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FOREWORD

The work reported herein covers Task 5 of the Statement of Work contained in Modification No. 7, 28 June 1966, to the Radioisotope Propulsion Program (POODLE), Contract AT(04-3)-517, for the AEC Division of Isotopes Development and the Joint AEC/NASA Space Nuclear Propulsion Office. This task was concerned with techniques for simulating radioisotope heat source characteristics using electrical resistance heaters. It was specifically oriented toward configurations and conditions applicable to POODLE heat sources. The Task Engineer was Eugene Nezgoda, who directly conducted experimental phases of the work. He was assisted by Joseph Licari, who performed the analyses. The complete Final Report on Modification 7 consists of this volume and others as listed below:

<u>Volume</u>	<u>Title</u>
I	Capsule Creep Strain Measurements and Analyses
IIA	Analytical Program for Creep in Axisymmetric Shells (CRASH)
IIB	Analytical Program for Creep in Axisymmetric Bodies (CRAB)
III	Oxidation and Diffusion in Noble Metal Alloy Claddings
IV	Performance of Low Thrust Nozzles
V	Simulation of High-Temperature Radioisotope Heat Source
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1. INTRODUCTION

The use of electrical heaters to simulate radioisotope sources permits relatively safe and inexpensive experimentation in the development of radioisotope thruster technology. The POODLE thruster requires a cylindrical heat source approximately 2 inches in diameter and 14 inches long. The heat source strength is 5 kilowatts at time of launch. It operates in the 2000-2200°C range for approximately 30 days.

A thruster test using a resistance heater was conducted in a previous phase of the POODLE program (Reference 1) to obtain system thermal characteristics and other basic design data. The test thruster utilized a graphite heater which was operated at 2000°C for 72 hours with hydrogen flow. In order to achieve higher temperatures and longer durations for simulating POODLE operation, a program was undertaken to develop refractory metal heaters. The program called for the design and testing of two different heaters configured to fit within the POODLE heat source envelope. They were to operate continuously in vacuum for 30 days at a uniform temperature of 2200°C (3992°F) along their entire length, a condition corresponding to a thruster in the no-flow condition with uniform axial isotope distribution and very small thermal losses at either end.

The requirement for attaining a uniform temperature profile along the heater length was given special attention. Since the power generated per unit length of the heater is a function of its local resistance, which in turn is strongly temperature-dependent, a detailed thermal analysis of the system was performed. Preliminary configurations for the heater, electrical leads and thermal insulation were selected, and computer thermal models of the components and system were constructed. Final component dimensions and the number of thermal radiation shields around the heater and leads were then determined analytically. Laboratory tests of the two heaters were performed at the design conditions, and comparisons with the analytical results were made.

2. HEATER DESIGN

2.1 DESIGN CONCEPTS

A heater design based solely on radiative heat transfer was adopted. Conduction through ceramic insulators had been considered but was not pursued because of chemical incompatibility and poor electrical properties in the vicinity of 2000°C . Proven POODLE technology was employed wherever possible, and design innovations were minimized to facilitate fabrication. Each of the two heater systems was composed of a heater, electrical leads connecting the heater with the power source, and thermal insulation surrounding the heater-lead assembly. One of the systems utilized a split cylindrical heater and the other a helical heater.

2.1.1 Material Evaluation

Candidate materials for use in fabricating the POODLE heater were graphite, molybdenum, tantalum, and tungsten. Both graphite and molybdenum POODLE thruster components have been used successfully in the past at temperatures up to 2000°C for short durations, but their evaporation rates preclude their use at 2200°C for extended periods of time.

Tantalum was of interest because of its high melting point (2996°C), relatively low evaporation rate, and its greater ductility compared to molybdenum and tungsten. It was eliminated from consideration, however, because of its affinity for hydrogen, which will be the working fluid in future POODLE tests. Absorption of hydrogen below 1000°C results in severe embrittlement of the material.

Tungsten was chosen as the heater material because of its high melting point (3395°C), favorable electrical and mechanical properties, low evaporation rate, and strength at high temperature.

The unsuitability of graphite and molybdenum for 30-day tests (720 hours) at 2000° to 2200°C , and the superiority of tungsten under the same conditions, is apparent from Table 2-1. The evaporation times shown were calculated from the following equation (Reference 2):

$$G = p' \sqrt{\frac{M}{2\pi RT}} = 5.833 \times 10^{-2} p \sqrt{\frac{M}{T}}$$

G = rate of evaporation, gm/cm²-sec

R = universal gas constant

p' = vapor pressure, dynes/cm²

p = vapor pressure, mm Hg

M = molecular weight

T = temperature, degrees Kelvin

Table 2-1. Comparison of Evaporation Rates

Material	Vapor Pressure (mm Hg)		Evaporation Time to Depth of 1 Mil (Hours)	
	2000°C	2200°C	2000°C	2200°C
Graphite	2×10^{-5}	7×10^{-4}	14	0.5
Molybdenum	1×10^{-5}	1.5×10^{-4}	60	6
Tungsten	4.7×10^{-9}	1×10^{-7}	173,000	7,600

2.1.2 Cylindrical Heater

A heater configuration similar to the one constructed from graphite and used successfully in previous short-duration tests was chosen for this application. However, for reasons explained above, tungsten was selected as the heater material instead of graphite. The previous heater (Figure 2-1) consisted of two half cylinders connected at one end to complete the electrical path. This configuration permits tailoring of the wall thickness to obtain the desired temperature profile.

As schematically shown in Figure 2-2, the new tungsten heater consisted of two half-cylinders, separated by axial slots for all but a small portion near one end. Heater ruggedness could have been enhanced by adding a stiffening ring at this end, but the local heat generation would have been decreased making it impossible to achieve a flat temperature

Figure 2-1. Graphite Heater After 72-Hour Test at 3600°F

Figure 2-2. Cylindrical Heater System Schematic- Conceptual Design

profile along the entire heater length. The length and outer diameter of 14.1 inches and 1.5 inches, respectively, were chosen to fit within the POODLE thruster module as configured at the time. Available data on the high temperature behavior of tungsten indicated that a heater wall thickness of 0.040 inches would be adequate (Reference 3).

An axially uniform radial heat flux could be achieved with a heater of uniform thickness if energy losses at each of its ends could be eliminated or compensated. Near the bottom of the heater, energy is lost by radiation to the axial insulation in the same manner as in the remainder of the heater, and additional energy may also be lost by radiation to the end insulation. Two means were available to reduce end losses. The first involved adding thermal insulation at the end of the heater to increase thermal resistance between the heater and test chamber, minimizing the temperature drop near the end of the heater. The second solution involved reducing the wall thickness of the heater near the end, resulting in a smaller cross sectional area, higher resistance, and higher local power generation to compensate for end losses. The latter method was selected because it was simpler and because experience gained in using it to achieve the flux profile specified would be applicable for more general profiles.

The achievement of a flat temperature profile in the heater also required that an adiabatic plane exist at the lead-heater interface so that no energy losses would occur through this end of the heater. Elimination of these losses could most easily be achieved by proper design of the leads and accompanying insulation. It was found that the heater cross section near the leads did not have to be altered.

2.1.3 Cylindrical Heater Leads

The leads were fabricated from tungsten, since their temperature will equal that of the heater at the heater/lead junction. Attachment of circular lead rods to the thin-walled heater cylinder (as in the previous graphite heater) was not considered in this instance, to avoid distortion of the heater geometry which would perturb the power generation and temperature profile near the interface. The leads were designed as half cylinder extensions of the heater, as shown in Figure 2-2.

Since electrical power was to be applied through water-cooled copper clamps attached to the leads, a very large axial temperature gradient in the leads was expected. While leads of short length would seem desirable in order to reduce the lead power generation, short leads permit high thermal conduction losses and might actually require higher power generation to maintain the required heater-lead interface temperature. In addition, maintenance of clamp temperature at approximately 100°C would be more difficult because of the larger heat flux conducted to the clamps. As a result of previous test experience, a lead length of 8 inches was used.

The same design options considered for the heater were applicable to the leads: contouring lead thickness or adjusting external insulation. If the leads were surrounded by thermal insulation similar to that of the heater, contouring would be necessary to generate enough energy to meet both conductive heat losses to the clamps and radiative losses to the shields. This would result in a total lead power generation of the same order of magnitude as the heater. Minimized power generation in the leads is desirable in order to minimize performance variations between electrically-heated and isotope-fueled thruster models. Accordingly, the amount of insulation surrounding the leads was increased, decreasing the energy lost by radiation. Ideally, with radiative losses eliminated by employing a very large number of shields, power generated in the leads could be reduced to the level of conduction losses to the water-cooled clamps. However, practical fabrication considerations dictated that less than 50 radiation shields be employed. The actual number of shields surrounding the active heater length was determined by detailed thermal analyses, as was the lead contour which would give an adiabatic interface and a temperature at the interface of 2200°C .

2.1.4 Helical Heater and Leads

In addition to the split-cylinder heater, an alternate heater configuration was experimentally evaluated. The most attractive alternate was a helical heater fabricated from a refractory metal rod coiled to a prescribed diameter and pitch.

In order to achieve the most realistic geometry possible, it was

desirable to close one end of the heater assembly and to pass the return lead through the interior of the helix as shown in Figure 2-3. The leads were merely extensions of the rod which formed the coil, and both leads protruded from the same end. This heater concept has several advantages. Fabrication is simple, since it merely involves coiling a refractory metal rod. In addition, the power generation per unit length of the heater can be controlled, as desired, by altering the pitch of the heater coils. However, analysis is difficult due to the irregular geometry and complex radiative view factors.

As in the cylindrical heater, tungsten was the only acceptable material. Because of its improved mechanical properties, 1 percent thoriated tungsten was used rather than pure tungsten. A preliminary analysis showed that a 0.25-inch diameter rod would permit operation within the electrical current capability of the test apparatus. A lead length of 8 inches, heater length of 14.1 inches and coil outer diameter of 1.5 inches were chosen, analogous to the split-cylinder heater. End losses were to be compensated by varying the heater coil pitch. It remained to determine analytically the pitch of the coil and the required thermal insulation for the heater and leads.

2.1.5 Thermal Insulation

The only practical thermal insulation for use with either heater design at the temperatures of concern was radiation shielding fabricated from refractory foils. Multiple shield molybdenum insulation had been used successfully in previous POODLE tests. However, these tests were conducted at lower temperatures and for shorter durations. Analyses also showed that the high rate of sublimation of molybdenum at the anticipated temperatures prohibited its use over the extended duration of the test. The affinity of tantalum for hydrogen, as mentioned earlier, also precluded its use as insulating material. Tungsten again appeared to be the most desirable material because of its chemical stability and extremely low vapor pressure even at these higher temperatures.

Thermal radiation shields must be effectively separated from each other to prevent conductive heat transfer from degrading insulation performance. Preliminary tests on mechanical dimpling, successfully

MATERIAL: TUNGSTEN/2 PER CENT THORIA 1/4 IN. DIA

Figure 2-3. Helical Heater - Conceptual Design

employed for molybdenum, showed that this method could also be used for the tungsten shielding, although the forming properties of tungsten are poorer. Considering cost, availability, and mechanical properties, tungsten sheet of 5-mil thickness was chosen. The axial shielding was composed of concentric cylinders, while end shields consisted of circular discs. In order to avoid electrical shorting, an inside diameter of 2.00 inches was chosen for the insulation, maintaining sufficient spacing between heater and insulation to prevent contact.

2.1.5.1 Cylindrical Heater Insulation

Forty-five concentric axial shields were used to minimize radiative heat losses from the heater leads. Four concentric axial shields were emplaced around the heater active length, and four circular shields were used at its closed end. An array of stacked circular disks was placed between the heater leads to minimize radiative heat exchange between the hot end of one lead and the cold end of the other. Inclusion of these disks also simplified the analysis, since it eliminated consideration of such exchange. Support and positioning techniques are discussed in Section 3.

2.1.5.2 Helical Heater

Because of the expense and complexity involved in fabricating tungsten radiation shields, it was desirable to employ the same shielding package with both heaters. This proved feasible, except for the heater lead shielding. Analysis showed that although the 45-shield lead insulation was satisfactory for the cylindrical heater leads, this amount of insulation was much too effective for the helical heater leads as explained in Paragraph 2.3.2. The analysis indicated that 15 shields would be sufficient.

2.2 ANALYTICAL TECHNIQUES

The heater system consisted of the heater-lead assembly enclosed in thermal insulation. Detailed thermal analyses of several alternative configurations were conducted in arriving at the best design. Independent thermal analyses of the insulation were performed to obtain effective conductance as a function of the number of shields and surface tempera-

ture of the innermost shield. These relationships were then used to describe the insulation in the complete system analysis. It was therefore necessary to construct analytical models of both the insulation and the complete heater system.

The thermal analyses were performed with the aid of a digital computer in order to determine the combined effects of variations in thermophysical properties with temperature; axial conduction along the heater and leads; radiation between heater and shielding and between shields; heat losses from pyrometer sighting holes; and heater and lead dimensional variations.

2.2.1 Computer Program

The TRW Thermal Analyzer Program (TAP) was chosen to perform the thermal analyses on an IBM 7094-II digital computer. The TAP program is a general purpose code which analytically simulates a heat transfer system by means of an electrical analog network. The resulting lumped-parameter system is a series of nodes representing points in the heater, leads, insulation and test chamber. These nodes are interconnected by thermal resistances representing the various heat transfer paths between the nodes. Although both steady-state and transient analyses may be performed with the program, only the steady-state mode was employed in the present analyses. For a steady-state solution to a given thermal network, TRW/TAP uses a modified relaxation method to solve the system energy balance expressed in the form of a system of simultaneous finite-difference equations. From an input of material thermophysical and electrical properties, system geometry, and electrical current the program computes a complete temperature description of the system. Using such a technique the number of shields required around the heater active length, the heater lead thickness, and the heater end geometry were determined.

2.2.2 Insulation Thermal Model

A complete thermal model of a multiple radiation shield insulation system composed of concentric foils must account for the following modes of energy exchange:

- 1) Radiation between shields
- 2) Conduction through any gas in the gap between the shields
- 3) Conduction through the surfaces in contact between the shields
- 4) Axial conduction along the shields

The test was conducted in a sufficiently high vacuum to neglect the effect on insulation performance of heat transfer by gaseous conductance between foils (mode 2).

An accurate evaluation of the effective contact areas between shields and the resultant net thermal resistance is extremely difficult. As a first approximation to mode 3, the limiting case of ideal shields with no contact between them was considered and an empirical correction factor was applied to arrive at an estimate of the performance of real shields with contact.

Axial conduction in the shields (mode 4) was not included in the thermal model. In the shields which surround the heater, axial conduction is negligible because of the small axial temperature gradient and small cross-section presented by the thin refractory foils. In the lead shielding, large temperature gradients may significantly affect system performance. However, analytical treatment of the multishield configuration around the leads was considered beyond the scope of the present analysis, since it would require an extensive thermal model and considerable computer time.

The thermal model used was idealized, in that only one-dimensional radiative heat transfer between shields was considered (mode 1). Emissivity of the shield material as a function of temperature was included in the model. As previously indicated and as described in Section 2.3.1, an empirical correction was applied for conduction at points of contact between shields. Insulation performance predicted in this manner was sufficiently accurate for the intended purpose.

2. 2. 3 Cylindrical Heater Thermal Model

The analytical model used for the cylindrical heater system consisted of the heater, leads, thermal insulation and test chamber. The computer network, shown schematically in Figure 2-4, required 110 thermal resistances and 55 nodes. The model accounted for axial heat conduction in the heater and leads. Data on insulation performance as a function of temperature, generated separately and corrected for shield contact effects, were included in the system model. These data were used to compute thermal resistance between the heater and test chamber wall, and between the leads and wall.

In the actual experiment, there were four pyrometer sighting holes through the heater insulation. Since energy losses through these holes affect the heater temperature, the sighting holes were included in the analytical representation. The end of the heater at which the two half-cylinders are joined could not be precisely described in the analytical model because the current density distribution at that junction was not known. At the other end of the heater, the description of the heater leads was simplified because the presence of thermal insulation between the leads made it unnecessary to consider radiative heat exchange between the leads.

Power generation in the leads and heater is a function of the electrical current and resistivity, as well as the geometry of the system. In the thermal model, current was assumed to be constant for a given case, but electrical resistivity, thermal emissivity, and thermal conductivity of the heater were introduced as functions of temperature.

Thermal boundary conditions were determined by the test chamber and water-cooled clamps on the power leads. The test chamber, assumed to be at 40°C, served as the thermal sink for all radiation losses. The clamps were maintained at 100°C and received all energy conducted through the heater leads.

The model was constructed to facilitate its use with various geometries and insulations. For any given combination of heater and lead geometry, thermal insulation, and electrical current level, a complete temperature map of the system can be obtained.

Figure 2-4. Thermal Network of POODLE Heater System

2.2.4 Helical Heater Thermal Model

The coiled heater system analytical model was similar to the split-cylinder model, but more approximations were necessary in calculating axial and radial energy transfer. Exact simulation of axial heat transfer would require inclusion of radiation view factors between coils. This additional complexity was considered unwarranted because the heater was designed to produce a flat axial temperature profile with little energy transfer between coils. Therefore, the coiled heater geometry was approximated by a cylindrical surface with the same outer diameter as the coil. The accuracy obtained using this approach depends upon the pitch of the coil. Although actual test data are required to determine the difference between theory and practice, this approach was believed to be reasonable for the heater rod and pitch dimensions considered.

2.3 DETAIL DESIGN

2.3.1 Cylindrical Heater Thermal Insulation

As mentioned above, 45 shields were used to insulate the leads. The number of shields required around the active heater length to radiate 5000 watts at 2200°C was computed. Separate thermal models for both heater and lead shielding systems were used to provide performance data based on idealized shielding, and these data were then corrected using extrapolated test data to obtain a more accurate description of the insulation performance.

Applicable experimental performance data for tungsten radiation shielding of the type used were essentially nonexistent. However, data for molybdenum shields were available from a previous POODLE test. This shielding consisted of 0.005-inch foils separated by mechanically-produced dimples. The emissivity of tungsten is only slightly higher than that of molybdenum and exhibits a similar temperature dependence. Available molybdenum data up to 2000°C (Figure 2-5) showed that the measured conductance of the shields was 20 percent higher than predicted by analyses accounting for all significant heat transfer modes. The ratio of actual conductance to ideal (heat transfer between shields by radiation only) conductance for the molybdenum shielding was evaluated as a function

Figure 2-5. Thermal Conductance of Radiation Shielding vs. Temperature (20 Molybdenum Shields with Dimples)

of temperature. The conductance ratio reflected the net magnitude of all differences between test and ideal conditions, including the effects of contact between shields and emissivity variations. Separation of these effects was impossible.

Several factors made direct application of these data to the tungsten shielding uncertain. The size and spacing of dimples in the molybdenum shields were different. The vacuum under which molybdenum data were obtained was not sufficiently low to preclude the possibility of an increase in emissivity due to surface oxidation. The number of shields (20) in the molybdenum system differed greatly from the number of tungsten shields used around the heater (less than 10) and around the leads (45). In addition, the effect on performance ratio of differences in system size was unknown.

Despite the differences cited, molybdenum shield performance data were extrapolated to the tungsten shielding system because of the general similarity of the two systems, in terms of configuration and material properties, and because of the lack of alternative scaling techniques. The ratio of experimental to ideal conductance, and its variation with temperature, was assumed to be the same for the tungsten insulation as for the 20-shield molybdenum insulation. This ratio was 1.5 at 2200°C.

Data for the 45-shield lead insulation were included in the heater system model. For the heater insulation, performance data were generated using different numbers of shields. Preliminary analyses for a heater temperature of 2200°C showed that 4500 watts could be accommodated with four concentric tungsten shields and 5500 watts with three shields. With 2200°C and 5000 watts established as design goals, the four-shield system was selected because the insulation performance was considered to be optimistic. Established performance data for this insulation was then included in the heater system model.

Thermal insulation between the two leads was also made of tungsten foils (Figure 2-2). Rigidity of the foil assembly was required to prevent electrical shorting due to contact between foils and leads. A series of 1-inch diameter tungsten disks was used. Small pieces of

tungsten wire were randomly welded to each disk to maintain separation while achieving a sufficiently rigid integrated structure. The spacing between disks and the gap between the disk assembly and leads was 0.125 inches--sufficiently small to preclude significant energy exchange between hot areas of one lead and cooler areas of the other. The multi-shield assembly was supported from the cooler end by a 1/8-inch diameter tungsten rod which added to the rigidity of the structure. It was assumed that this insulation was sufficiently effective to preclude significant axial heat losses and heat transfer between leads.

2.3.1.1 Heater

The heater length of 14.1 inches and constant wall thickness of 0.040 inch were dictated by thruster geometry and material property considerations. All cases were analyzed at a current of 718 amperes. This current satisfies the heater power and temperature requirements to within the accuracy of the analyses and was therefore employed as the design value for this study. Analyses showed a reasonably flat heater temperature profile except at the closed end where a temperature drop of about 120^oC occurred in the last 2 inches. This end, where the heater hemicylinders are connected, was suspected as a potential problem area. Because the current density distribution was not defined in this region, the temperature drop calculated was uncertain.

To reduce the temperature gradient, it was necessary to increase power generation at the closed end. This could be accomplished by decreasing the length of the joint and/or the cross section of the heater near the end. Results of several system analyses performed with changes in the end-geometry are shown in Table 2-2. A step reduction in thickness from 0.040 to 0.034 inches over the joint length substantially increased temperatures near the end but was undesirable from a fabrication standpoint. It was also undesirable to overheat this area of the heater because strength at the joint was critical. Accordingly, a tapered end combined with a reduced joint length was chosen. This produced a nearly flat temperature profile and provided a safety margin against overheating.

Table 2-2. Effect of Variations in Heater End-Geometry

	Case 1	Case 2	Case 3	Case 4
Heater thickness over joint length (inches)	0.040	0.036	0.034	Taper From 0.040 to 0.034
Joint length (inches)	1.084	1.084	1.084	1.000
Lead power (watts)	750	760	760	760
Heater power (watts)	4755	4805	4815	4790
Temperatures ($^{\circ}\text{C}$)*				
T_{27}	2220	2220	2220	2220
T_{54}	2220	2220	2220	2220
T_{28}	2215	2215	2215	2215
T_{31}	2225	2225	2225	2225
T_{36}	2220	2225	2225	2225
T_{42}	2180	2195	2210	2195
T_{47}	2075	2115	2135	2100

Additional System Parameters

Heater thickness - 0.040 inches (constant)

Current - 718 amps

Heater insulation - 4 tungsten shields

Lead insulation - 45 tungsten shields

*Numbers refer to locations shown in Figure 2-4

2.3.1.2 Heater Leads

An 8-inch lead-length was selected, as discussed previously. The heater system model was used to determine the lead thickness required for a negligible temperature gradient across the lead-heater interface, i. e. , to produce an adiabatic surface at the interface. Results for a number of constant axial thicknesses are shown in Table 2-3, where the location of temperatures shown may be determined from Figure 2-4. A lead thickness of 0.098 inches was selected since it provided the required flat temperature profile at the lead-heater interface. At the same time, insulation surrounding the leads was sufficiently effective to limit lead power to less than 16 percent of the power generated in the active heater.

2.3.1.3 Final Heater System Design

A summary of the final, split-cylinder heater system design as shown in Figure 2-2 is given below.

Heater

Length:	14.1 inches
Outside diameter:	1.5 inches
Thickness:	0.040 inches from lead-heater interface to joint; 0.040 to 0.034 inch taper over 1.00 inch joint
Material:	Tungsten

Leads

Length:	8.00 inches
Outside diameter:	1.5 inches
Thickness:	0.098 inch over entire length
Material:	Tungsten

Insulation

Material:	0.005 inch tungsten sheet
Quantity:	4 shields around heater 45 shields around leads

Table 2-3. Effect of Variations in Lead Thickness

	Case 1	Case 2	Case 3	Case 4	Case 5
Lead thickness (inches)	0.104	0.103	0.100	0.098	0.095
Lead power (watts)	680	690	740	750	800
Heater power (watts)	4750	4750	4750	4755	4760
Temperatures ($^{\circ}\text{C}$) *					
T_{27}	2140	2145	2190	2220	2250
T_{54}	2145	2150	2190	2220	2245
T_{28}	2175	2175	2200	2215	2225
T_{31}	2225	2225	2225	2230	2230
T_{36}	2220	2220	2220	2220	2220
T_{42}	2180	2180	2180	2180	2180
T_{47}	2075	2075	2075	2075	2075

Additional System Parameters

Heater thickness - 0.040 inches (constant)

Current - 718 amps

Heater insulation - 4 tungsten shields

Lead insulation - 45 tungsten shields

*Numbers refer to locations shown in Figure 2-4

Performance Parameters at 2200°C

Current:	718 amps
Heater power:	4790 watts
Lead power:	760 watts

Calculated axial temperature profiles at the nominal design condition are shown for the leads in Figure 2-6 and for the heater in Figure 2-7. The heater-lead interface is essentially an adiabatic plane. Approximately 80 watts are lost through the four pyrometer sighting holes. As a result, a slight perturbation in the heater profile is observed. Otherwise, variation in heater temperature is very slight over the 13.1 inches between the lead-heater interface and the heater joint. The temperature drop over the last two inches has been limited to 120°C, with a radiation loss of 60 watts from the closed end. The total heater power generated is 4790 watts. The lead power is 760 watts, or 16 percent of the heater power. A total of 560 watts are conducted from the leads to the water-cooled clamps. These analytical results indicated that the final heater design would satisfy design objectives.

2.3.1.4 Off-Design Performance

The design analyses were based upon the best available tungsten thermal conductivity, electrical resistivity, and thermal insulation data. However, the actual values of these parameters may vary appreciably from those employed in the analyses. Calculations were therefore repeated for the cases listed below, which assume various percentage changes in material properties or insulation performance. It should be noted that heater temperatures were only roughly the same for all cases since the purpose of these analyses was to determine the approximate changes in current and power required to reach design levels.

<u>Case</u>	<u>Variation from Design Description</u>
1	Ideal thermal conductance between heater and chamber and between leads and chamber. This would provide a minimum value for current and power since this would represent the maximum shielding effectiveness.
2	80 percent of design lead-to-chamber conductance

Figure 2-6. Predicted Axial Temperature Profile of Cylindrical Heater Leads

Figure 2-7. Predicted Axial Temperature Profile of Cylindrical Heater Element

<u>Case</u>	<u>Variation from Design Description</u>
3	120 percent of design lead-to-chamber conductance 110 percent of design heater-to-chamber conductance
4	150 percent of design lead-to-chamber conductance 130 percent of design heater-to-chamber conductance
5	110 percent of tungsten thermal conductivity over entire temperature range
6	Variation in tungsten thermal conductivity from 115 percent of design value at 90°C to 85 percent of design value at 2200°C
7	Variation in tungsten thermal conductivity from 85 percent of design value at 90°C to 115 percent of design value at 2200°C
8	110 percent of design tungsten electrical resistivity over entire temperature range

Results in Tables 2-4 and 2-5 show that reasonable changes in current can compensate for relatively large variations in insulation performance. In the worst case considered, only 824 amps and 6280 watts are required to reach the desired heater temperature range. At the same time, the flatness of the heater profile is acceptable. These off-design analyses showed that effective compensation could be made during the test for reasonable differences between expected and realized system behavior.

2.3.2 Helical Heater

2.3.2.1 Thermal Insulation

The analytical data generated to describe the performance of the insulation for the split-cylinder heater was initially employed to describe the insulation in the coiled heater system. The four-shield heater insulation was shown to be adequate, but the 45-shield lead insulation was too effective, resulting in excessively high lead temperatures. This was attributable to the small surface area of the coiled heater leads. The lead insulation data were modified and, after several additional analyses, it was found that 15 shields surrounding the heater leads result in an adiabatic surface at the lead-heater interface. The calculated axial

Table 2-4. Off-Design Performance Variations in Insulation

	Design	1	2	3	4
Lead Power, watts	760	585	695	800	1005
Heater Power, watts	4790	4075	4560	5250	6280
Current, amps	718	669	714	757	824
Temperatures ($^{\circ}\text{C}$)					
T_{27}	2220	2130	2220	2220	2280
T_{54}	2220	2140	2220	2220	2275
T_{28}	2210	2170	2210	2220	2250
T_{31}	2225	2225	2225	2235	2240
T_{36}	2225	2225	2220	2230	2235
T_{42}	2195	2190	2195	2205	2215
T_{47}	2105	2105	2100	2110	2110

Table 2-5. Off-Design Performance Variations in Thermal Conductivity and Electrical Resistivity

	Design	5	6	7	8
Lead Power, watts	760	730	725	780	750
Heater Power, watts	4790	4780	4780	4800	4770
Current, amps	718	718	718	718	681
Temperatures ($^{\circ}\text{C}$)					
T_{27}	2220	2165	2200	2225	2205
T_{54}	2220	2170	2200	2220	2200
T_{28}	2210	2190	2205	2215	2205
T_{31}	2225	2225	2225	2225	2220
T_{36}	2225	2225	2225	2225	2220
T_{42}	2195	2195	2195	2195	2220
T_{47}	2105	2110	2100	2115	2130

temperature profile of the heater leads is shown in Figure 2-8.

2.3.2.2 Heater and Leads

To simplify the system, the leads were designed to be merely 8-inch extensions of the 0.25-inch diameter rod of which the heater is composed. As previously mentioned, it was necessary to return one lead to the opposite end of the coil by passing it through the center of the helix.

In the initial heater design, 19 equally-spaced coils were used with a 0.75-inch pitch. End losses in this design caused a temperature drop of 120°C over the last 1.5 inches of the heater, while the remainder of the heater temperature profile was very flat. In an attempt to compensate for the end losses, a new heater was designed consisting of 16 coils with a 0.75-inch pitch, and 4 coils (occupying the last 2 inches of the heater) with a 0.5-inch pitch. Increased power generation at the cold end resulted in a negligible temperature variation over the heater length (Figure 2-9). This design was adopted. Its characteristics are summarized below:

Heater

Length: 14.1 inches, first 16 coils on a 0.75-inch pitch and last 4 coils on a 0.5-inch pitch

Material: 0.25-inch diameter, 1 percent thoriated tungsten rod

Leads

Length: 8 inches each with one lead returned to opposite end of heater through interior of coil

Material: 0.25-inch diameter, 1 percent thoriated tungsten rod

Insulation

Material: 0.005-inch tungsten sheet

Quantity: 4 shields around heater
15 shields around leads

Figure 2-8. Predicted Axial Temperature Profile of Helical Heater Leads

Figure 2-9. Predicted Axial Temperature Profile of Helical Heater

Performance Parameters at 2200°C

Current: 300 amps

Heater power: 4800 watts

Lead power: 600 watts

3. FABRICATION

3.1 HEATER

3.1.1 Fabrication of Cylindrical Heater

A detail drawing of the tungsten split-cylinder heater is shown in Figure 3-1. It consisted of two parallel half cylinders separated by axial slots. The half cylinders were joined at the end opposite the leads to complete the electrical circuit.

Vapor deposition was chosen as the fabrication technique for this heater. This technique had been used successfully for resistojet heaters operating at comparable temperatures (Reference 4). It eliminated the need for a welded joint in the structurally critical area at the end of the heater. One of the major advantages of vapor-deposited tungsten is its ability to resist grain growth. The resistance to grain growth does not appear to be related to impurities and segregates in the metal, but rather to the lack of a driving force for grain growth (Reference 5). Since the metal is highly oriented and has only low-angle grain boundaries, surface energies at the grain boundaries, which serve as a driving force in promoting grain growth, are eliminated. Also, the metal has little stored energy due to mechanical strain. If either of these conditions is altered, i. e., if high-angle grain boundaries or mechanical work are introduced, grain growth upon heating does occur. Figure 3-2 illustrates the low-angle grain boundary in vapor-deposited tungsten, characteristic of material in as-deposited condition.

Chemical vapor deposition of tungsten is basically the deposition of tungsten metal onto a hot (600° to 700°C) substrate by decomposing a volatile tungsten compound by thermochemical reduction. The resulting structure is a sound, dense, crystalline body of high purity. The method used in this application involved the thermochemical reduction of a tungsten halide, WF_6 , with a gaseous reducing agent (H_2):

The vapor deposition operations were performed by San Fernando Laboratories of Pacoima, California. The substrate was a stainless steel mandrel with a stepped diameter at the heater-lead interface. The

Figure 3-1. Fabrication Drawing of Vapor-Deposited Tungsten Cylindrical Heater

Figure 3-2. Electron Micrograph of a Single Grain Boundary in Vapor-Deposited Material, as Received - Magnification 10,000X

first attempt to deposit tungsten on this mandrel proved unsuccessful because a portion of the deposited tungsten adhered firmly to the mandrel surface. A second mandrel was machined, the initial problems were resolved, and the tube was completed as shown in Figure 3-3.

The vapor-deposited tungsten tube was delivered to L. A. Gage of Sunland, California, for grinding and slotting operations. To prevent failure during grinding, a low melting compound (RIGIDAX) was poured into the tube and allowed to harden at room temperature. Machining of the two 1/8-inch wide longitudinal slots was accomplished by an elox process (electrical discharge machining) which required specially designed electrodes as illustrated in Figure 3-4. The tungsten tube is shown clamped in position with the copper-tungsten electrode positioned above. During the machining operation both the work piece and electrode were immersed in a dielectric oil which acted as a coolant and a flushing medium.

Macroscopic examination of the finished heater revealed three areas of concern. One area, shown in Figure 3-5a located 1-inch from the lead end, could not be cleaned in the final grinding operation because of insufficient vapor-deposited tungsten material in this region. A groove approximately .03 inches wide and .01 inches deep was located on the outer surface at the heater-lead interface shown in Figure 3-5b. The third area was located at the end of the heater opposite the heater leads. The cross-section at this location revealed a laminar structure consisting of three layers visibly separated from each other as shown in Figure 3-6.

The area shown in Figure 3-5a did not pose a problem since the defect was superficial when compared to the relatively heavy lead wall thickness of 0.098 inch. The groove shown in Figure 3-5b was located in what seemed like a critical area since the heater element dimensions at that point varied from 0.098 to 0.040 inch and the area would operate at a temperature of 2200°C. Although recrystallized tungsten is notch sensitive, and the groove might have affected the structural integrity at this point, the problem did not warrant refabrication. The laminar structure shown in Figure 3-6 posed a serious

3-5

Figure 3-3. Tungsten Vapor Deposited Tube

Figure 3-4. Elox Set-up for Tungsten Vapor-Deposited Tube

Figure 3-5a. Macroscopic Imperfections in Finished Tungsten Cylindrical Heater

Figure 3-5b. Macroscopic Imperfections in Finished Tungsten Cylindrical Heater

Figure 3-6. Laminar Structure in Tapered Section of Tungsten Vapor-Deposited Heater

problem since it was located in the tapered section of the heater and extended 1/4 inch inward from this end. To avoid crack propagation, a 5/16-inch long section was eloxed off this end, and further macroscopic examination revealed that although the cross-sectional structure was laminar, the separations were no longer visible.

The microstructure of the lead cross-section was examined, as shown in Figure 3-7, revealing a highly oriented grain structure which typically results from tungsten vapor-deposition techniques. Several interfaces are visible between layers indicating deposition interruptions during fabrication.

A back-up heater, similar in design to the first, was ordered from General Electric Company, Dover, Ohio. This unit was to be fabricated from two wrought tungsten plates formed into half-cylinders, machined to final dimensions, and joined at one end by Tungsten Inert Gas (TIG) welding. Repeated attempts to fabricate the heater proved unsuccessful, and further work on the heater was terminated.

3.1.2 Fabrication of Helical Heater

To obtain experience in fabricating small diameter tungsten coils, a 2-foot rod of 1/4-inch diameter W-1% ThO₂ was coiled by Super Metals Corp. of Santa Fe Springs, California. This sample material was coiled after first heating the thoriated tungsten rod to approximately 800°C. The tight bends required at the bottom of the heater were formed with excellent results.

A 10-foot length of thoriated tungsten rod was delivered to Super Metals for forming of a full-scale helical heater. The fabrication procedure involved pre-heating the material to a temperature of 700°C to 800°C prior to coiling on a steel mandrel. The first heater was coiled with a 0.75-inch pitch but could not be used because a portion of the rod was broken during fabrication and the resultant heater did not meet the specifications. A second heater was then fabricated with a nominal 0.75-inch pitch except for the last four coils which had a 0.5 inch pitch; it is shown in Figures 3-8 and 3-9.

Figure 3-7. Structure of Tungsten Vapor-Deposited
in Heater Lead Area as Received

Figure 3-8. Thoriated Tungsten Helical Heater

Figure 3-9. Enlarged View of Thoriated Tungsten
Helical Heater - Pretest

3.2 THERMAL INSULATION

Tungsten sheet (0.005-inch thick) was chosen as the material for the thermal radiation shielding. A sample of tungsten sheet (GE 15-S) was received from the General Electric refractory metals plant in Cleveland, Ohio. Preliminary fabrication tests were carried out by TRW Systems. Since tungsten is brittle at room temperature, attempts to deform unheated material resulted in severe fracture of the test specimen. However, at 150°C a 0.050-inch deep dimple was successfully formed, and repeated testing at this temperature produced uniform deformations without failure of the material. To provide a margin of safety, actual production dimpling was carried out at 250°C using an internally heated dimpling machine. Figures 3-10 and 3-11 illustrate the effects of variable temperature and dimple depth.

Tantalum rivets were used in joining each of the 45 cylindrical lead shields and 4 heater shields. Holes were punched with a 0.054-inch diameter hand punch at room temperature, and 0.052-inch diameter rivets were used at a spacing of one inch. Prior to the first heater test, a sample cylinder heated for 5 hours at 2200°C in a vacuum of 1×10^{-6} torr showed no visible deformation. The forming of individual cylindrical shields eliminated the spiral conduction effect present in multi-shields formed from a continuous length of material. This design also facilitated the addition or removal of shields as required by subsequent design changes. Holes of 1/4-inch diameter were then eloxed through the four full-length shields to facilitate pyrometer sightings on the heater surface at four axial locations and on each shield surface. The individual thermal insulation shields are shown in Figure 3-12, and the assembled shield package is shown in Figure 3-13.

Figure 3-10. Dimpling of 0.005-inch Thick Tungsten Sheet (GE 15-S) Showing Brittle-Ductile Transition Point at 150°C. Dimple Depth is 0.050 Inch; Dimple Radius is 3/32 Inch.

Figure 3-11. Dimpling of 0.005-inch Thick Tungsten Sheet (GE 15-S)
Showing Effect of Excessive Deformation. Dimple
Depth: (D) 0.050 inch, (E) 0.075 inch, and (F) 0.100 inch

Figure 3-12. Individual Tungsten Thermal Insulation Shields

Figure 3-13. Assembled Thermal Insulation Package

4. TEST FACILITY DESIGN

The heat source simulation tests were conducted at the TRW Systems Inglewood Test Facility. Basic components of the test facility included a test chamber, high vacuum pumping station, thermocouple reference junction, and multi-channel recorders as shown in Figure 4-1. A schematic drawing of the test facility is shown in Figure 4-2.

4.1 TEST FACILITY REQUIREMENTS

Selection of the two major test components (the test chamber and vacuum station) was based on the requirement for performing the tests at high temperature (up to 2200°C) and low vacuum (less than 5×10^{-6} torr) for periods of 30 days or longer. The unique configuration of the heater and thermal radiation shield assembly required a special view port for monitoring heater and shield temperatures with a ratio pyrometer. The view port was covered by a protective stainless steel swing-away shield except when pyrometric readings were being taken. The high electrical current (up to 800 amperes) through the heaters required design of special heater clamps and high-vacuum feed-throughs. In addition, to enable prolonged unattended operation of the facility, it was necessary to design a fail-safe electrical circuit protecting the test assembly in the event of system malfunctions.

4.2 VACUUM CHAMBER

A cylindrical test chamber 24 inches in diameter and 36 inches high was designed and fabricated from type 304 stainless steel to accommodate the heater and shield assemblies. A 17-inch long by 1-inch wide rectangular view port, with a stainless steel swing-away shield, was mounted vertically on the test chamber. A water-cooled jacket extended the full height of the test chamber. One-half inch copper tubing was also used to water-cool the top and bottom chamber plates. The bottom plate of the chamber was attached to the pump port of the vacuum station while the removable top plate was used for instrumentation and water-cooled power connections which extended into the vacuum chamber via special vacuum feed-throughs. The high current vacuum feed-throughs, and the water-cooled clamps used to feed electrical energy to the split cylinder heater are shown in Figure 4-3. The complete heat source simulation assembly is shown in Figure 4-4.

Figure 4-1. Heat Source Simulation Test Facility

Figure 4-2. Heat Source Simulation Test Schematic

Figure 4-3. 1000 Ampere Water Cooled Vacuum Feed-Through

Figure 4-4. POODLE Heat Source Simulation Test Assembly Schematic

4.3 VACUUM STATION

The vacuum station was a CHA Industries Model SS-600 packaged pumping station complete with instrumentation which included a dual thermocouple-single ionization gauge with an overall range of 1000 microns to 2×10^{-10} torr. Other features of the system included an electrically controlled pneumatic high-vacuum valve and a liquid nitrogen cold trap assembly. This system, with an all stainless steel diffusion pump and a 15 cfm mechanical pump, had a pumping speed of 1800 liters/second.

4.4 INSTRUMENTATION

A 24-channel recorder provided a continuous record of the thermocouple measurements taken at various axial and radial locations within the heater assembly. W-5%Re/W-26%Re and chromel/alumel thermocouples were used at different temperature levels. (Location of these thermocouples is discussed in Sections 5.1 and 5.2). An electrical thermocouple reference junction provided a continuous 32°F reference point for all thermocouples. This unit was fully automatic and eliminated the necessity for periodic maintenance of the ice-bath reference junction used in previous tests. A pair of voltage pick-off leads, consisting of 0.005-inch diameter tungsten wire, was attached to the heating element and lead interface. Additional leads were attached to the copper clamp. In this manner, it was possible to differentiate between the power to the heater proper and to the heater leads. Because of the obvious limitations imposed upon thermocouples operated at high temperatures for long durations, pyrometer temperature measurements were also taken at four axial locations on the heater surface, and on the four heater shields. A two-color (ratio) pyrometer was used in preference to a brightness optical pyrometer because the former requires no emissivity correction factors (Reference 6), giving more accurate temperatures.

4.4.1 Control Console

Electrical power was supplied to the heater using a 220 volt, 60 cycle, single-phase variable transformer (T1) which was connected to a power transformer (T2) as shown schematically in Figure 4-2. The

power transformer, with two taps on the secondary windings, allowed a choice of 15 volts and 2000 amperes or 30 volts and 1000 amperes depending on specific heater requirements. Power connections to the heater were made with flexible copper cables rated at 2000 amperes. Since tungsten resistivity at 2200°C is about 13 times that at room temperature, the variable transformer was used to prevent current surges which could result if full power were inadvertently turned on. The console, shown in Figure 4-1, contained the variable transformer used to adjust the heater voltage and the electrical meters used to monitor the electrical test parameters.

4.4.2 Fail-Safe Circuits

The long duration of the heat source simulation tests (720 hours) made continuous surveillance impractical. Therefore, it was necessary to utilize fail-safe controls to protect the heater system and facility from power, water, or vacuum pump failures resulting in excessive air pressure in the test chamber. The basic components of the fail-safe system shown in Figure 4-2 included an under-voltage trip (UV TRIP); water flow switches (S1 and S2); electrically operated, normally closed pneumatic gate valve (V1); and electric relays (K1, K2 and K3). This circuit was designed to shut off the power in case of a system malfunction and close the high-vacuum gate valve, thereby isolating the test chamber and maintaining a vacuum while the heater temperature dropped to ambient. This preserved the integrity of the heater assembly in case of a system shut-down during periods of unattended operation and permitted restarting of the test after corrective measures were taken.

5. TEST RESULTS

5.1 CYLINDRICAL HEATER TEST

The tungsten vapor-deposited split-cylinder heater test was initiated August 18, 1966 with the objective of operating continuously at 2200°C for 30 days (720 hours). The test was successfully concluded September 23, after a total of 850 hours in operation, 800 hours of which were uninterrupted at a temperature of 2200°C. A vacuum of 3×10^{-7} torr was maintained. The test assembly as observed through the vacuum chamber view port during the test is shown in Figure 5-1.

Figure 5-2 presents steady-state temperatures recorded at various radial and axial locations. The heater temperature was monitored using a two-color pyrometer at four axial locations through holes A, C, E and G. Temperatures measured at these points fit the predicted profile very well (Figure 5-3). However, the heater temperature at the tapered end was somewhat less than predicted. This can be partially attributed to the fact that the test heater did not precisely duplicate the configuration employed in the analyses. As described in Section 3.1.1, it was necessary to reduce the heater length slightly during heater fabrication to avoid propagation of longitudinal cracks. As a consequence, the heater end was not tapered along the entire 1.00 inch of the joint, resulting in a lower power generation than predicted and a lower temperature in this area. The 5/16-inch reduction in heater length is equivalent to reducing the heater power at the design condition by approximately 100 watts.

Table 5-1 presents a comparison of test parameters with the analytical predictions.

The observed power generated in the heater leads (1968 watts) differed considerably from that predicted (760 watts). The increase in lead power may have been partly due to the higher-than-anticipated interface temperature between the heater and water-cooled clamps. That temperature was maintained at 314°C during the test rather than at 100°C as assumed in the analyses. However, the major cause appears to be in the performance of the lead insulation. A three-dimensional thermal

Figure 5-1. 2200°C POODLE Heat Source Simulation Test

Figure 5-2. POODLE Thermocouple Locations and Pyrometer Sight Holes

Figure 5-3. Axial Temperature Profile in Split Cylinder POODLE Heater

Table 5-1. Analytical and Experimental Parameters
for Cylindrical Heater

Heater Parameter	Units	Test Value	Analytical Value
Voltage	Volts	5.94	6.67
Current	Amps	800	718
Resistance	Ohms	0.0074	0.0093
Power	Watts	4750	4790
Temperature	°C	2200	2200

analysis of the 45 layers composing the insulation system was beyond the scope of the design task. It was recognized that axial thermal conduction in the radiation shielding could significantly alter the effectiveness of the shielding and thereby affect power generation in the leads. The flat axial temperature profiles in the lead insulation (Figure 5-2) verify that axial conduction in the shielding did, indeed, have an important effect on the shielding and heater lead performance. However, the effect was felt solely in the area of the leads and it was possible to maintain the adiabatic heater-lead interface by raising the current to a level slightly above that predicted.

5.2 HELICAL HEATER TEST

Testing of the W-1%ThO₂ coiled heater was initiated October 8, 1966, and an uninterrupted operating span of 720 hours was completed on November 11. The vacuum was again maintained at 2.0×10^{-7} torr. Figure 5-4 presents steady-state temperatures recorded at various radial and axial locations. The heater temperature was monitored, as in the first test, using a two-color pyrometer at four axial locations through holes A, C, E and G. Temperatures at these locations are plotted on the analytically predicted profile in Figure 5-5. The experimental heater temperature profile is very flat, indicating that the pitch change at the heater end was effective in raising the temperature of this region. At the same time, the approximate technique employed to

Figure 5-4. Thermocouple Locations for Tungsten Coiled Heater Test

Figure 5-5. Axial Temperature Profile of Helical Tungsten Heater, Predicted vs. Actual

determine the required number of lead thermal radiation shields appears satisfactory since the heater-lead interface temperature is very close to the desired value of 2200°C.

The agreement between experimental (718 watts) and predicted (600 watts) lead power generation was much better for this test than for the split-cylinder heater. Table 5-2 presents comparisons of steady-state experimental results with analytical predictions.

Table 5-2. Analytical and Experimental Parameters for Helical Heater

Heater Parameter	Units	Test Value	Analytical Value
Voltage	Volts	17.22	16.00
Current	Amps	315	300
Resistance	Ohms	0.054	0.053
Power	Watts	5424	4800
Temperature (Maximum)	°C	2200	2200

The predicted heater power output showed a larger deviation from the predicted value than in the first heater. Axial radiation losses to the leads could have been higher in this case because of the larger view factor resulting from the helical construction. Since there should have been no change in the heater insulation (4 axial shields), another possible cause may have been a higher-than-predicted emissivity on the surface of the coiled heater. Tungsten oxide, formed on the heater surface during fabrication, was removed by blasting with glass beads; this may have raised the emissivity of the heater from approximately 0.3 to 0.5. The higher resultant power requirement was met by raising the current above the predicted value.

5.3 POST-TEST MATERIAL EVALUATION

All test assembly components were examined at the conclusion of each test. The tungsten insulation shields and heater surfaces were

bright and clean due to slight surface material evaporation which occurred at low vacuum (2×10^{-7} torr).

Post-test inspection of the split-cylinder heater, shown in Figure 5-6, revealed that the mid-plane diameter of the heater section expanded from 1.500 inches to 1.571 inches. Figure 5-7 shows the effect of this bowing on a portion of the eloxed slots which had a uniform width of 1/8 inch before the test. In addition, some blistering occurred on both inner and outer surfaces of the leads and heater. This was probably due to expansion of partially decomposed tungsten hexafluoride (WF_6) which was used to fabricate the heater and which may have been trapped in intra-granular voids. Upon heating to $2200^{\circ}C$, this gas expanded and caused the tungsten to blister.

Post-test inspection of the coiled W-1% ThO_2 heater, as shown in Figure 5-8, revealed that this unit had bowed a maximum of 0.140 inch. Accurate measurements taken at locations indicated in Figure 5-9, before and after the test, are summarized in Table 5-3. The combined effects of creep strain and bowing of the heater resulted in a net change in overall length from 13.680 to 13.649 inches.

Figure 5-6. Post-Test View of Vapor-Deposited Tungsten Cylindrical Heater

Figure 5-7. Enlarged View of Cylindrical Tungsten Heater Post-Test

Figure 5-8. Post-Test View of Helical Tungsten Heater

Figure 5-9. Measurements of Spiral Heater

Table 5-3. Coil Spacing in Helical Heater (Inches)

Location	Before Test	After Test	Change
A-B	0.430	0.452	+0.022
B-C	0.515	0.545	+0.030
C-D	0.498	0.520	+0.022
D-E	0.463	0.485	+0.022
E-F	0.495	0.515	+0.020
F-G	0.500	0.524	+0.024
G-H	0.467	0.481	+0.014
H-I	0.465	0.470	+0.005
I-J	0.511	0.519	+0.008
J-K	0.484	0.483	-0.001
K-L	0.505	0.503	-0.002
L-M	0.525	0.516	-0.009
M-N	0.491	0.475	-0.016
N-O	0.512	0.498	-0.014
O-P	0.485	0.467	-0.018
P-Q	0.363	0.341	-0.022
Q-R	0.351	0.324	-0.027
R-S	0.296	0.265	-0.031
S-T	0.271	0.244	-0.027
A-T	13.680	13.649	-0.031
1-2	1.497	1.496	-0.001
3-4	1.492	1.497	+0.005
5-6	1.490	1.477	-0.013

6. CONCLUSIONS AND RECOMMENDATIONS

The results of the two heater tests showed that both heaters performed satisfactorily at 2200°C for 30 days. In addition, design techniques employed to tailor the axial heater temperature profile proved effective. For the split-cylinder heater, the use of appropriate lead insulation and lead contouring along with heater end tapering resulted in a nearly flat axial heater temperature profile. The use of lead insulation and coil pitch variation in the coiled heater design also resulted in a flat axial heater temperature profile. The excellent overall agreement between test results and analytical predictions for each heater showed that the analytical techniques employed in the design were highly satisfactory and, therefore, can be employed with reliability in future heater designs.

The unique thermal insulation systems employed in the heater tests proved very effective. Separation of concentric tungsten shields by means of mechanical dimpling was successful even for the high temperatures and extended test durations. However, it appears that imposition of a strong axial temperature gradient on such insulation can significantly alter its performance. Therefore, it is desirable in future applications to analytically describe the insulation system in at least two dimensions in order to ensure that this effect will not prevent achievement of the particular test objectives.

The tungsten vapor-deposition process employed to fabricate the split-cylinder heater was very effective in producing a sound reliable unit. This method eliminated the fabrication problems inherent in hot-forming and welding of wrought tungsten plate, and the excessive machining required to fabricate a cylindrical heater from a presintered tungsten ingot.

The coiled heater design also proved to be very effective and has distinct advantages over other concepts. Fabrication is simplified since it merely involves the proper coiling of a preheated refractory rod to a given configuration. In addition, the power generation per unit length of the heater can be controlled by altering the pitch of the heater coils.

However, thermal analysis of this configuration is more difficult due to the irregular geometry, complex radiation view factors, and inter-coil dimensional changes which occur at high temperatures during long test periods.

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