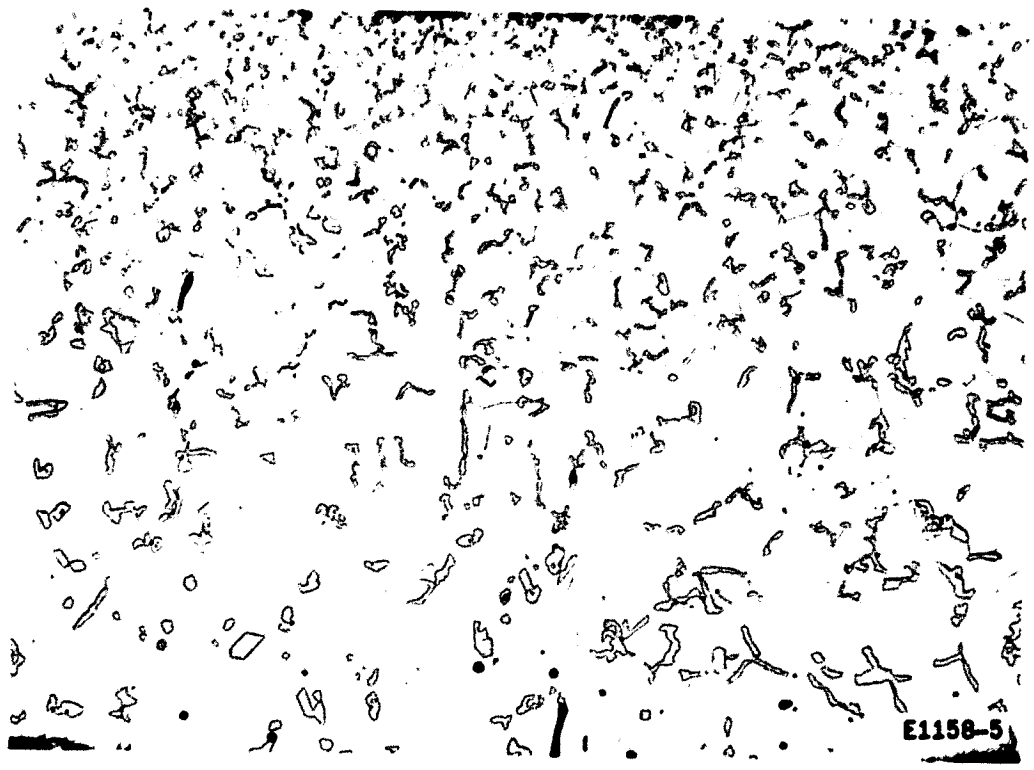


Figure 76. Hastelloy X Sheath From Heater S/N 28 After 1500 Hours at 2000°F. Etched: 50 CH_3 OH-50 HCL-10, 3% H_2O_2 Electrolytic. Mag: 75X

TABLE XXXVII

ELECTRON MICROPROBE ANALYSIS OF MATRIX AND SEPARATE PHASE FOUND IN HASTELLOY X SHEATH OF HEATER S/N 28 AFTER 1500 HOURS AT 2000°F

	Composition - %	
Element	Matrix	2nd Phase
Ni	55	2-3
Cr	22	23
Fe	19	2-3
Mo	6	72

TABLE XXXVIII

CARBON, OXYGEN, NITROGEN AND HYDROGEN ANALYSES FOR HASTELLOY X HEATER SHEATHS

(Heaters S/N 20 and S/N 28)

Hastelloy X:	Analysis - ppm			
	C	O	N	H
As-Received	839	1	204	1
Heater S/N 20, After Test	118	18	108	4
Heater S/N 28, After Test	210	32	172	3

TABLE XXXIX

OXYGEN, NITROGEN AND HYDROGEN ANALYSES FOR PLATINUM-10% RHODIUM HEATER ELEMENT WIRE*

(Heaters S/N 20, S/N 22 and S/N 28)

Pt-10% Rh Wire	Analysis - ppm		
	Oxygen	Nitrogen	Hydrogen
As-Received	30	1	1
Heater S/N 20, After Test	265	221	5
Heater S/N 28, After Test	421	223	2
Heater S/N 22, After Test	287	70	3

* Pickled in mixed HF-HNO_3 acid prior to analysis.

ability of the element wire, (2) its appearance and ductility after test, and (3) its post-test microscopic appearance. In the last instance, porosity, voids, melting or vaporization, and apparent zones of surface reaction are additional indicators of decreasing reliability at longer test periods. Such signs of uncertain reliability were first noted in one of the 1500-hour test heaters, S/N20.

Heater S/N2A operated at 2000°F in a highly reliable manner with stable resistance characteristics for 6607 hours. At that time the heater open circuited when a lead wire failed external to the heating element itself. The failure is shown in Figure 77. Both power leads were severely necked in this area due either to pinching by the Lava "A" plug during original swaging or because of DC migration and corrosion effects at the Lava "A" plug during operation. Note that in Figure 77 the Lava "A" plug and its portion of the sheath have been removed in an attempt to repair the heater. A higher magnification of the necking of the lead wires and thermocouple wires in the area of the Lava "A" plug is given in Figure 78.

When the sheath was removed, there was no evidence of reaction between it and the BN fill material. The platinum element wire itself was still ductile except for the first few turns at the end opposite the lead wire end of the heater where some surface deterioration was observed; this is shown in Figure 79.

Relative Resistance Stability - One of the simplest criteria for measuring the stability and reliability of a resistance heater

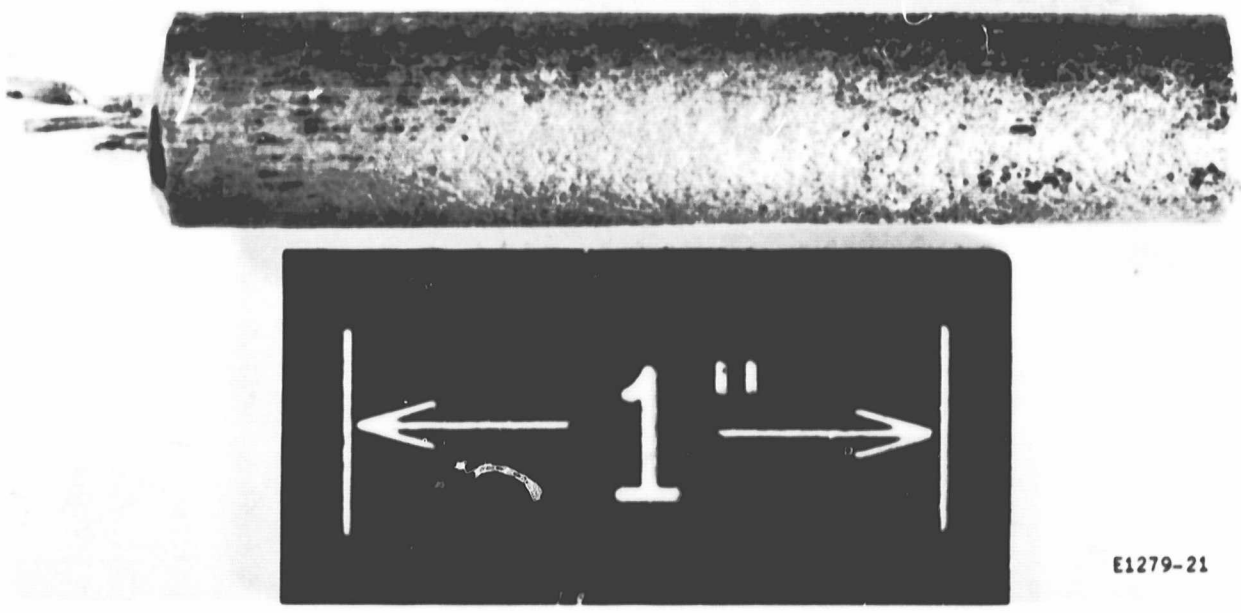


Figure 77. Heater S/N 2A After 6607 Hours Testing at 2000°F. Note Evaporation Effects on Surface of Inconel 600 Sheath and Failed Lead Wire. (C66111704)

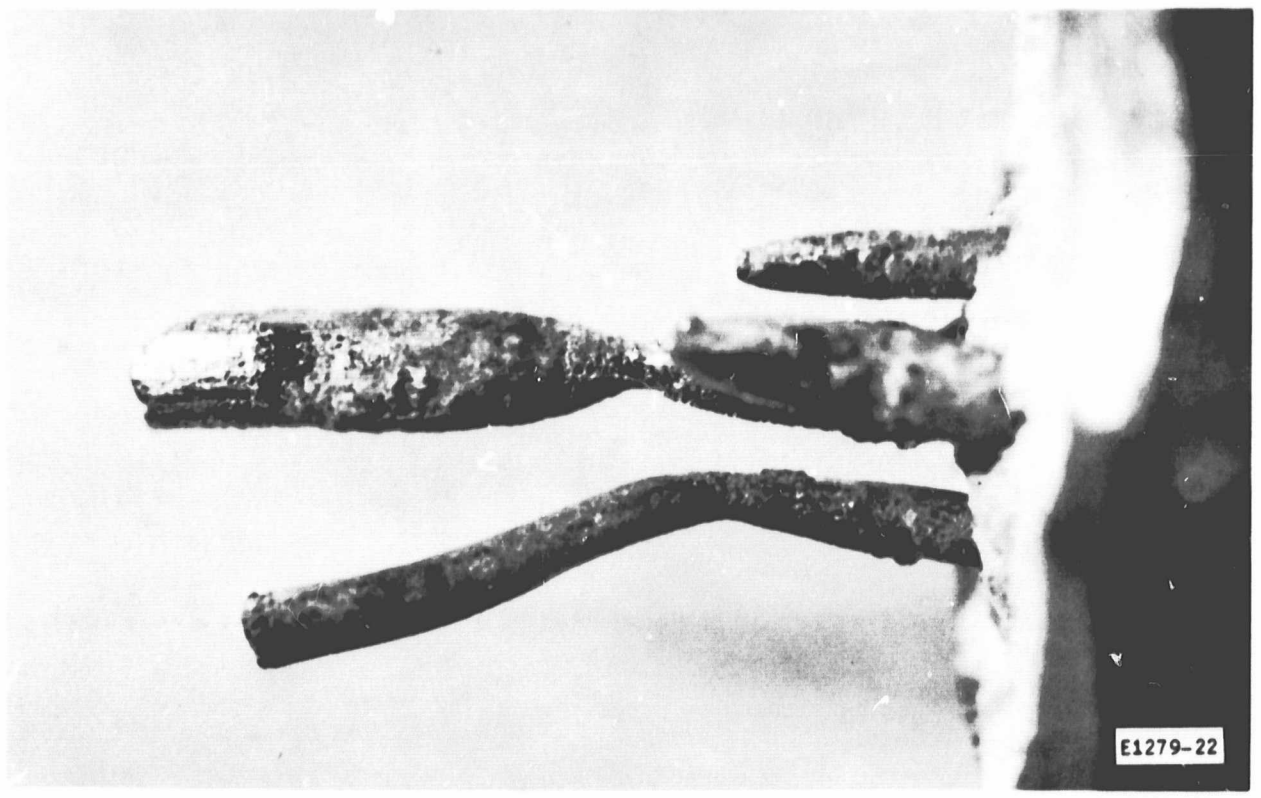
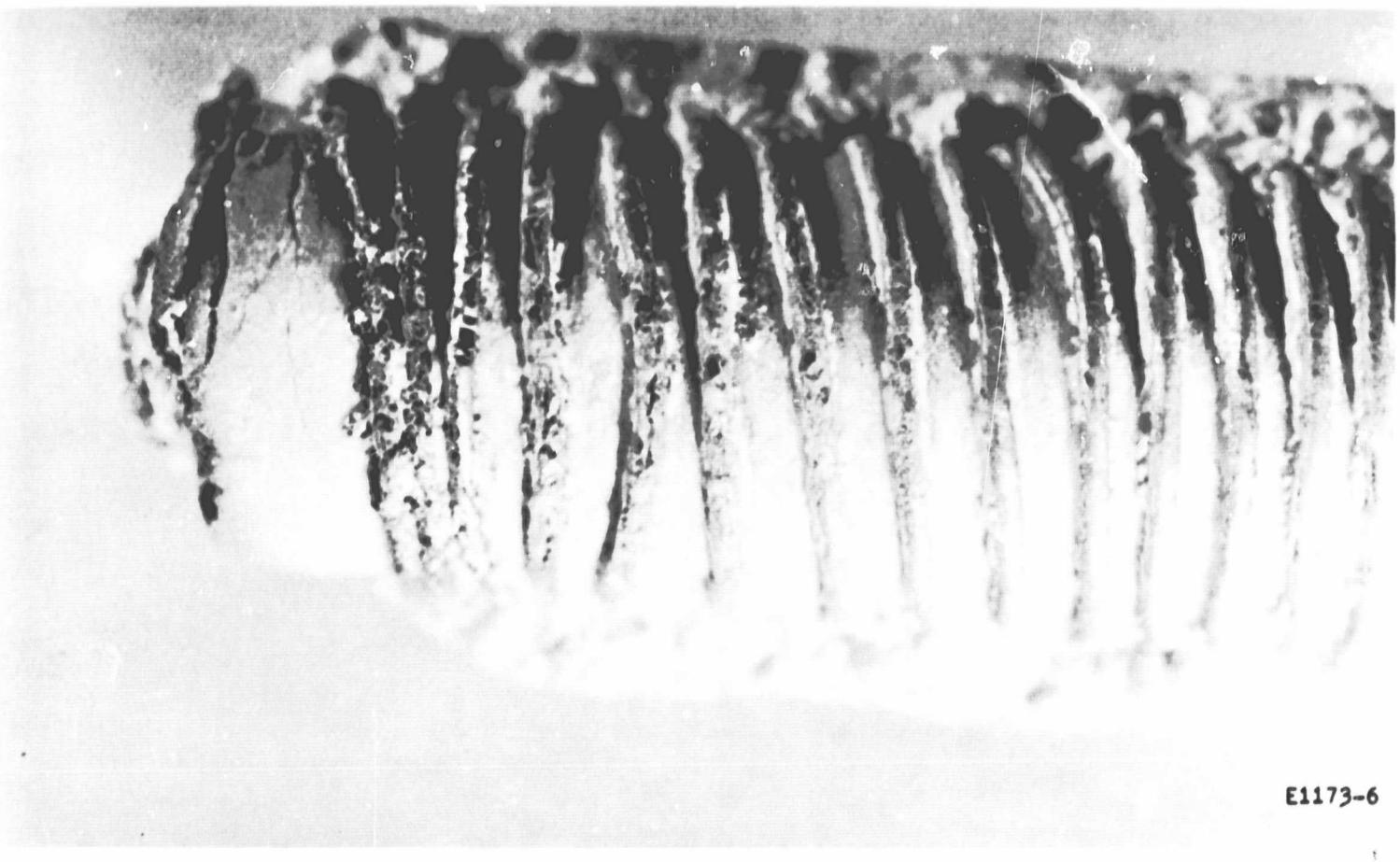


Figure 78. Failed Lead Wire End of Heater S/N 2A After 6607 Hour Testing at 2000°F. Note Initial Nicking of Wire Occurred During Manufacture. (C66111703)



E1173-6

Figure 79. Local Deterioration of Platinum Wire at End of Element in Heater S/N 2A. (C66112998)

is the stability of its electrical resistance at a given temperature measured at different times. The percent change in resistance per hour represents the rate of change in resistance and is, therefore, a suitable means for comparing different heater elements. A comparison of the relative resistance stabilities of several heaters listed for long durations is given in Table XL. The stability of heater S/N2A which ran for 6607 hours is apparent in its low value of 1.28×10^{-4} % change in hot resistance per hour. Heater S/N20, which showed significantly greater deterioration than did its counterpart, heater S/N28, has a rate of change in resistance about 8 times that of heater S/N28. The alumina core heaters, S/N16 and S/N19, have even higher rates of resistance change; that for the heater with an alumina fill as well as an alumina core is higher by 50% than that for the heater with an alumina core but a denser BN fill.

TABLE XL

RELATIVE CHANGE IN HOT RESISTANCE FOR SEVERAL HEATERS AFTER TESTING FOR EXTENDED PERIODS OF TIME

Heater No.	Materials	Test Duration-Hours	Resistance Change-%/Hour
S/N 2A	MgO Core, BN Fill, Pt Element, Cr-Al, T.C., Inconel Sheath	6607	1.28×10^{-4}
S/N 20 (20W)	MgO Core, BN Fill, Pt-10% Rh Element, Cr-Al T.C., Hastelloy X Sheath	1549	16.3×10^{-4}
S/N 28 (30W)	MgO Core, BN Fill, Pt-10% Rh Element, Cr-Al T.C., Hastelloy X Sheath	1551	2.2×10^{-4}
S/N 16	Al_2O_3 Core, BN Fill, Pt Element Cr-Al T.C., Inconel Sheath	2559	23.1×10^{-4}
S/N 19	Al_2O_3 Core, Al_2O_3 Fill Pt-10% Rh Element, Cr-Al T.C., Inconel Sheath	1440	31.3×10^{-4}

7. Thermal Cycling Tests

As a means of indicating the expected life under intermittent operation of the heater in its space application, thermal cycling tests were conducted on a total of eight heaters.

The heaters were brought to approximately 2000°F in 4 hours; 8 hours were required for cooling to about 250°F. Two thermal cycles were performed per day.

A 20-watt prototype heater, S/N22, failed after 32 cycles and a total of 292 hours of heating time. In addition to the appearance of microcracks on the sheath and a grey coloration along the length of the MgO core, which are discussed below under Heater Sheath Cracking and under DC Migration Effects, the platinum wire had recrystallized with its grain boundaries at right angles to the axis of the wire; the wire had failed intergranularly at the 4th turn from the lead wire end of the heater.

A 30-watt heater, S/N25, was temperature-cycled in a manner similar to S/N22. Failure occurred after 26 cycles and 104 hours of testing when an open circuit appeared in the platinum-10% rhodium element wire. Examination of failed heater revealed an intergranular failure in the platinum-10% rhodium heating element wire, similar to that observed in the above heater, S/N22, within two turns of the lead wire end of the heater, shown in Figures 80 and 81 Notice that the wire is very lustrous for this short-time cyclic test as compared with the frostlike appearance of the heater element

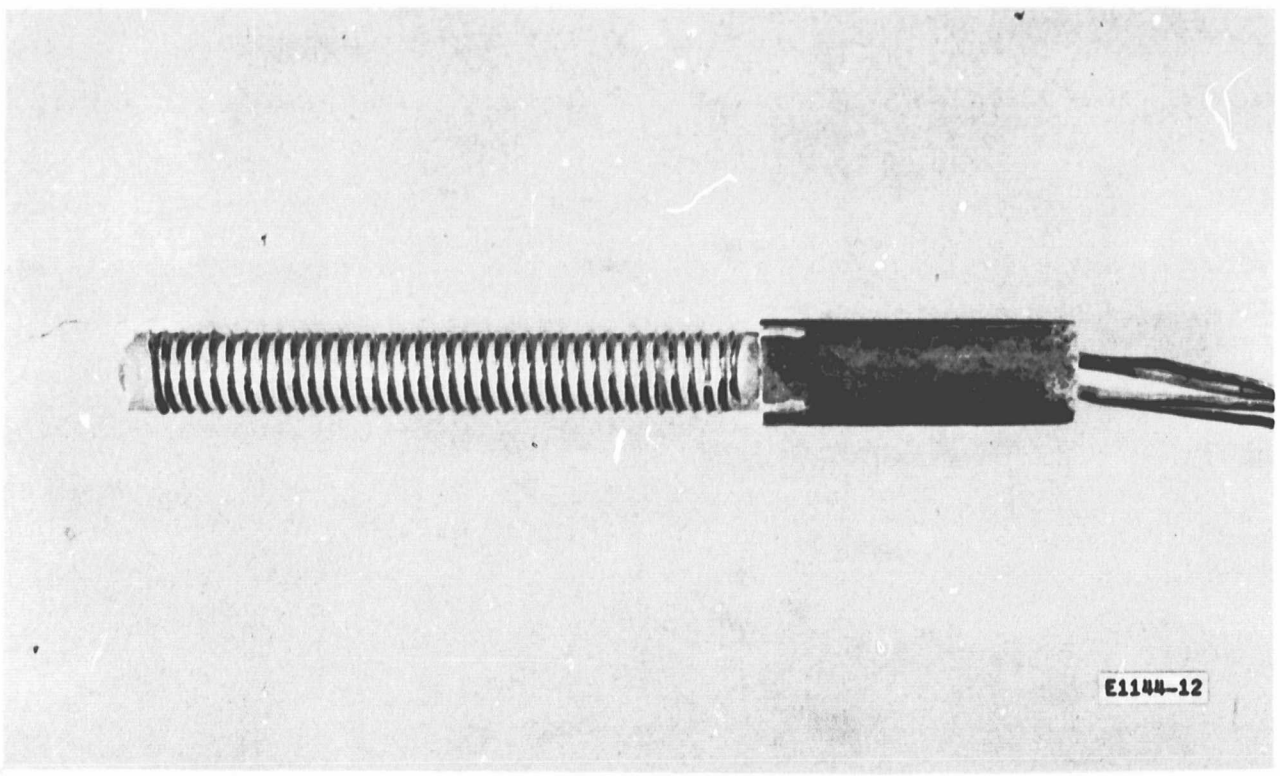


Figure 80. Core of Pt-10% Rh Wound Heater S/N 25 After 26 Cycles to 2200°F. Note Intergranular Failure at Second Turn From Lead Wire End. (C66081709)

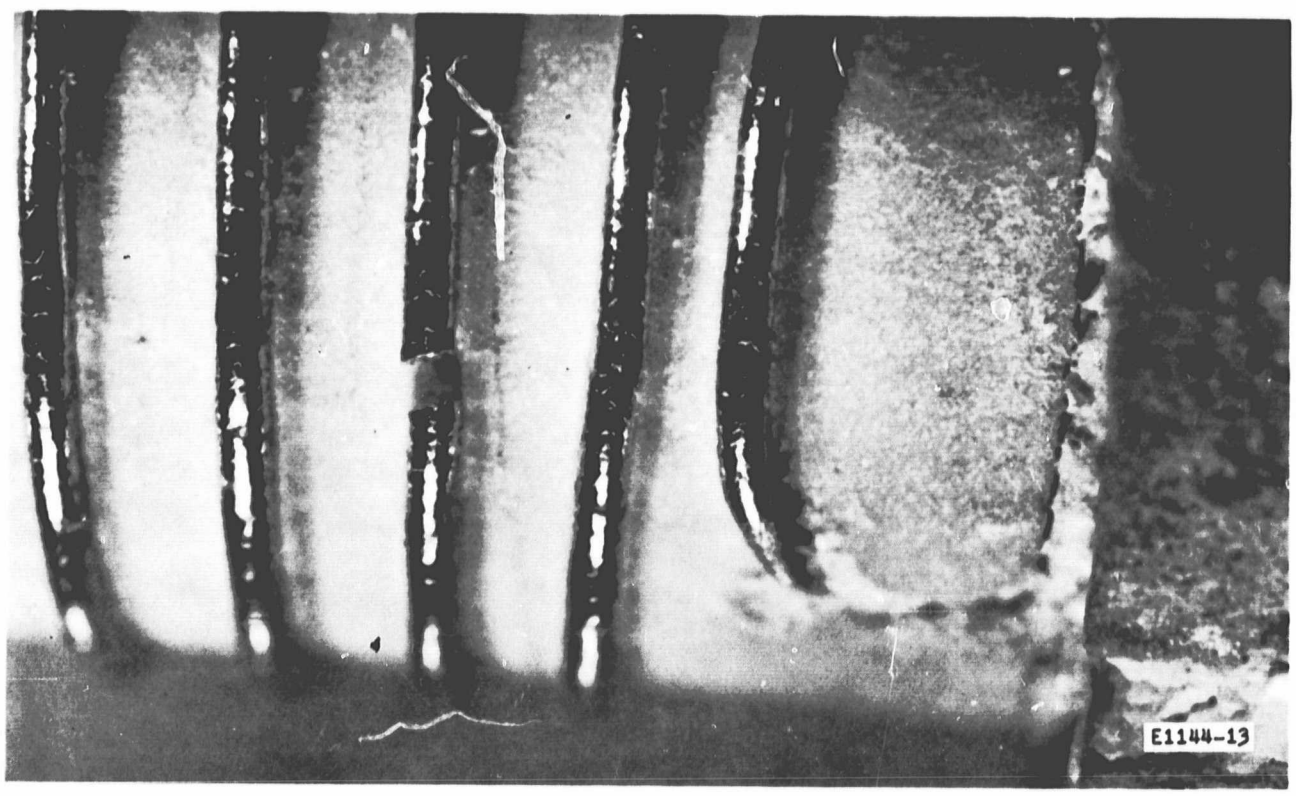


Figure 81. Intergranular Fracture of Pt-10% Rh Wire in Heater S/N 25 After 26 Cycles to 2000°F. (C66081708)

wires from the previously described 1 500-hour tests. The large grain size, pronounced grain boundaries, and intergranular failure are, undoubtedly, the result of repeated thermal stresses. A "ratcheting" mechansim was, undoubtedly, involved in which rapid heating of the constrained element caused it to plastically upset upon itself in compression during initial heating; during the process of achieving thermal equilibrium at 2000°F, tensile stresses were developed along the length of the element, and these finally produced intergranular failure. Additional thermal cycling tests were conducted on three 20-watt prototype heaters (Lot No: 17) in which the heating current was regulated to prevent excessive current and power input to the wire due to the low cold resistance of the heater wire at the start of heating.

Each of the three heaters was independently brought up to a temperature of 2000°F, and measurements of the electrical input required to maintain that temperature were recorded. Each was then independently connected into a circuit which was set to limit the initial current through the heater element to approximately 120% of the current required at 2000°F; these heaters were thermal cycled, allowing 4 hours for heat up to 2000°F and 8 hours to cool down to approximately 300°F. Heater S/N43 failed after 11 cycles of operation.

All failures occurred by open circuiting of the heater element and were similar in appearance to the thermal cycle failures in

heaters S/N22 and S/N25. The wire was recrystallized and bright. Failure occurred intergranularly at random locations along the length of the heating element. For example, failures occurred in heater S/N43 at a location 8 turns from the lead end and at another location 33 turns from the end opposite the leads. The appearance of a typical failure in heater S/N45 is shown in Figure 82.

Without changing from the basic platinum alloy system, which had demonstrated compatibility with the other materials and processes used in fabricating these heaters, a heater element alloy was investigated which was more resistant to recrystallization and grain growth. A powder-metallurgy platinum wire material, Thermoplatinum FG, produced by Electric Thermometers, Inc. of Kearny, New Jersey, had demonstrated an ability to resist recrystallization and grain growth for 400 hours at temperatures to 2600°F. After being resistance heated for 100 hours at 2000°F, specimens of platinum wire and Thermoplatinum FG were microetched and compared as shown in Figure 83, 84, and 85. The Thermoplatinum wire indicated a definite fiberous grain structure as compared with the equiaxed grain structure and the transverse grain boundaries of the platinum wire. Thermoplatinum FG wire specimens were also heated in vacuum for one hour at temperatures of 2000, 2100, 2200, and 2500°F. While it was possible to view only the microstructures transverse to the wire diameter, the nature of these grain boundaries indicated a decided resistance to recyrstallization.

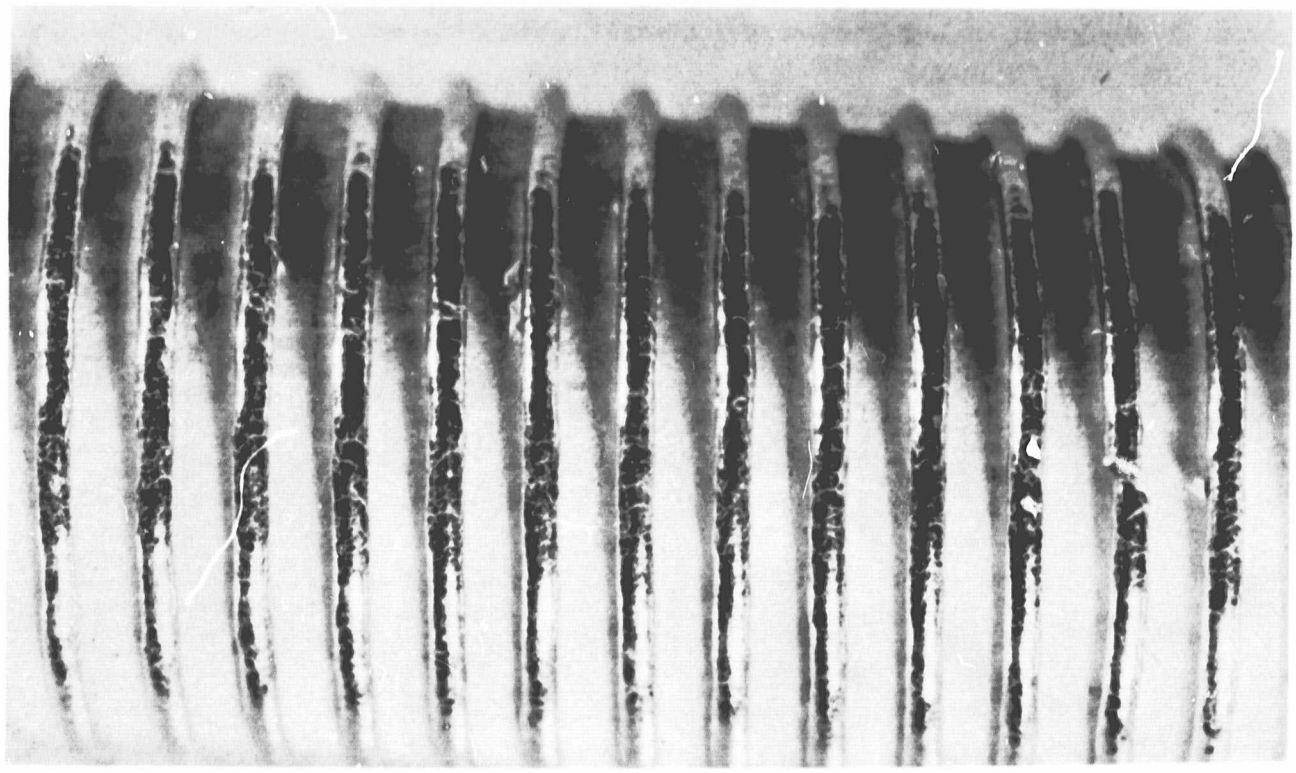


Figure 82. Intergranular Thermal Cyclic Failure in Pt-10% Rh Element Wire of Heater S/N 45 After 13 Cycles to 2000°F.

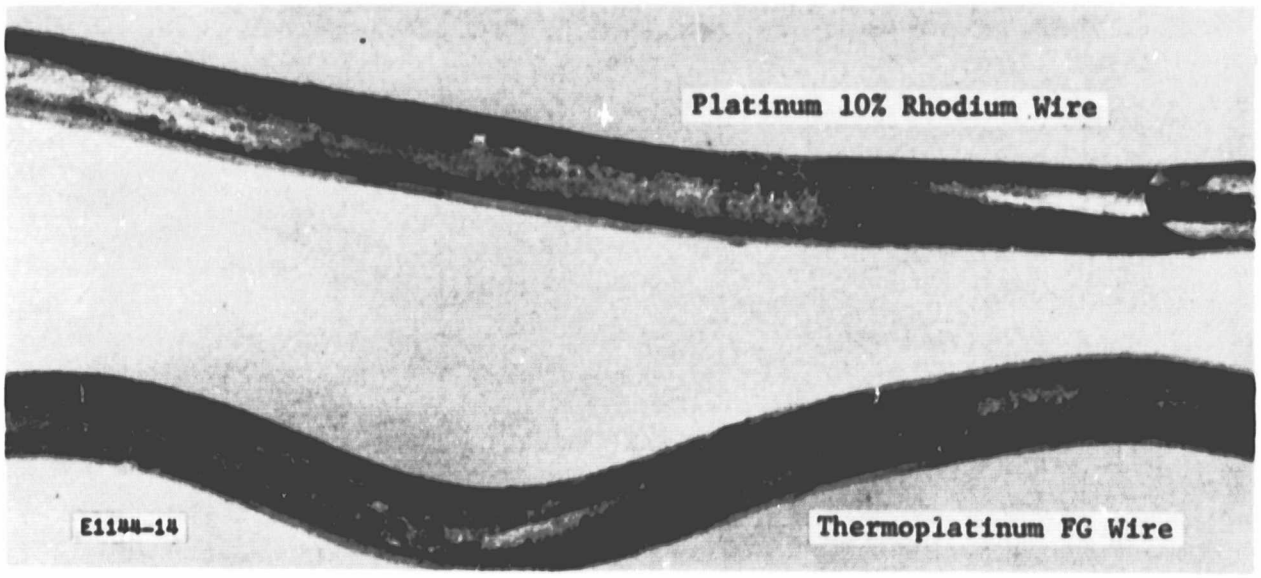


Figure 83. Comparison of 10 Mil Dia. Platinum 10% Rhodium Wire and 10 Mil Diameter Thermoplatinum FG Wire After 100 Hours at 2000°F. (C66090228)

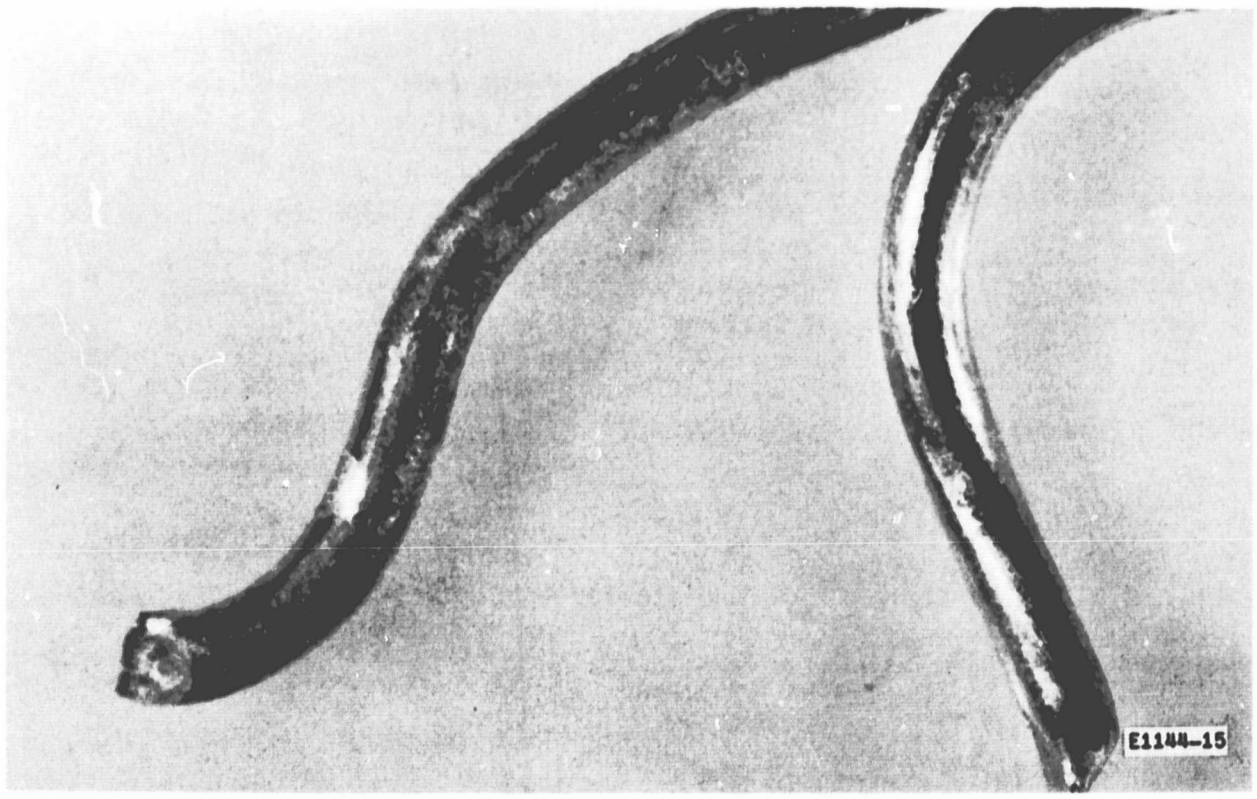


Figure 84. An Alternate View Showing Comparison of 10 Mil Diameter Platinum 10% Rhodium Wire and 10 Mil Diameter Thermoplatinum FG Wire After 100 Hours at 2000°F. (C66090229)

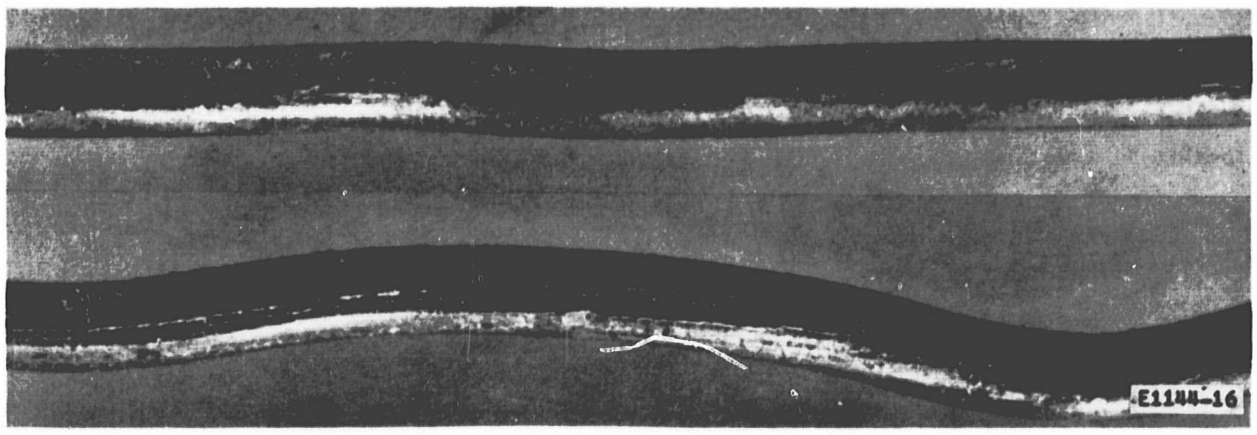


Figure 85. A Third View Showing Comparison of 10 Mil Diameter Platinum 10% Rhodium Wire and 10 Mil Diameter Thermoplatinum FG Wire After 100 Hours at 2000°F. (C66090230)

On the basis of the apparent improvement in recrystallization characteristics of the Thermoplatinum FG wire, a decision was made to evaluate the resistance to failure of this wire under the thermal cycle conditions as they exist in an actual heater. Three 20-watt heaters were prepared with 0.010-inch-diameter Thermoplatinum FG heater wire, 0.035-inch-diameter platinum-10% rhodium power leads, MgO cores, BN fill, and annealed Hastelloy X sheaths. These heaters, S/N 54, S/N 55, and S/N 56 (Lot No. 20), failed after 28, 36, and 55 cycles, respectively. Failures occurred intergranularly after recrystallization had taken place. The appearance of the Thermoplatinum recrystallized wire was different than that observed in conventional platinum-10% rhodium thermal cycled heaters. The grain boundaries were oriented along principal shear planes at 45° to the wire axis. Even though the wire was resistant to recrystallization at temperatures to 2500°F for short times in the unstressed condition, the addition of thermal cyclic compressive and tensile stresses promoted the type of recrystallization and grain "offset" or "sag" as seen in Figures 86 and 87. The intensity of grain boundary definition and the extent of grain "offset" appeared to be uniform over the major portion of the heater but were much less severe near the negative lead wire end. While it is possible that this variation was due to thermal effects, such as a lower temperature at the negative lead wire end of the heater, this is not likely. Another possibility is the diffusion of impurity elements into the heater wire as the result of a DC

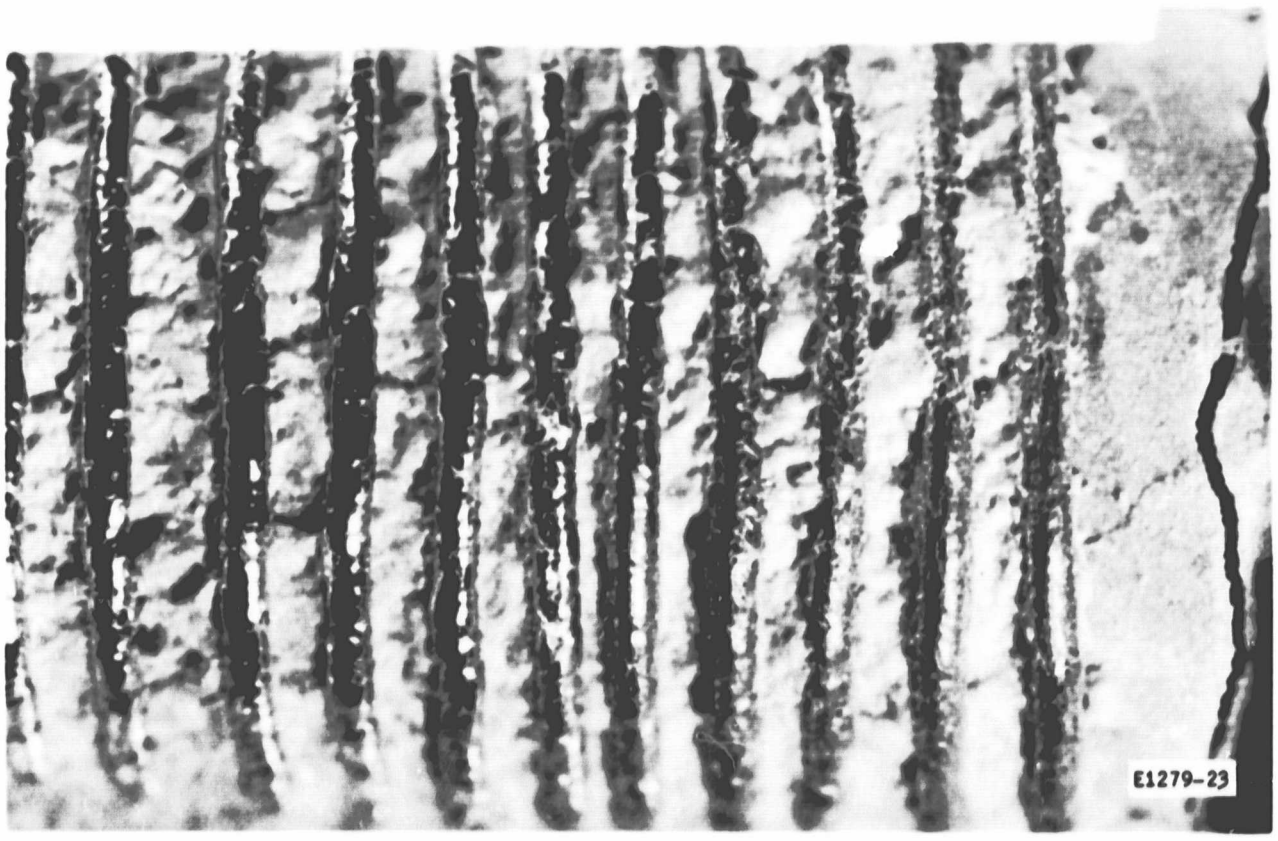


Figure 86. Negative Lead End of Thermoplatinum FG Heater S/N 56 After 55 Thermalcycles to 2000°F. Note the Apparent Decrease in Severity of Grain "Offset" at the Negative End of the Heater Wire. (C67011121)

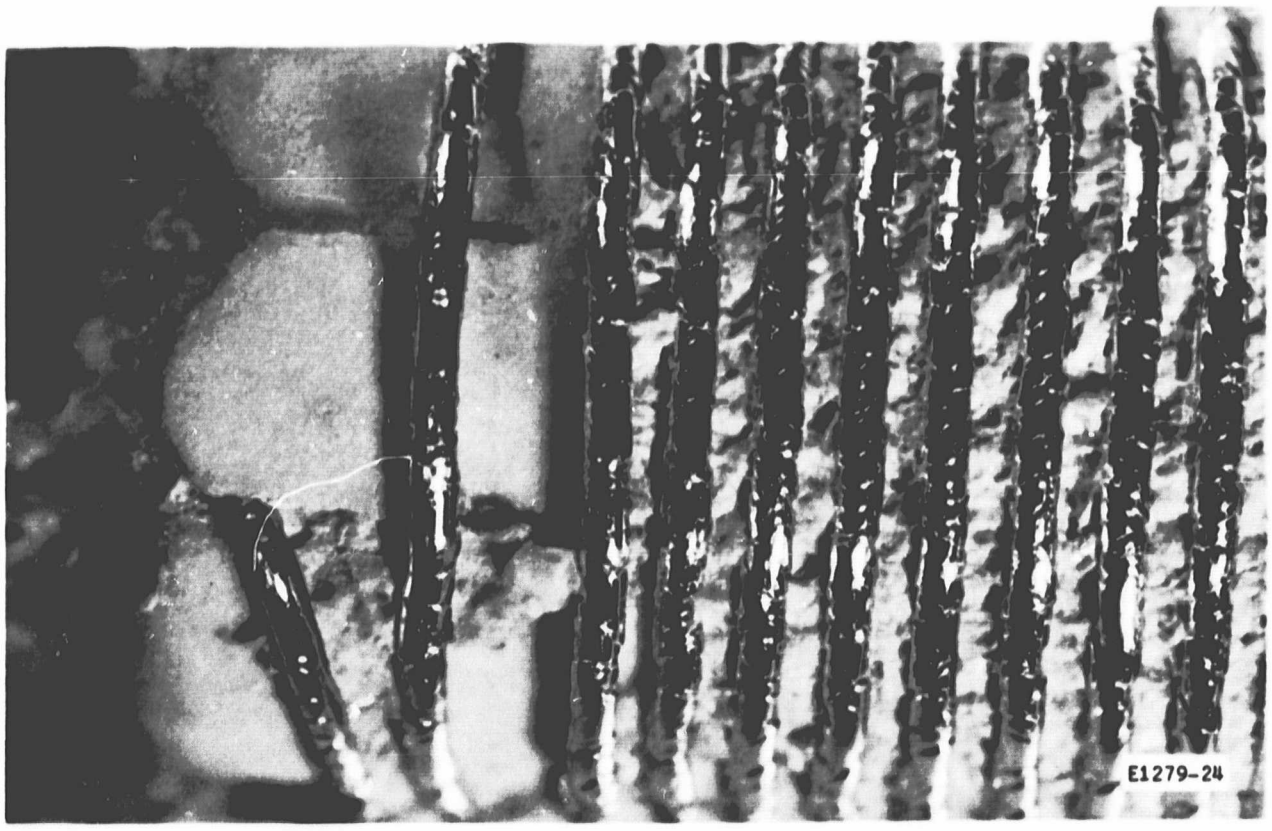


Figure 87. Positive Lead Wire End of Thermoplatinum FG Heater S/N 56 After 55 Thermal Cycles to 2000°F. Note 45° Grain Boundaries and Offset of Adjacent Grains. (C67011120)

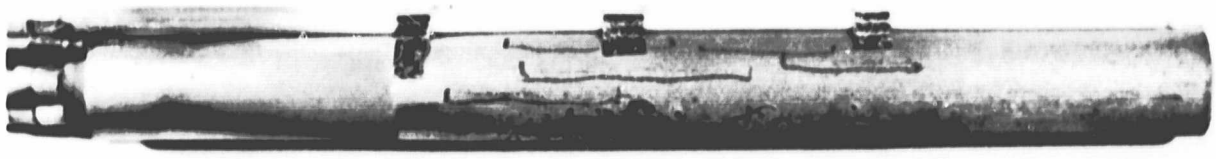
voltage potential; it is suggested that such a diffusion process under the influence of cyclic strain might very well accelerate the recrystallization process. While the use of platinum wire of better recrystallization resistance (in the free state) resulted in some significant improvement in thermal cycle resistance, it was not sufficient to meet the possible future needs for intermittent operation of hot thruster devices in space.

8. Hastelloy X Heater Sheath Cracking

Inconel 600 was used for the sheath material in all the earliest swaged development heaters, because of the immediate availability of tubing. However, it was desired to use Hastelloy X as the sheath material for "hardware" heaters since that same material was being used for the thruster components and had, in addition, demonstrated its ability to catalyze the decomposition of the ammonia propellant.

During the testing of some of the first Hastelloy X sheathed heaters axial cracks formed in the hot zones of the heaters. This was initially observed (1) in heater S/N20 after only one cycle to 2000°F in a thruster heat shield mockup, (2) in heater S/N22 after 32 temperature cycles to 2000°F in a heat shield mockup, and (3) in a 30-watt heater, S/N28, after being heated for 2 to 3 cycles to 1800°F in an actual thruster body. The nature of these cracks is shown in Figure 88. A photomicrograph of a typical crack is shown in Figure 89.

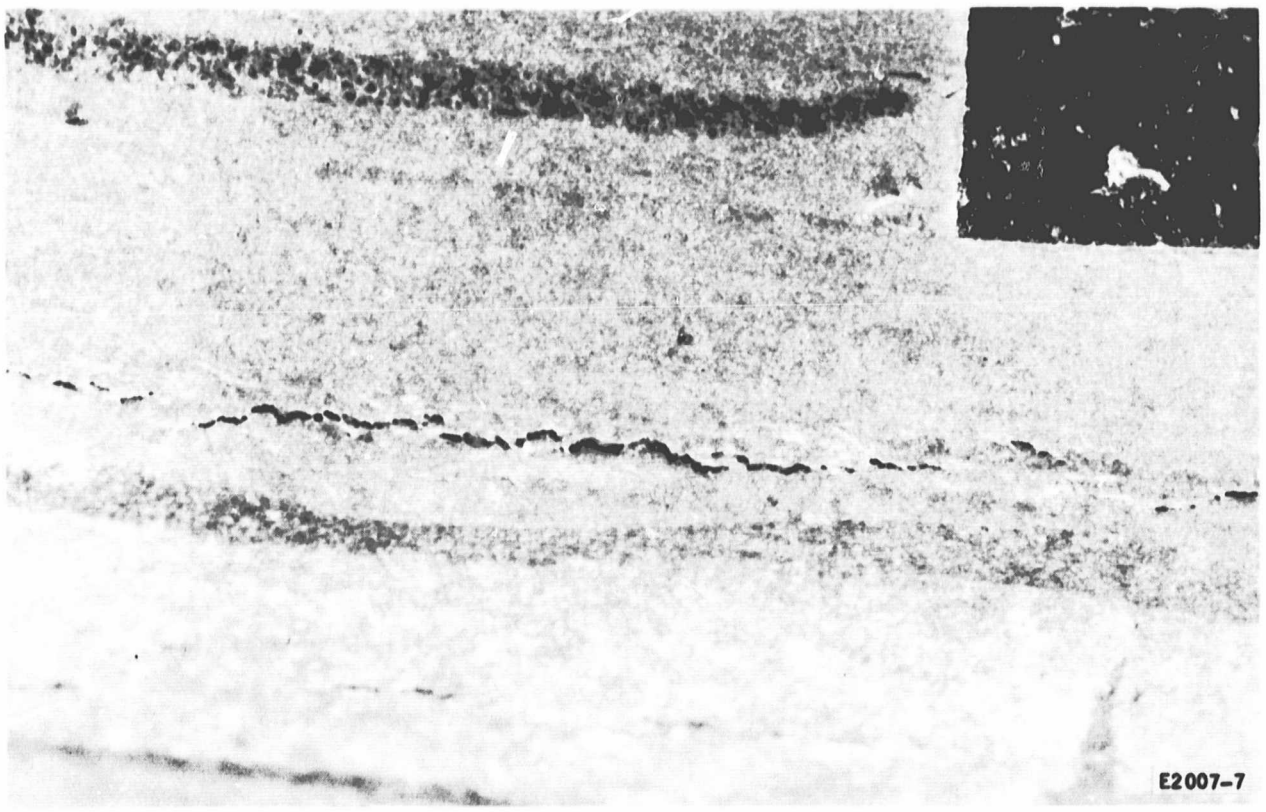
It was presumed that cracking of the sheath was the result of limited ductility in the Hastelloy X alloy, either as the result of (1) axially dispersed impurities (inclusions) within the material, (2) the presence of embrittling precipitates, or (3) cold work effects produced during swaging of the heater. Since heat was produced within the heater and was transferred through the Hastelloy X sheath during heater startup, the high thermal expansion and higher temperature of the MgO core, undoubtedly, produced the hoop stresses required to cause cracking.



E2007-5

Figure 88. Heater S/N 22 (HSK 2000-20P) After Having Been Temperature Cycled 32 Times (By Being Energized and Then De-Energized) in a Thruster Heat Shield Mockup. (Note Multiplicity of Cracks in the Hastelloy X Sheath)

Mag: 1.8X (C660610103)



E2007-7

Figure 89. Closeup View of Crack in Hastelloy X Sheath of Heater S/N 22.

Mag: 25X (C660610104)

Photomicrographs are shown in Figures 90 through 93 of the as-swaged Hastelloy X heater sheaths and of the cracks found in various sheaths after exposure of the heaters to elevated temperatures. The structure of the as-drilled Hastelloy X tube free from initial cracks is shown in Figure 90. Figure 91 shows the cold worked structure of the as-swaged heater sheath and the absence of cracks in the sheath. Figure 92 shows the same location of heater sheath S/N 23; the presence of radial cracks produced under the influence of hoop stresses within the heater sheath is indicated in the sheath area itself, but decreases in intensity toward the end plug where stresses were lower because of the supporting influence of the plug. The radial orientation of the cracks is shown in a transverse section of heater sheath S/N 34 in Figure 93; the presence of strain aging is indicated by intergranular carbide precipitates oriented in the radial direction and along slip lines.

The material contained few inclusions, as observed in unetched micrographs; therefore, inclusions were not believed to be responsible for cracking. The cracks occurred as the result of low ductility under stress as the heater core expanded more rapidly during heater startup. The major reason for cracking was attributed to strain induced precipitation of carbides as aggravated by the reduced ductility inherent in the cold worked, swaged heater sheath.

When the cracks were first observed in test, an as-swaged

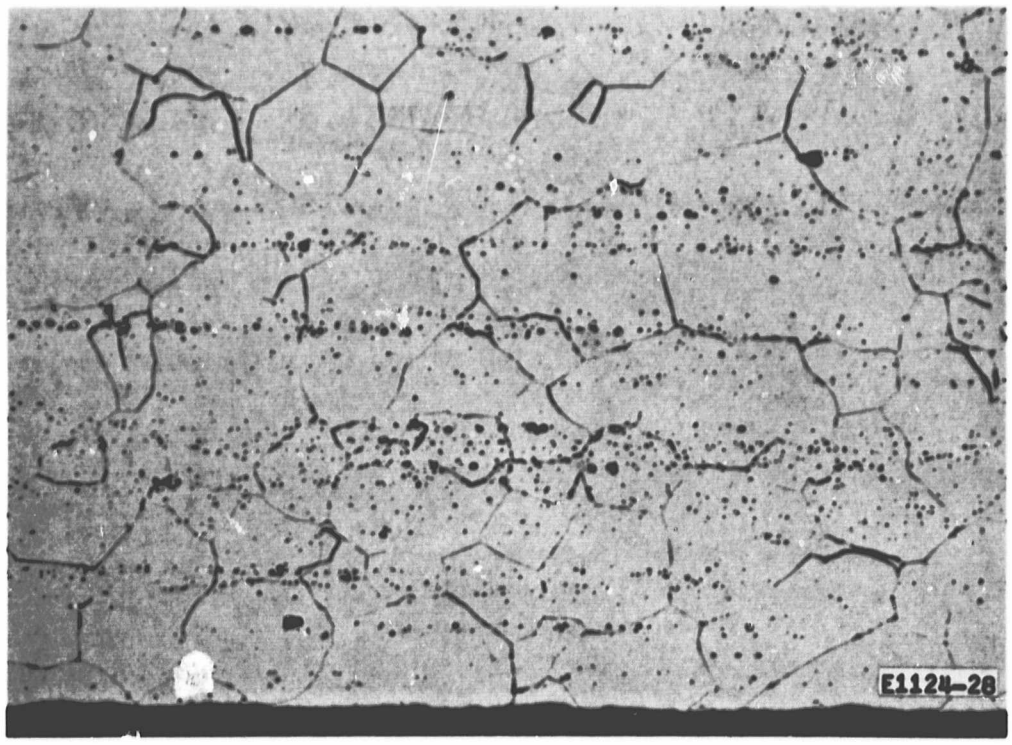


Figure 90. Longitudinal Section of Hastelloy X Gun-Drilled Tubing as Machined. (C050112)

Etchant: 50 CH_3OH - 50 HCl - 10, 3% H_2O_2 Mag: 100X

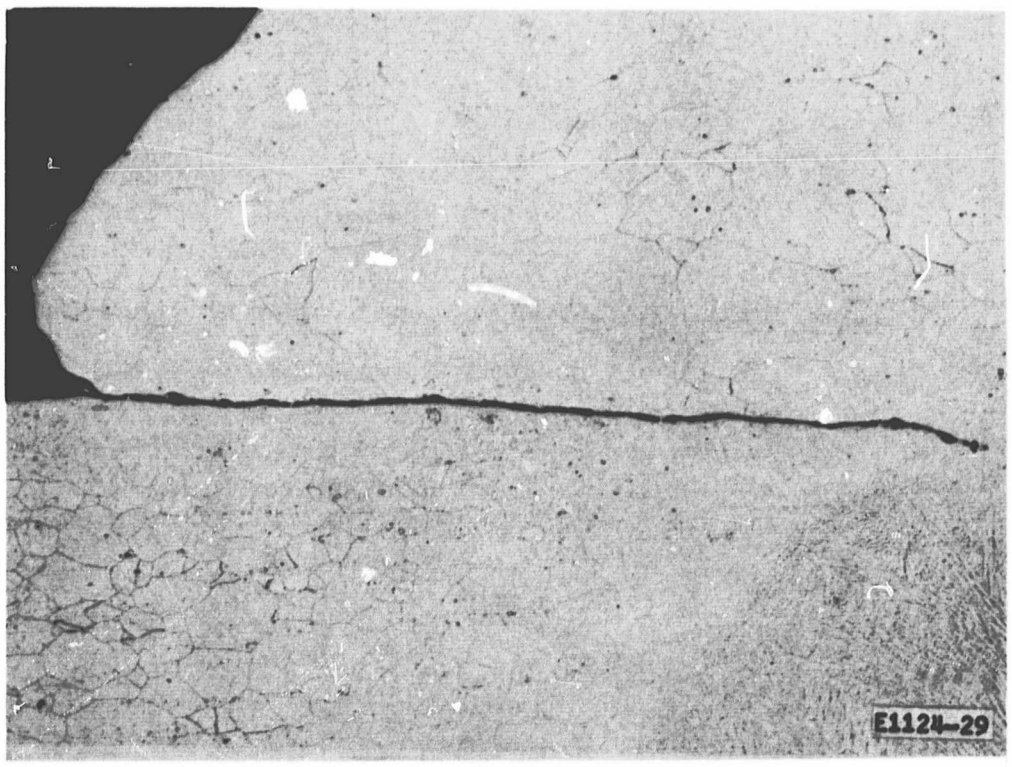


Figure 91. Longitudinal Section of Hastelloy X Gun-Drilled Heater Sheath as Swaged. (C070212)

Etchant: 50 CH_3OH - 50 HCl - 10, 3% H_2O_2 Mag: 50X

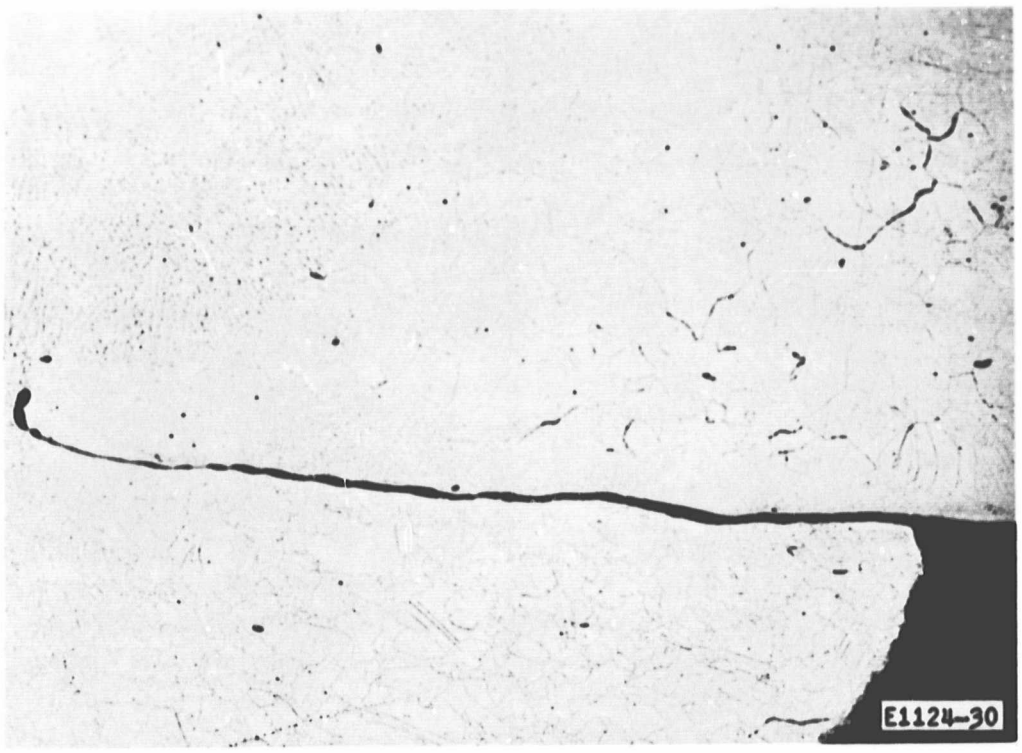


Figure 92. Longitudinal Section of Hastelloy X Heater Sheath, S/N 23, After Test. (C070412)

Etchant: 50 CH_3OH - 50 HCl - 10, 3% H_2O_2 Mag: 50X

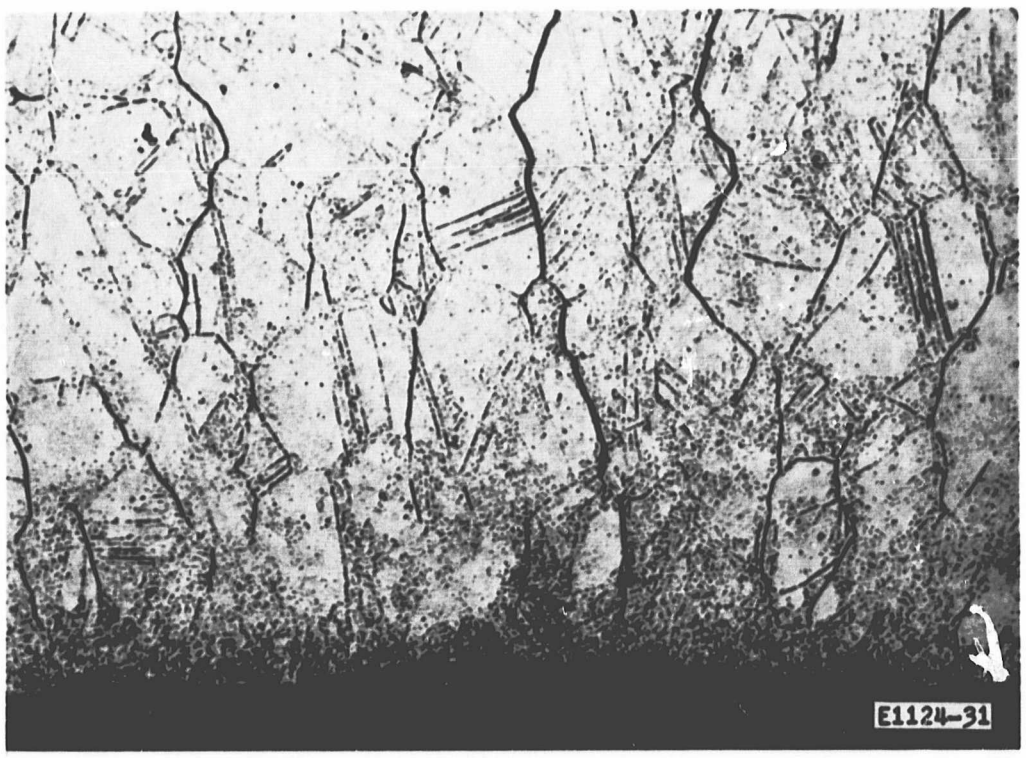


Figure 93. Transverse Section of Hastelloy X Heater Sheath, S/N 34, After 2000°F Annealing. (C050413)

Etchant: 50 CH_3OH - 50 HCl - 10, 3% H_2O_2 Mag: 100X

heater (S/N25) was annealed in a vacuum furnace for one hour at 2000°F; application of heat from the outside of the heater was intended to expand the metal sheath away from the core until the Hastelloy X sheath reached an annealing temperature where residual cold work effects in the sheath would be stress relieved. After such a heat treatment, a heater was cyclic tested to 2000°F for six cycles without the formation of cracks. However, during the subsequent annealing of a group of six 20-watt heaters, three (S/N30, 31 and 32) were successfully annealed, but the last three (S/N33, 34 and 35) developed surface cracks.

The first three to be annealed in vacuum were heated to about 700°F and held briefly to permit the low pressure to recover in the vacuum chamber as the heater outgassed; subsequently, the furnace chamber was raised rapidly to 2000°F, and no cracks were apparent in the sheaths. In the annealing of the next two heaters this holding temperature was in the 900-1000°F temperature range; these heaters had definite strain induced cracks after this annealing treatment. The last heater was brought to 2000°F as quickly as possible; only minor surface cracks were observed, and these were machined from the heater in subsequent operations. It was apparent that strain age cracking would occur unless the heater sheath was rapidly heated through the strain-aging temperature range of 1200°-1400°F to an annealing temperature of 2000°F. When this was properly accomplished, there were no further evidences of cracking. The success of the fast-annealing technique was assured

when 25 additional Hastelloy X heaters were processed without cracks.

In analyzing the strain-age cracking problem, the following additional facts become evident.

The published data for unworked Hastelloy X indicated excellent ductility over the entire temperature range. Tensile tests on cold-rolled Hastelloy X sheet by the Haynes Stellite Company indicated room-temperature tensile elongations of 32, 20, and 7 per cent after cold working to 5, 15, and 30 per cent reduction in area. Based upon the above room-temperature ductility, it would appear that sufficient ductility should have been available to preclude the observed cracking. Since the heaters were swaged through an estimated 15-20% reduction in area, the cold working imparted to the metal both limited the ductility and accelerated strain-induced precipitation and embrittling reactions occasioned by the stresses imposed by initial heating to 2000°F.

The hardness data shown in Table XLI were accumulated to assist in analyzing the cracking problem. The actual hardness of the supposedly mill-annealed bar was not R_b 99, as certified by the vendor, but was 103. This represented a 33-point increase in Brinnell hardness over that expected for mill-annealed material, indicating some discrepancy in the processing of the original material by the supplier. When annealed to 2000°F, this hardness dropped from R_b 103 to R_b 93, or about 60 points on the Brinnell

TABLE XLI

HARDNESS MEASUREMENTS ON VARIOUS HASTELLOY X SPECIMENS

Hastelloy X Material	Hardness					
Unitemp HX (AMS 5754D; Heat C 7875)	Bhn	R_b	R_c	15T	15N	Comments
Vendor Certificate - 5/8" Bar, 2150°F Anneal	228-235*	98.1-99	20.3-21			
Actual Hardness - 5/8" Bar	(258)	(103)	26*			
5/8" Bar Annealed 2000°F - 1 Hour A.C.	106	63	--	80.5*		(Circumference)
	175	88*	--			(Circumference)
	199	93*	(12)			(Center End)
As-swaged Heater S/N 29	293	(106)	31*			(Plug End)
	269	(104)	28		74*	(Sheath)
Annealed Heater S/N 25	150	82*	--			(Plug End)
Post Test Heater S/N 22	140	78*	--			
Machined and Annealed Tubing	149	81	--	87*		
Data by Erdeman:**						
Hastelloy X - 2150°F Anneal	188	90-91	(10)			
Hastelloy X - Anneal + 5% C.W.	228	98*	20			
Hastelloy X - Anneal + 25% C.W.	302	(107)	32.1*			

NOTES:

* Denotes measured value; others are for comparison.
**Erdeman, Jr., V. J., "Hastelloy Alloy X Recrystallization Study," General Electric Company, DM 61-139, May 3, 1961.
Brackets indicate values beyond scale limits and are for comparison only.

scale. The hardness of the as-swaged heater sheath was only R_b 104 and, after heating to 2000°F, was R_b 81. It is estimated that the swaging of the Hastelloy X sheath achieved 15-20% cold work; this degree of cold work in a properly mill-annealed material should have resulted in an as-swaged hardness considerably less than R_b 106 (Brinnell 293) which was observed in swaged heater S/N29. Subsequently, heater sheaths were reannealed prior to use in the fabrication of heaters to assume the lowest possible hardness after swaging. This undoubtedly added to the resistance of the material to strain age cracking.

As a further means of assuring resistance to this type of cracking, additional Hastelloy X bar stock was ordered to a modified mill processing schedule designed to achieve a pre-precipitation of the carbide precipitates responsible for strain age cracking. The material was warm rolled below 2000°F, followed by a 1950°F anneal. This low temperature process has been used where finer grain size and improved fatigue resistance were needed in jet engine components. By precipitating carbides during the warm rolling operation, the tendency to strain age in later heater fabrication processes should be reduced. This material was not received in time to be of use in the present program.

c). DC Migration Effects

Since the heater elements operated on direct current, the possibility existed for the migration of metallic impurity elements under a constant polarity voltage potential. This effect was noted in some of the earliest heaters in the vicinity of the Lava "A" aluminum silicate end plugs. At and around the positive power lead, a darkening of the Lava "A" plug occurred; this was shown in Figure 66. In some cases the platinum wire itself had been corroded. The exact nature of these defects was not investigated in detail since the obvious and feasible solution was to eliminate this plug in prototype heaters.

Effects of more significance were noted in prototype heaters. Heater S/N22, which was thermal cycled to failure, and heaters S/N20 and S/N28 serve to point out these effects.

Heater S/N22 failed after 32 cycles to 2000°F. Its positive lead was embrittled, as indicated by a failure of this lead near the ceramic core when the heater was removed from test. The microstructure of this positive lead wire (and the adjoining element wire) is shown in Figure 94. The second phase contained up to 8% calcium, as determined by electron microprobe examination, which had severely embrittled the platinum-rhodium wire as indicated by the presence of cracks through the phase. A comparison of the composition of the matrix and second phase was as follows:



Figure 94. Positive Lead Wire (Lower) and Element Wire (Upper) from Heater S/N 22. Matrix Contains 90 Pt - 10 Rh - 0.5 Ca; Second Phase Contains 90 Pt - 2 Rh - 8 Ca as Determined by Electron-Microprobe Examination.

Etchant: Unetched Mag: 75X

Element	Composition - % Matrix	2nd Phase
Pt	90	90
Rh	10	2
Ca	0.5	8

This finding suggested that a direct current migration effect involving the diffusion of calcium from the magnesia core (or from the boron nitride) must have been responsible for the embrittling effect. The magnesia core was suspected as the more likely source, since it contained 0.4% calcium (see Table XXXIV).

Another DC migration effect was observed in heater S/N22. The magnesia core had developed a grey discoloration along its length only on that half of the core which was surrounded by the positive power lead. This was the cnly instance in which a DC migration effect had been noted in the core itself. This discoloration also adhered to the positive Pt-10% rhodium power lead. The positive power lead was embrittled, as mentioned above, and broke off during handling.

The white and grey areas of the MgO core were very similar as determined by X-ray diffraction, but spectrographic analysis indicated increased quantities of manganese and nickel in the grey area surrounding the positive power lead. The chemical analytical procedures were not sufficiently accurate to permit positive conclusions, but it is possible that the increased manganese and

silicon may have contributed to embrittlement of the heater and power lead wires.

Heaters S/N20, a 20-watt heater, and S/N28, a 30-watt heater, were both tested for approximately 1500 hours at 2000°F and have been discussed under Long-Duration Tests. Heater S/N20 showed the higher increase in resistance and definite indications of severe corrosion or localized melting. The photomicrographs of the element wire from this heater, which were referenced above, appeared to show a phase which could be similar to the 8% calcium phase noted in heater S/N22. Electron microprobe analyses were performed on the wire from the 1,500-hour tested heater, S/N20; they verified that calcium migration into the platinum wire was responsible for the higher rate of resistance increase for this heater and for the embrittlement of its heater wire.

B. 3000°F Heater

3000°F Heater - A 125-watt electrical heater was required to provide electrical simulations for a radioisotope heated thruster operating at 3000°F. A right cylindrical volume 1-1/2 inches in diameter and 4 inches long was selected as the space which a 125-watt radioisotope capsule and thruster body would require within its radiation shielding.

In order to minimize thermal conduction losses through the electrical leads, a low current, high voltage tungsten heater filament was used. The heater was intended to operate at about 40 volts and 3 amperes at 3000°F. The coil-type filament consisted of 35.4 inches of 8.8-mil-diameter tungsten wire wound on a 28-mil-diameter mandrel. The coil was cantilever suspended in the form of a "V" by means of three tungsten filament supports. Power was supplied through two tungsten leads. The power leads and filament supports were 20-mil-diameter tungsten; they were arrayed in parallel and equally spaced in a ceramic Lava electrical insulator block with sufficient room for 39 intervening layers of 3-mil tantalum radiation shielding between the filament and the ceramic terminal support.

The details of the design are shown in Figure 95. Techniques were developed for welding the tungsten wires to the tungsten power leads in such a manner that the welds could not be stressed by movement of the filament wire or power lead.

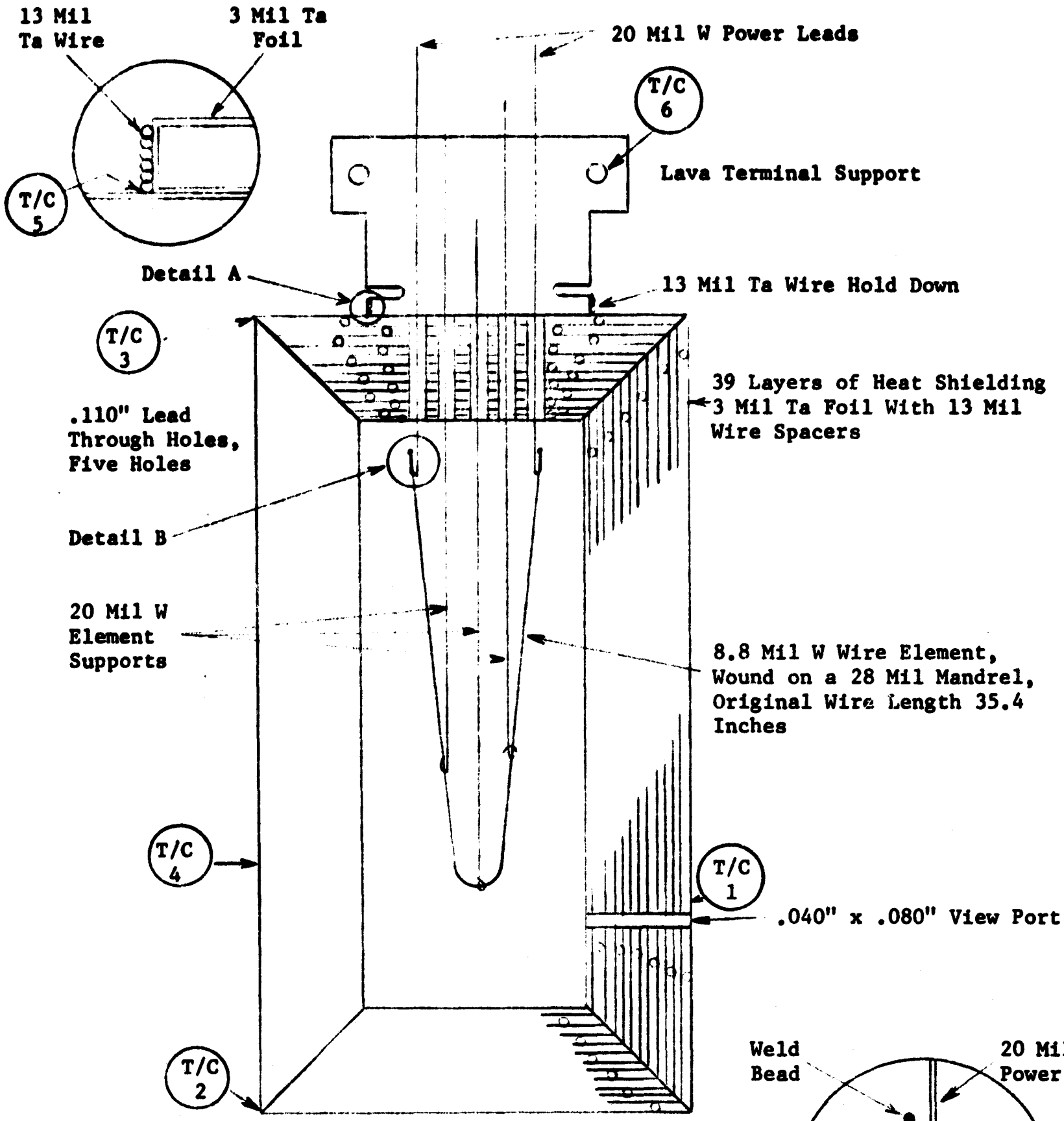


Figure 95. Design Details of 3000°F, 125 Watt Heater, Full Scale.

E1279-25

It was necessary to reduce radiation losses through the holes in the shielding needed for power leads and filament supports. Special eloxing techniques were used to machine the 0.110" diameter holes through 39 layers of tantalum shielding after the radiation shields were firmly attached to the Lava electrical insulator. An optical viewport 0.040 inch by 0.080 inch for temperature measurement purposes was eloxed through the cylindrical portion of the radiation shielding. The details of this construction are shown in Figures 96, 97, and 98.

The 3000°F heater was installed in a Varian, ion getter pumped vacuum chamber 18 inches in diameter and 30 inches high and pumped by a 400 liter-sec pump. Platinum-10% rhodium thermocouples were attached in the following places: on the outer radiation shielding adjacent to the optical pyrometer viewport; at the corner of the outer shielding opposite the terminal end; at a point on the cylindrical outer shielding about two-thirds the distance from the terminal end; at the interface between the Lava "A" electrical insulator and the outer end disc shielding; and at the colder side of the Lava "A" terminal at the bolt holding together the split halves of the terminal.

All parts of the heater had been previously outgassed in a vacuum furnace at 1500°F for four hours at a pressure less than 5×10^{-5} torr.

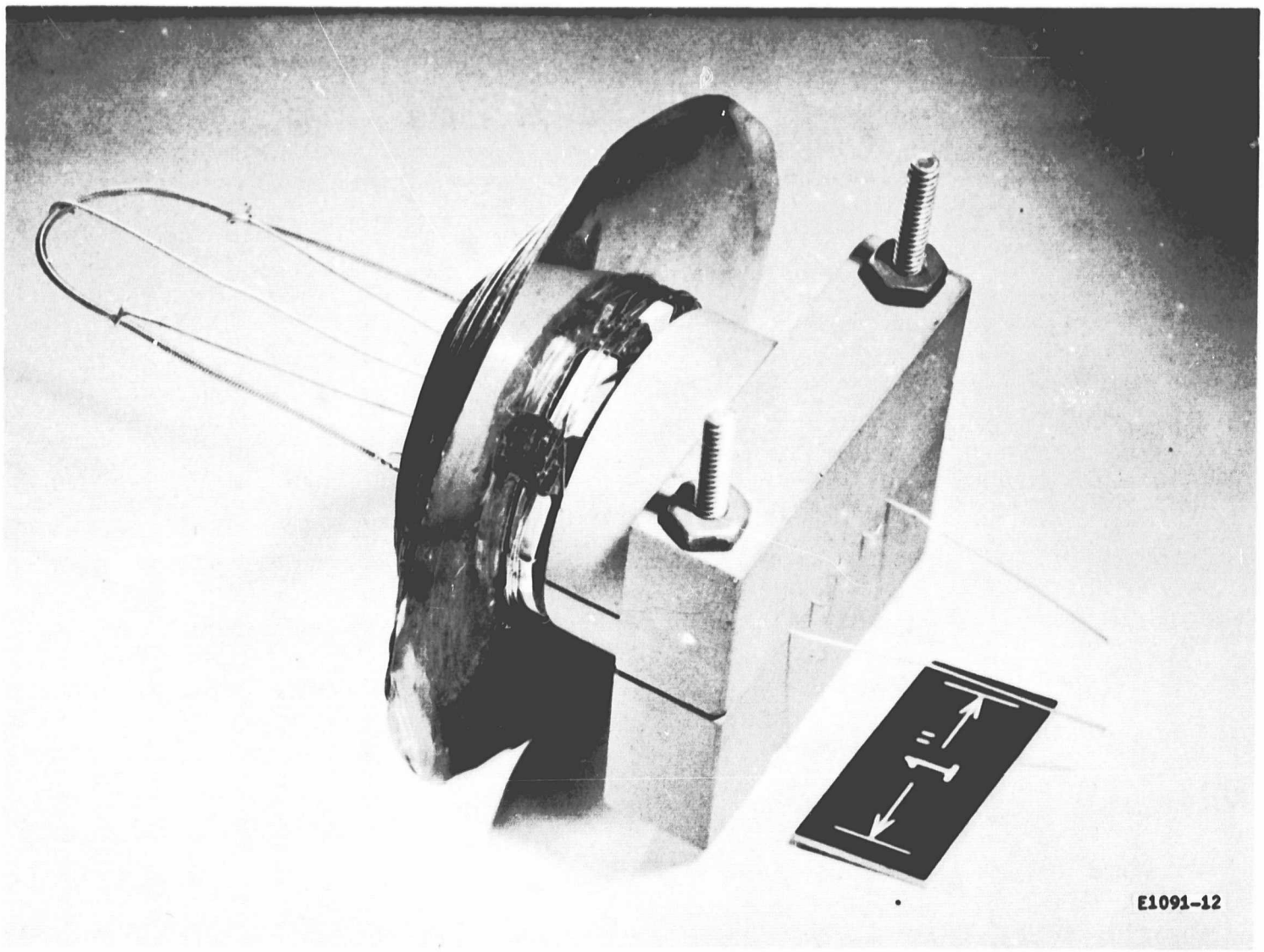


Figure 96. 3000°F Heater Element Assembly Showing Method of Attachment of Radiation Shields and Power Leads and Supports to the Lava "A" Terminal Support. (C660610114)

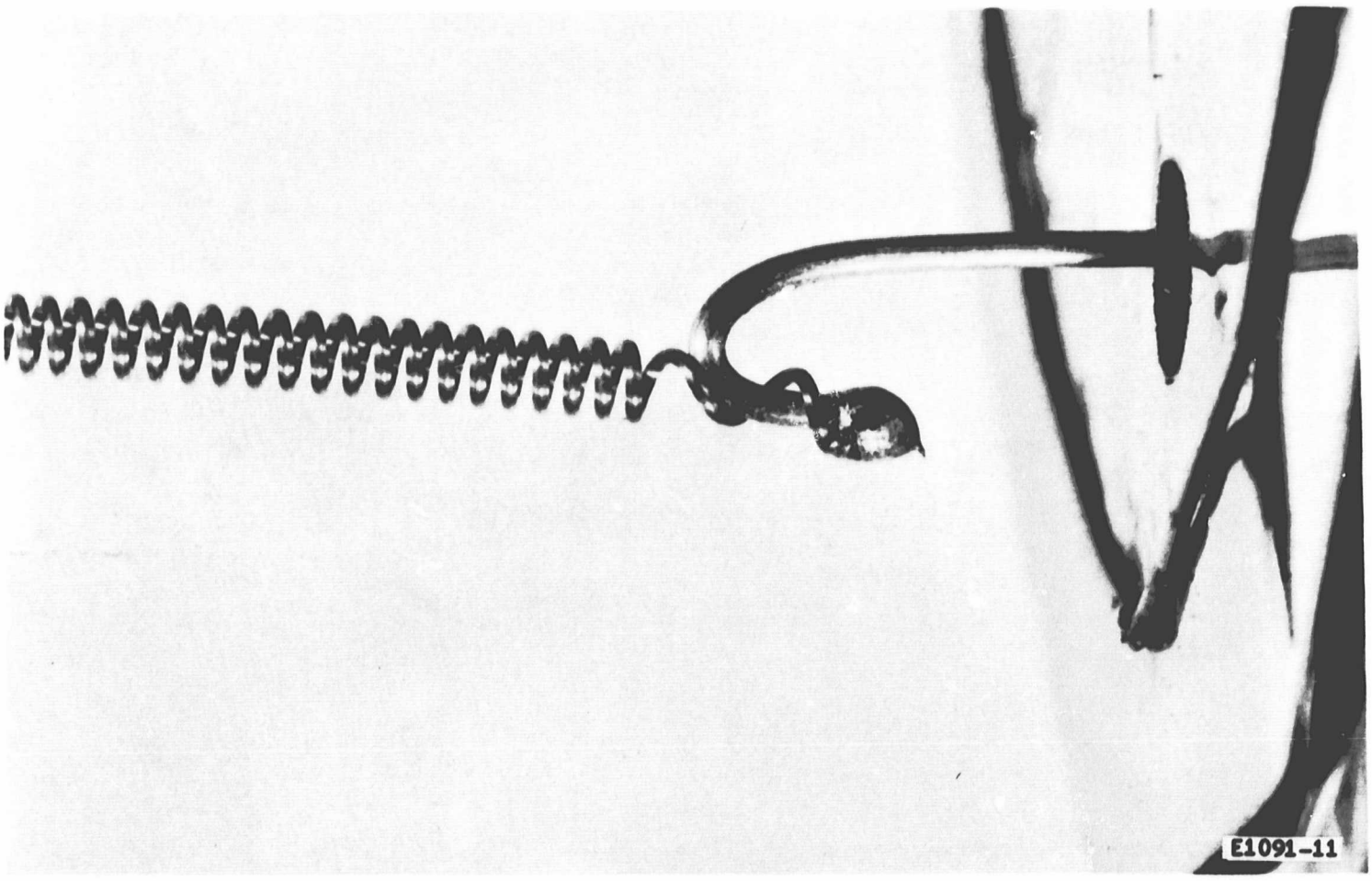


Figure 97. Method of Making Stress Free Weld Joint Between Heater Wire And Power Lead, 125 Watt, 3000°F Heater. (C660610112)

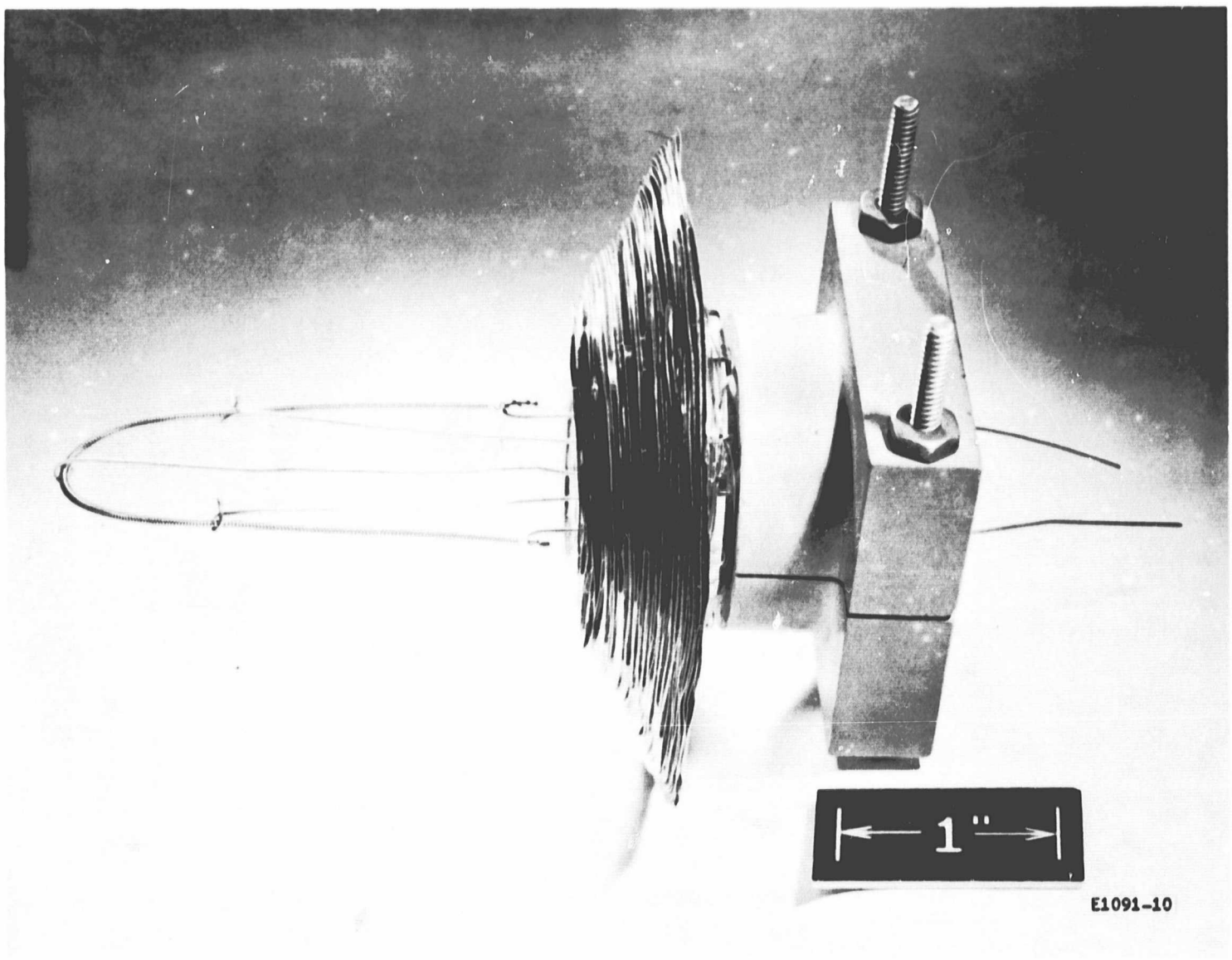


Figure 98. Assembled Heating Element 125 Watt, 3000°F Heater. (C660610113)

After installation of the heater in the vacuum chamber, power was supplied to the heater, and it was further outgassed for two hours at a pressure of 2 X 10^{-6} torr or less; power was increased gradually to 112 watts, and the interior temperature reached 3100°F. The heater was cooled to room temperature and again slowly heated to 3100°F while the various temperatures were read. Table XLII contains the test data for the initial operation of this furnace. After the furnace had operated in equilibrium at a temperature over 3000°F for more than 2-1/2 hours, the amperage momentarily fluctuated to higher values, indicating a shorting condition. The power was reduced, and the shorting condition was eliminated as the internal layers of shielding cooled to a lower temperature. Shorting again occurred and was eliminated by again reducing the voltage. After this process was repeated several times, the test was terminated.

Inspection of the end disc radiation shielding at the end of this initial test indicated failure of the spot welds joining the several layers of discs and spacer wires; the inner end discs were thus allowed to move axially toward the heater element where they made intermittent contact and produced momentary shorts.

It is encouraging to note that the high temperature resistance element and shielding performed very well except for the above electrical shorting. Heat losses were very low, as indicated by the low temperatures of 773°F and 394°F on the Lava "A" terminal

TABLE XLII

3000°F 125 WATT HEATER TEST DATA

Time, Hours	Volts	Amps	Interior Temp.-°F	Outer Shield Temperature-°F				Lava Plug Temperature-°F		Pressure Torr
				1	2	3	4	5	6	
0	40	2.8	R.T.	R.T.	R.T.	R.T.	R.T.	R.T.	R.T.	9.8×10^{-9}
:30	--	--	2750	78	110	164	134	214	170	3.4×10^{-8}
1:00	--	--	3140	87	770	790	801	733	313	1.6×10^{-7}
1:30	36	2.5	3160	87	811	832	840	773	394	6.3×10^{-7}
2:00	--	--	3010	out	765	776	777	721	385	5.4×10^{-7}
3:30	30	2.2	3010	out	764	780	780	722	390	3.9×10^{-7}
3:45	20	2.8	2975	out	730	740	738	695	383	3.2×10^{-7}
4:30	15	2.3	2780	out	702	704	702	660	373	2×10^{-7}
5:00	10	1.7	2480	out	600	612	611	582	346	1×10^{-7}
5:30	6	1.2	2150	out	495	512	512	501	310	5.4×10^{-8}
6:00	5	*	2000							

* Direct short; ammeter pegged

Thermocouple Locations:

1. Outer shield adjacent to pyrometer viewport
2. Junction between cylindrical shield and end disc opposite heater terminal
3. Junction between cylindrical shield and end disc adjacent to heater terminal
4. Cylindrical shield
5. Junction between Lava "A" terminal and end disc radiation shield
6. Cold side of Lava "A" terminal near bolt hole

plug at the hot and cold faces when the furnace itself was at 3160°F with a power input of 116 watts. Outer radiation shield temperatures of approximately 800°F are reasonably low for such a high internal temperature.

After the initial operation of this heater, several improvements were made. The circular radiation shields, through which passed the power leads and filament supports, were securely fastened by means of tantalum wire straps. The power leads were extended further into the furnace to diminish the possibility of shorting in contact with the end shields. A new tungsten heater filament was installed. To insure the alignment of optical pyrometer sight holes through the many radiation shields, a 1/8-inch-diameter tantalum tube was inserted into these holes, which were enlarged from their original 0.040" X 0.080" size to accomodate this tube.

The heat losses in subsequent tests were greater since the more compact assembly of the end disc radiation shields did not permit as good a fit with the cylindrical furnace shields as occurred earlier; the addition of a 1/8-inch diameter tantalum tube at the optical sightport also increased the heat losses.

The heater was installed briefly in the vertical position in an ion getter pumped vacuum chamber and heated to a steady state temperature of 3000°F as measured by optical pyrometer measurements at a power input of 134 watts (42 volts, 3.2 amps). The outer

radiation shield temperature was in the 700-800°F range.

The test data for the complete 500-hour test are shown in Table XLIII. Thermocouples were attached to the outer radiation shielding (1) at the center of the end disc opposite the filament support terminal, (2) at the edge of the cylindrical radiation shield at its intersection with the end disc, and (3) on the cylindrical shield near one of the metal cradle supports. Thermocouples were also installed along the coldest face of the Lava terminal support, at the junction between the Lava terminal support and its adjacent radiation shield, and at the outer radiation shield near the tantalum tube inserted into the optical viewport. Frequent measurements were taken of the heater current and voltage, interior temperature and outer surface temperatures, and vacuum chamber pressure. The heater was brought to an internal temperature of 3000°F, and the heat shielding temperatures were allowed to reach equilibrium. The power required to maintain the 3000°F temperature was 149 watts. Earlier tests required only 134 watts to reach 3000°F with the heater in the vertical position and without the addition of the 1/8-inch-diameter tantalum tubing installed through the radiation shielding viewport. In original tests with this heater, only 90 watts were required to achieve 3000°F internal temperatures, but the conical fit of the heater element shielding with the cylindrical shielding was much better initially.

During the 500-hour endurance test, the cylindrical shielding

TABLE XLIII

HEATER S/N 2B TEST DATA
100% PLATINUM HEATER ELEMENT WIRE
MAGNESIA CORE
BORON NITRIDE FILL

Elapsed Time From 2000°F Start, Hrs (Approx.)	Electrical Data				Temperatures, °F		Differential Between T/C Jctns. #12 & #13, °F
	Measured		Calculated				
	Applied DC Voltage, Volts*	DC Current, Amperes	Input Power, Watts	Resistance, Ohms	Interior, T/C Jctn. #12	Cartridge Surface, T/C Jctn. #13	
0	10.50	1.52	15.95	6.90	2008	2005	3
1.76	10.60	1.58	16.75	6.70	2000	2000	0
21.70	10.40	1.55	16.10	6.70	1975	1970	5
21.72	10.60	1.58	17.65	6.71	Power reset as indicated		
23.10	10.75	1.60	17.20	6.71	2000	1995	5
27.20	10.60	1.55	16.40	6.81	1996	1985	11
43.80	10.50	1.52	15.98	6.91	1980	1965	15
87.50	10.60	1.55	16.40	6.84	1980	1965	15
96.90	10.60	1.55	16.40	6.84	1975	1960	15
112.20	10.60	1.55	16.40	6.84	1980	1960	20
135.50	10.60	1.52	16.00	6.96	1969	1952	17
144.00	10.60	1.52	16.10	6.97	1969	1952	17
161.00	10.60	1.53	16.20	6.94	1968	1950	18
169.00	10.60	1.52	16.10	6.97	1957	1938	19
185.00	10.60	1.55	16.41	6.83	1968	1949	19
192.50	10.60	1.55	16.42	6.83	1970	1950	20
200.00	10.60	1.55	16.42	6.83	1970	1950	20
			End of test				

Initial room ambient resistance = 1.60 ohms
Final room ambient resistance = not available, lead broken off
Environmental pressure variation during test = 1.2×10^{-6} to 1.0×10^{-7} mm Hg

* Measured at power terminals outside vacuum tank.

slowly shifted at the open, conical end (because of inadequate fit-up), and the heater shorted out after about 370 hours of testing. The heater was removed from the vacuum chamber; the terminal support, end radiation shielding, and heater filament assembly were removed from the cylindrical radiation shielding. After the cylindrical radiation shielding had been adjusted to prevent further shorting of the heating element, the heater was reassembled and the test continued to completion.

The satisfactory operation of the heater during the 500-hour endurance test provided a sufficient indication of its reliability to permit the final design of the 3000°F heater and thruster. There was no deterioration of the heater components, which operated in a stable manner under constant power input conditions. The increase of power losses with (1) improperly fitted radiation shielding and (2) incorporation of the 1/8-inch-diameter optical viewport tube gave concrete evidence of the increased power losses which could be expected if a 3000°F thruster were built with its necessary structural support and freely radiating nozzle area.

3000°F Thruster - The layout of the 3000°F thruster was completed; some detailed component drawings were prepared, and some component materials were ordered for its fabrication. The overall configuration of this thruster is shown in Figure 99. The design of the heater incorporated the basic design used in the 500-hour test, but improvements were made in the method of installing and

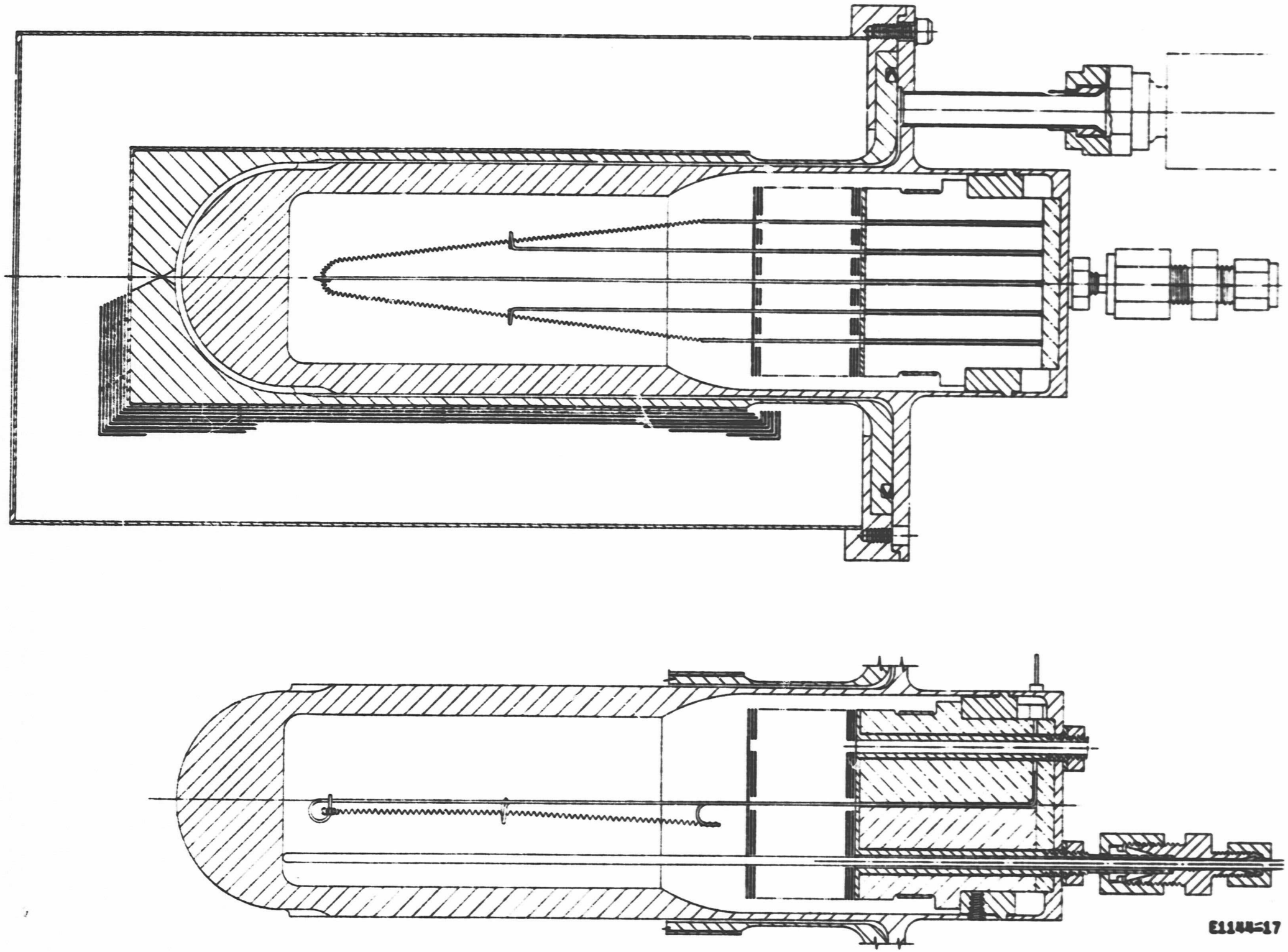


Figure 99. Electrical Simulation of 3000°F Radioisojet Thruster.
(From Drawing 246R723)

retaining the filament supports and in adapting the Lava terminal to meet the requirements of the thruster. In order to minimize the joining requirements in assembling the thruster components, the inner body and its flange, and also the outer body and its flange, were designed as integral parts machined from TZM molybdenum bar stock 4-1/4 inches in diameter. While the precision machining of these integral components would be difficult, the elimination of welds for joining (1) the flanges to the thruster cylinders and (2) the nozzle to the outer cylinder would appreciably improve the reliability and the manufacturability of the thruster. Only one low temperature braze joint would be required in the thruster itself, namely, that of the ammonia supply tube to the aft thruster flange.

Because the 500-hour heater tests on the 3000°F heater indicated significant heat losses with minor variations in heat leak path configurations, a decision was reached with NASA to terminate any further work on this thruster. It is doubtful that the radiation and conduction heat losses at 3000°F could be kept within reasonable limits in a practical thruster device where high thermal conductance paths exist through the TZM molybdenum structural supports and where the free radiation area from the thrust nozzle was significant.

IV CONCLUSIONS

1. Predicted performance of the TSK2000-1P thruster was verified with specific impulse measurements above 250 seconds recorded at GSFC.

2. The modular design concept employed in the TSK2000-1P design has been proven to allow interchangeability of components.

3. The performance of the TMJ2000-5P multijet thruster was less than predicted. Nozzle design modifications resulted in improved performance although a significant pressure drop still existed in the flow path annulus.

4. Catalytic decomposition was proven with the TSK2000-1C thruster test bed. A major increase in delivered specific impulse was measured at temperatures between 1500°F and 2000°F.

5. Radioisotopic heating of a thruster was demonstrated with the TSK2000-1RE thruster design. Maximum temperature reached during the testing was less than predicted due to excessive conductive losses in the heater support section.

6. Molybednum was found to be an excellent heat shielding material although reproducibility of fabrication was not demonstrated.

7. High emissivity coatings are effective in reducing heat shielding outer surface temperatures.

8. Low emissivity coatings (i.e. gold plating) is unaffective above 1000°F due to diffusion into the base material.

9. Thruster length to diameter ratio appears to optimize between 1.5 and 2.5 depending on heat shielding material. This is compatible with existing thruster design practice.

10. The 3000°F simulated radioisojet needs further design work to solve complex materials joining and sealing problems.

11. A 2000°F, swaged, cartridge-type heater has demonstrated excellent resistance stability and operating life for periods up to 6,600 hours at 20 to 30 watt power levels. The final configuration heater consisted of a magnesia core surrounded successively by a platinum-10% rhodium heater wire, boron nitride fill, and a Hastelloy X swaged sheath.

12. The selected heater does not have sufficient life under thermal cycling conditions to consider its use where intermittent operation is required.

13. The extent of mass transfer of metallic elements from the outer surfaces of the swaged heater does not appear to offer significant

problems within the periods of time investigated; however, metal vaporization from the inner surfaces of the sheath require the use of ceramic fill materials, such as MgO or BN, which densify during swaging to prevent transfer of the metal vapors to the heating element.

14. Migration of calcium from the magnesia core into the platinum alloy heating element under the influence of a DC voltage potential results in the formation of brittle phases within the element and in increased electrical resistance of the wire over a long period of time.

15. Strain age cracking, which was observed in Hastelloy X swaged heater sheaths during initial heater operation, can be eliminated by a process of "plunge" annealing the swaged heaters at 2000°F in vacuum prior to their operation.

16. A molybdenum-containing brittle phase developed within the Hastelloy X heater sheaths after 1,500 hours of testing at 2000°F but did not adversely affect the performance of the heaters.

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V RECOMMENDATIONS

1. The TSK2000-1P single-jet thruster should be incorporated into a flight package for additional testing as part of a complete system for potential flight application.

2. The TMJ2000-5P multijet thruster design should be modified to increase the flow path volume and to eliminate pressure dropping restrictions. Further work in the design of a low-heat-loss supporting structure is required.

3. Radioisojet testing should be continued at least for a year and preferably for one-half-life. Performance testing should be expanded to provide additional correlation between electrical heating and radioisojet heating.

4. Additional effort should be expended in providing a reproducible means of fabricating heat shielding packages of molybdenum foil.

5. Alternate coating materials to provide the low emissivity qualities of gold plating should be investigated.

6. No further 3000°F radioisojet development should be initiated until a genuine need for such a thruster is established.

7. The successful MgO, Pt-10% Rh, BN, Hastelloy X, swaged heater system should be used for steady-state testing and development of thrusters and for initial flight hardware but should not be subject to intermittent operating requirements.

8. Because of the observed indications of calcium transfer from the magnesia core to the platinum alloy wire under DC voltage potentials, higher purity magnesia or alumina cores should be used in platinum wire heaters.

9. Because of the observed chromium (and other) metal element evaporation and mass transfer from chromel-alumel thermocouples, particularly in platinum wound heaters, thermocouples should not be installed within swaged heaters unless they are of the same base alloy system as the heater elements themselves.

10. Additional heater materials evaluation work should be undertaken to identify those materials which are more resistant (1) to failure under thermal cycling and (2) to the diffusion of impurity elements into the heater wire which results in increased element resistance or embrittlement. More refractory alloy element wires and higher purity core materials should be investigated in a testing program designed to understand the factors relating to heater reliability.