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DEVELOPMENT OF A GRAPHITE RADIANT HEATER

By F.W. Brodbeck, D.Q. Durant, and R.D. Taylor

Prepared by

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for Langley Research Center

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1.0 SUMMARY

The performance of graphite radiant heaters as a high heat flux source for thermostructural tests has been investigated. The detailed design investigation revealed that the limiting factor was the evolution of smoke which induced electrical arcing. This occurred when the graphite temperature reached approximately 5300°F. This problem was extensively investigated to determine the influence of purge gas composition, various grades of graphite, element spacing, impressed voltage, and element geometry on the maximum operating temperature. Prototype testing demonstrated that a graphite radiant heater can provide an absorbed heat flux of approximately 220 Btu/ft^2-sec to a 2 x 2-foot cold-wall structure.

2.0 INTRODUCTION

Structures for hypersonic cruise vehicles will encounter severe heating conditions. Within the propulsion system the heat flux level may be as high as 500 Btu/ft^2-sec. Structures to withstand this environment will employ unique thermal protection systems (TPS); however, before an optimum TPS can be designed a host of factors must be investigated and the results evaluated in terms of flight weight requirements. To effectively do this, ground test equipment will be required whereby various TPS concepts may be subjected to realistic heating conditions for evaluation. Electrical heaters using tungsten filament quartz-envelope lamps are widely used for generating radiant energy; however, for a number of well-known reasons, these lamps are limited to a heat flux level of less than 100 Btu/ft^2-sec. To provide a higher heat flux level necessary for testing of advanced structures, radiant heaters using solid graphite resistance elements have been considered.

The work reported herein is the result of an investigation to establish the operating characteristics and limitations of graphite in a radiant heater application. The development effort led to the fabrication of a graphite radiant heater capable of heating an area of approximately 4 square feet. The heater operated from three 480-volt ignitron power supplies. Performance goals desired were 1 hour of satisfactory operation at 250 Btu/ft^2-sec with a design operating level of 500 Btu/ft^2-sec.

An investigation of the properties limiting the maximum attainable temperature of the graphite was conducted. A preliminary design study and development testing of hardware components were performed. Then a prototype heater assembly was designed and fabricated and exhaustive testing was conducted to determine the maximum performance envelope and the limiting factors. Tests were performed at a pressure of 15 psia and 265 psia.

3.0 EXPERIMENTAL DEVELOPMENT TASK

The major problem area development effort of this program was the investigation of the electrical arcing phenomenon and the maximum operating temperature of graphite in the application as a freely radiating heat source. The arcing investigation utilized an apparatus designed to secure basic data on the spacing required to hold off a given voltage at various temperatures and on the effects of configuration and surrounding materials. The arcing investigation revealed a maximum operational temperature of approximately 5300°F for the specific grade of graphite utilized, since, as the graphite element approached this temperature, copious quantities of electrically conductive smoke were emitted, thereby creating an arcing environment. To determine independently the effects of current density and temperature upon the arcing phenomenon, arcing experiments were conducted with elements of constant cross-sectional area but various perimeter to area ratios. Several different graphites including small grain graphite, pyrolytic graphite, and vitreous carbon were investigated in an effort to maximize the operational temperature and also to this end, attempts were made to form elements with a tantalum carbide coating. Further experiments included emittance enhancement, evaporation rate measurement, and the effect of various purge gases.

3.1 ARC INVESTIGATION

3.1.1 TEST OBJECTIVE. The basic purpose of the arc investigation was to examine the effects of component spacing, applied voltage, and graphite element temperature upon the arcing phenomenon in an effort to establish trends and define operational envelopes which would be utilized in the design of a graphite radiant heater. Because of the desirability of using graphite felt covered heat shields with graphite radiant heaters, the effect upon arcing due to the introduction of felt near the element was also studied. Further, since it was known that at high temperature the graphite elements emit smoke, a determination of the arcing potential of the smoke environment was made.

3.1.2 TEST PLAN. The arcing phenomenon experienced with graphite radiant heaters can be generally described as sudden, unpredictable, and often extremely damaging. To cope with this, an apparatus was designed in which there could be independent variation of the various arcing parameters such as voltage, spacing, materials, and temperature along with arc current limitation and detection. A bell jar type of operation made quick turn around possible and allowed for a large amount of experimentation per unit time. By incorporating a separately excited electrode, the basic procedure involved setting a fixed arc excitation voltage on the electrode which was placed at some fixed distance from the heater element, slowly increasing the element temperature until an arc was indicated, and finally measuring the element temperature at which the arc occurred.

3.1.3 TEST APPARATUS. The arc investigation test apparatus, illustrated in Figure 1, consists of a Pyrex-glass bell jar set on a stainless steel base-plate through which pass connections for electrical power, water, instrumentation, and nitrogen purge gas. The heater element, an Airco Speer Carbon Co. grade-890S graphite strip 12 inches long x 0.5 inch wide x 0.080 inch thick, was held by two pairs of graphite clamp blocks which were screwed to 1-inch diameter graphite support rods. These rods were supported by water-cooled copper posts, one of which was mounted on a hinged base and spring loaded to

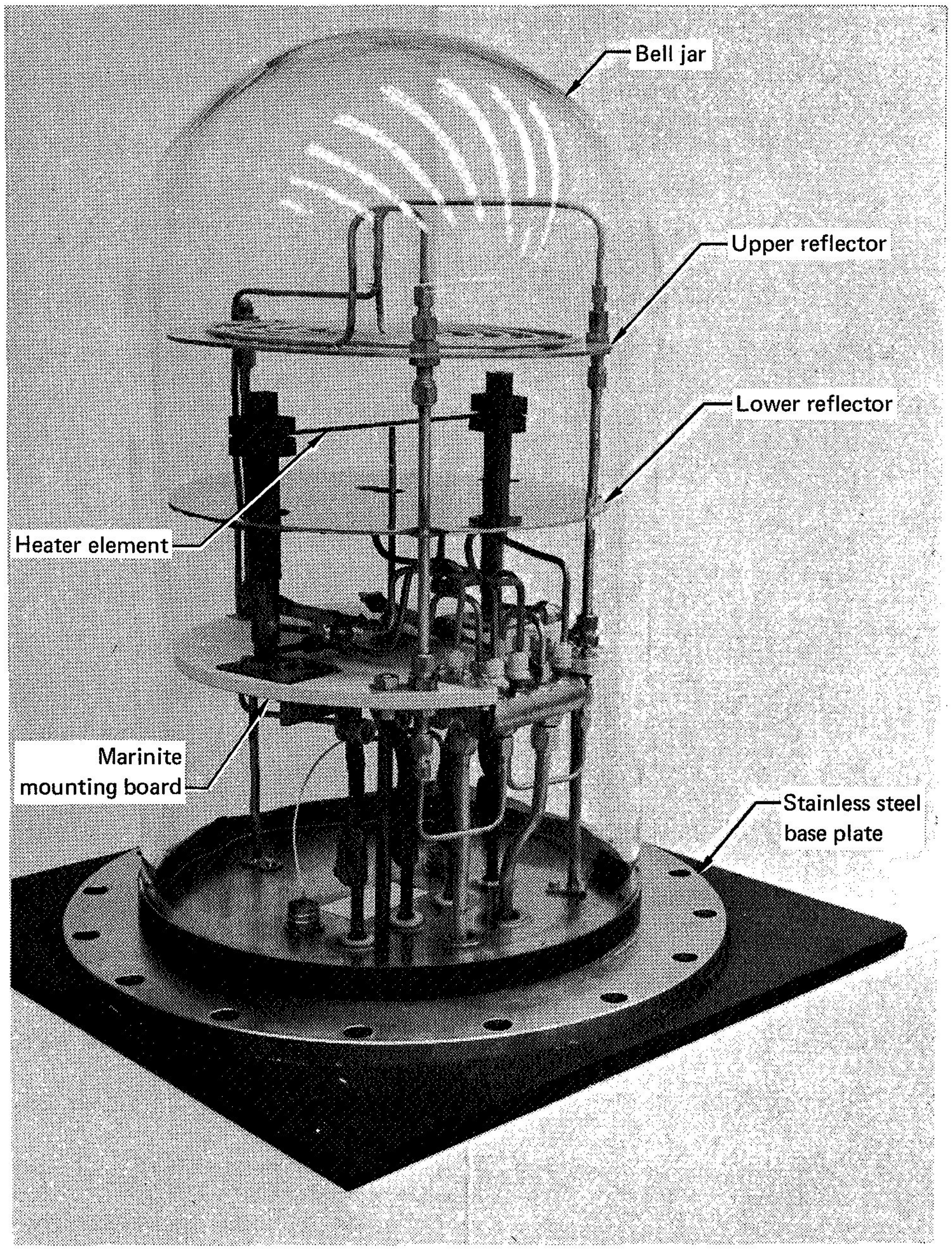

Figure 1 Test Apparatus for General Arc Investigation

place tension on the strip to provide for thermal expansion. Electrical insulation was provided by the Marinite mounting board and by nylon insulating fittings in the water lines to the copper posts.

Circular, nickel-plated, water-cooled copper heat shield plates were positioned 3.0 inches above and below the heater strip. These plates were used to protect the surrounding parts of the apparatus, enclosure, and observers from excessive heat inputs and, only incidentally, increase the heating efficiency of the strip.

Figure 2 is a close-up view of the heater strip and a strip-type electrode. Electrode shapes investigated were attached to a 0.312-inch threaded graphite rod protruding through a slot in the lower heat shield plate. This rod was attached to the Marinite insulating board in such a manner that electrode height and spacing were easily varied over a wide range. Arcs were established between the electrode blocks and the center of the heater strip.

To provide felt contamination around the electrode gap, a felt-lined enclosure, c-shaped in cross section, was placed around the heater strip and gap. Clearance between the electrodes and enclosure was typical of that encountered in a conventional graphite heater module. This is shown in Figure 3.

To evaluate arcing during high temperature smoke emission, an electrode was constructed to provide a 0.250-inch gap between the electrode and the top of the heater strip as shown in Figure 4. The gap was oriented directly over the strip so as to be in the path of the smoke evolved from the strip.

The electrical system, shown in the schematic of Figure 5, is, in essence, two separate systems: one to supply power to heat the graphite strip and the other to generate, limit, and monitor the arc.

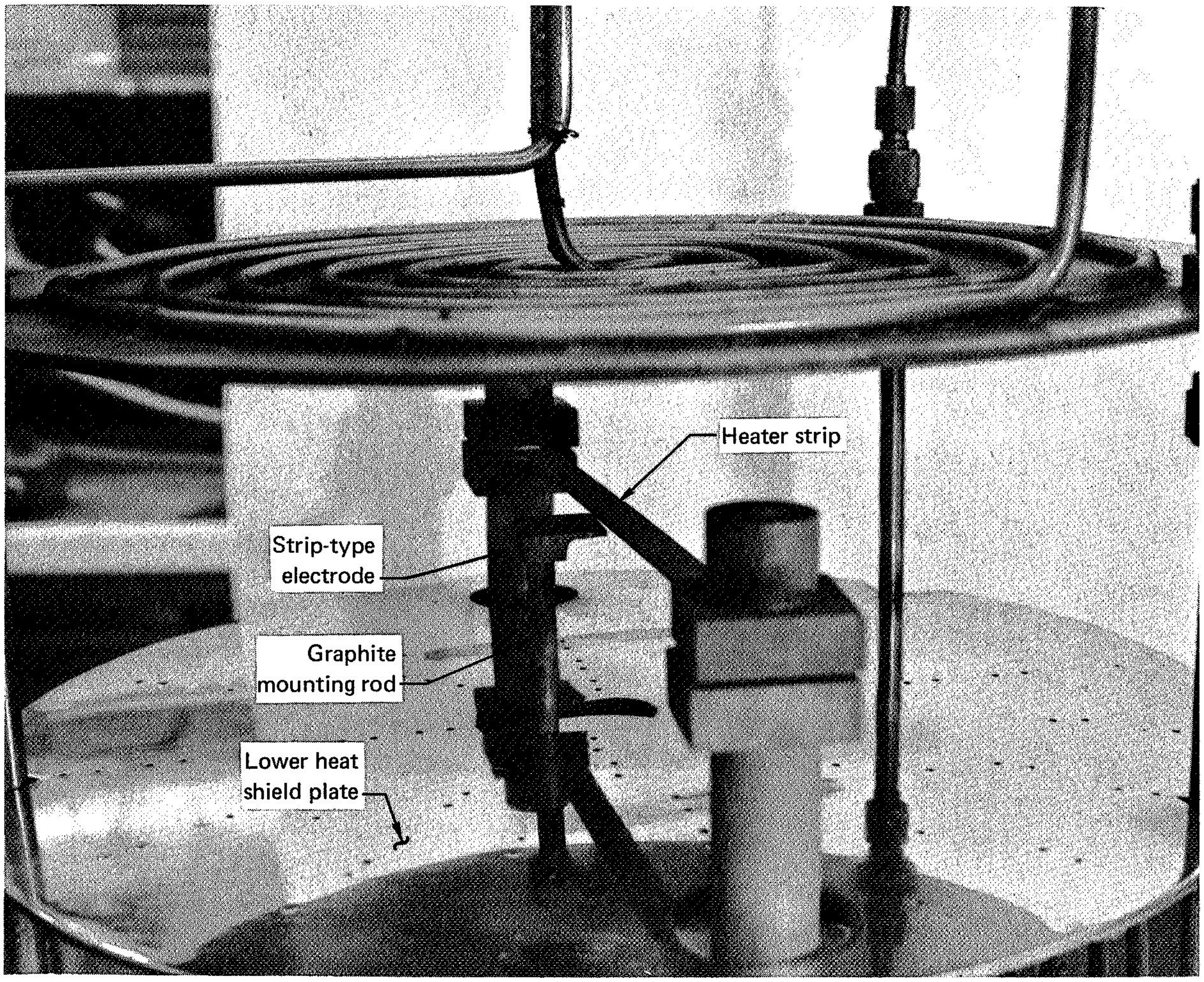

Figure 2 Heater Strip and Electrode Showing Strip-to-Strip Geometry

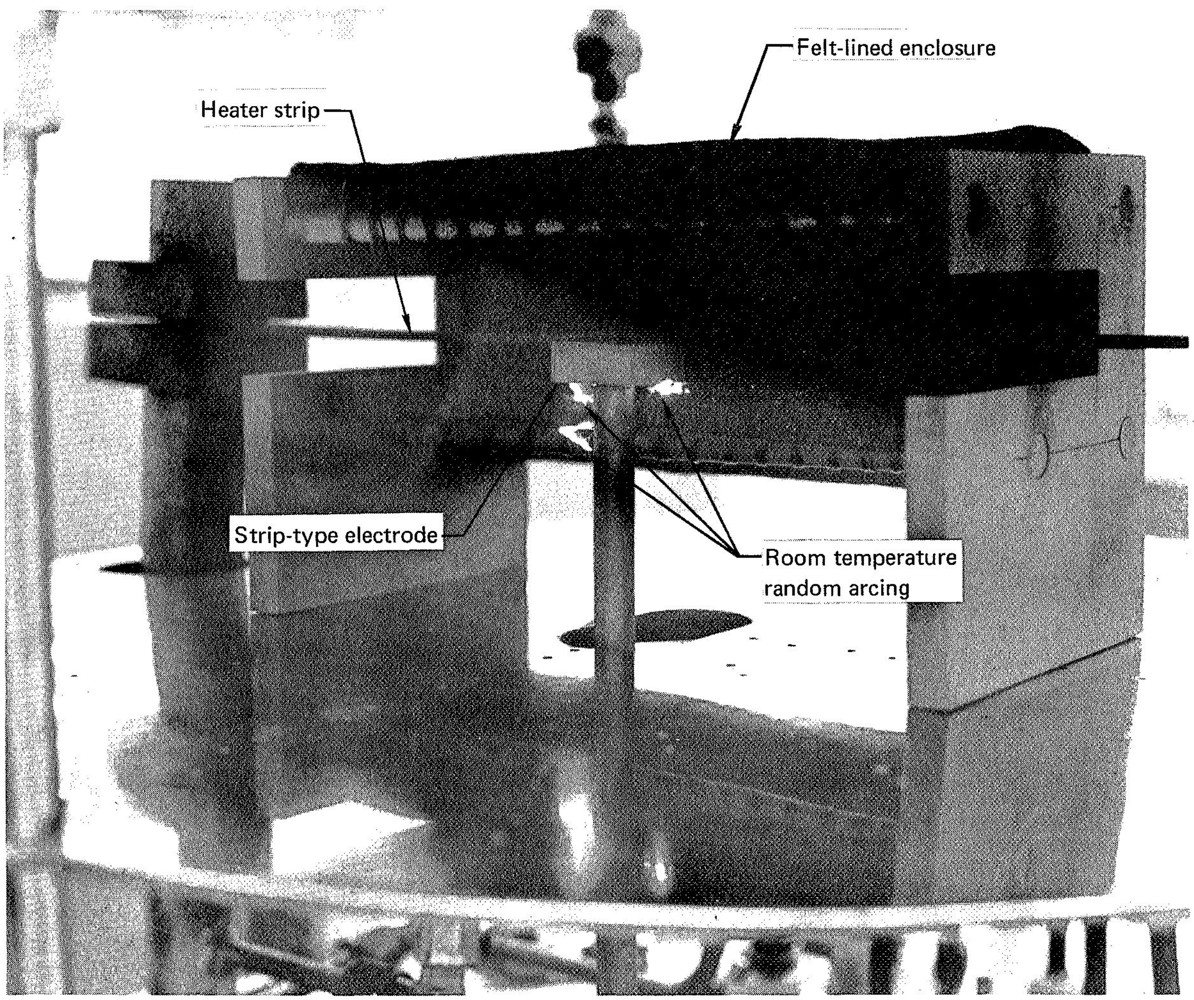

Figure 3 Room Temperature Arcing Produced by Graphite Fibers

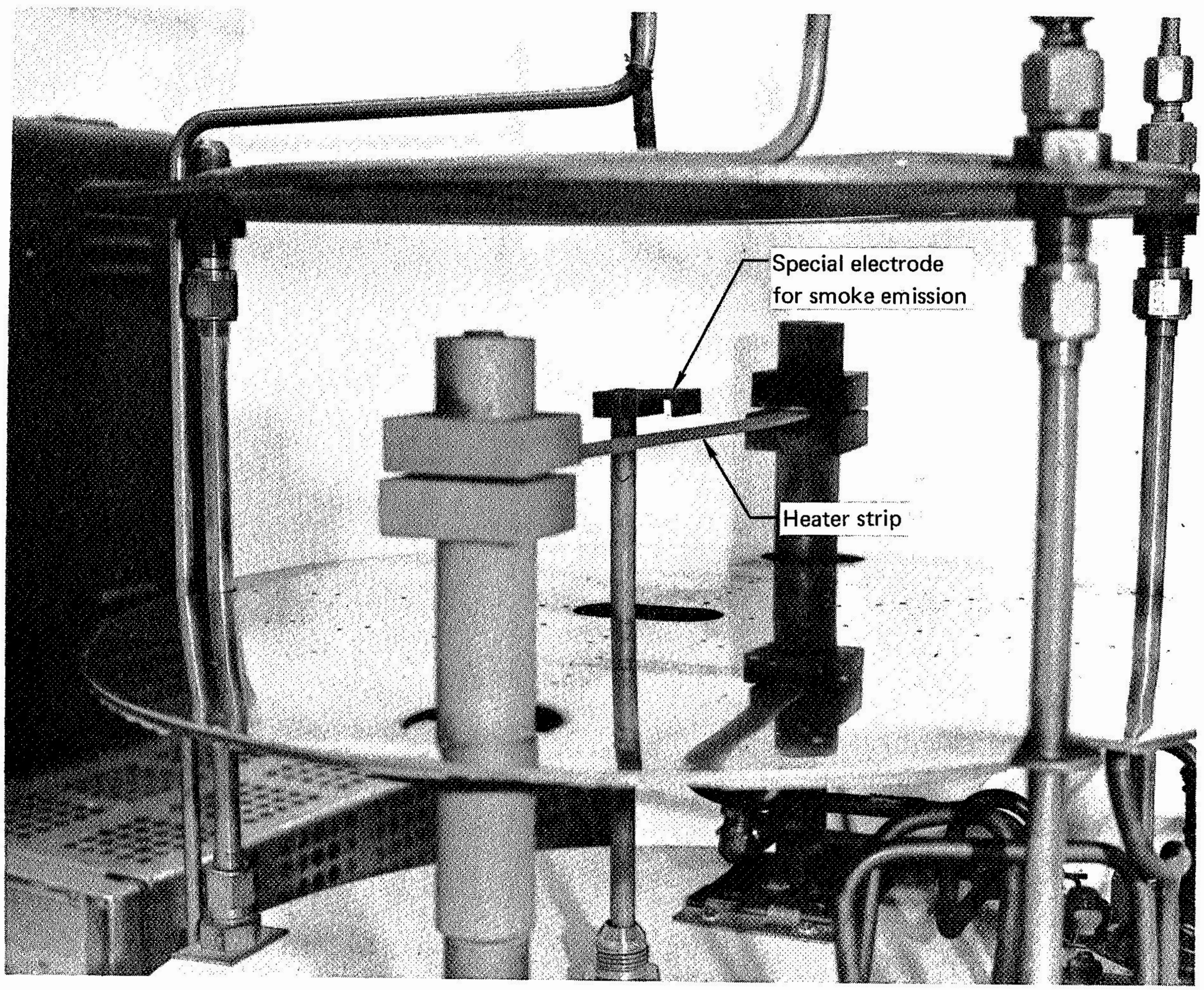

Figure 4 Heater Strip and Electrode Utilized to Evaluate Arcing During Smoke Emission

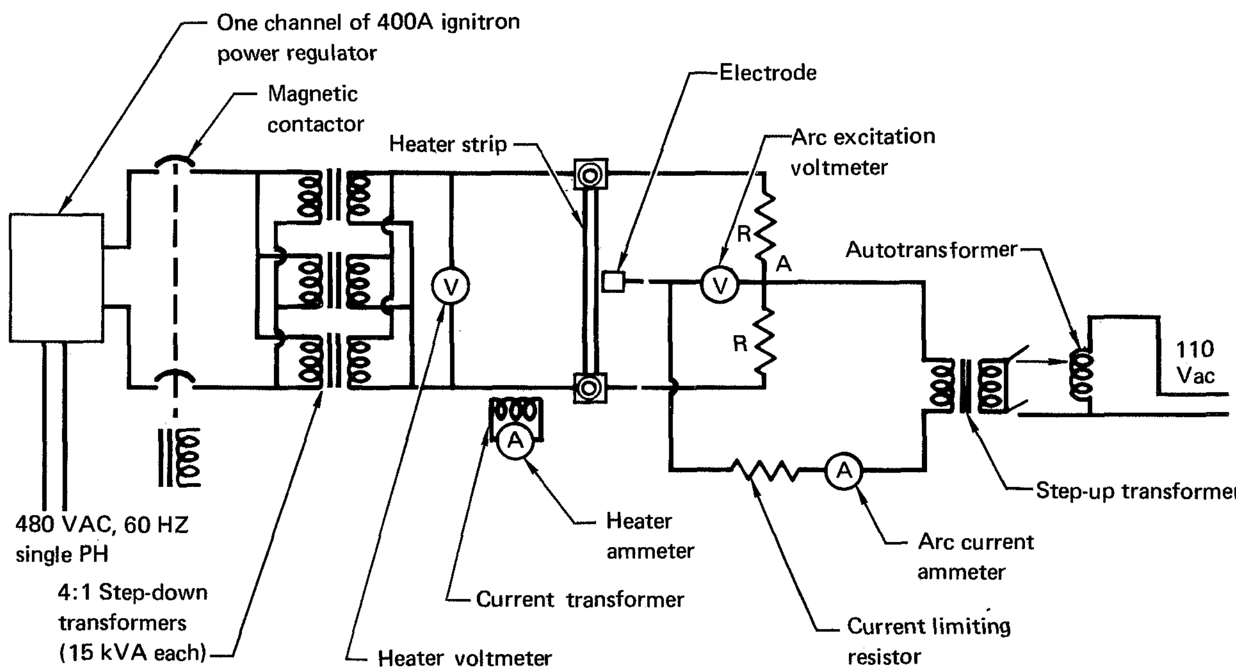

Figure 5 Electrical Schematic of Apparatus for General Arc Investigation

Three 15 kva step-down transformers, in parallel connection, supply 110-volt AC power to the heater strip. One channel of a 400-ampere capacity ignitron power regulator furnishes phase-controlled, 480 volt, single-phase AC power to the primaries of the step-down transformers. A magnetic contactor in the line between ignitron unit and transformers provides for emergency power shutdown. Heater strip temperature is measured with an optical pyrometer and controlled manually by varying the firing angle of the ignitron unit.

The arcing voltage supply is arranged so that voltage across the electrode-to-strip gap may be varied independently of the voltage applied across the heater strip by the 15 kva transformers. A step-up transformer, supplied by a variable auto transformer connected to its primary, provides a variable 60-Hz AC excitation voltage. One side of the step-up transformer secondary is connected to the electrode; the other side would be connected, if it were not for practical difficulties, to the center of the strip. Instead, this side is connected, through an ammeter and current-limiting resistor, to point A, Figure 5, which is maintained at the same electrical potential as the center of the strip by two equal dropping resistors R connected in parallel with the strip. The voltage between the electrode and the center of the strip may thus be varied with the auto transformer and measured with the voltmeter V. Current flow in an arc is limited by the series resistor to a value low enough to avoid serious damage to the electrode or strip. The ammeter provides one indication of the presence of arcing.

3.1.4 RESULTS AND DISCUSSION. Arc testing was begun with the strip-to-strip electrode geometry, shown in Figure 2, in an effort to determine the inter-strip gap required to prevent arcing. The procedure described in 3.1.2

was repeated for a number of electrode gap spacings from 0.050 inch to 0.175 inch and the data is presented in Figure 6. The data points on this graph indicate the voltage and temperature at which an arc starts and since, presumably, no arc will occur below this voltage at this temperature, this voltage is defined as the hold-off voltage. As could be expected, the hold-off voltage decreases with increasing temperature at a given gap setting and as the gap setting was increased, the hold-off voltage at a given temperature increased. Also shown in Figure 6 is an operational envelope for a typical graphite radiant heater which is defined by the maximum output voltage of the ignitron power supply and the temperature at which excessive smoke emission occurs. Clearly, for arc-free performance, the inter-strip gap spacing must be of a magnitude such that the hold-off voltage-temperature relationship is entirely outside of this envelope. It can be seen that the 0.150-inch and 0.175-inch data satisfy this condition. This data corroborates previous in-house testing when it was found that a 0.125-inch gap between strips was insufficient but a 0.250-inch gap performed successfully.

The above testing procedure was repeated with the graphite felt enclosure, described in 3.1.3 and shown in Figure 3, surrounding the element to determine the effect of the felt contamination on the hold-off voltage-temperature relationship. The results of this testing are shown in Figure 7 for an electrode spacing of 0.100 inch. From the plot it is seen that there does not appear to be a significant change in the hold-off voltage produced by the felt contamination at temperatures up to approximately 4000°F. Above this temperature the presence of the felt lowers the hold-off voltage about 50 volts. Other tests at different gap spacings confirm this result.

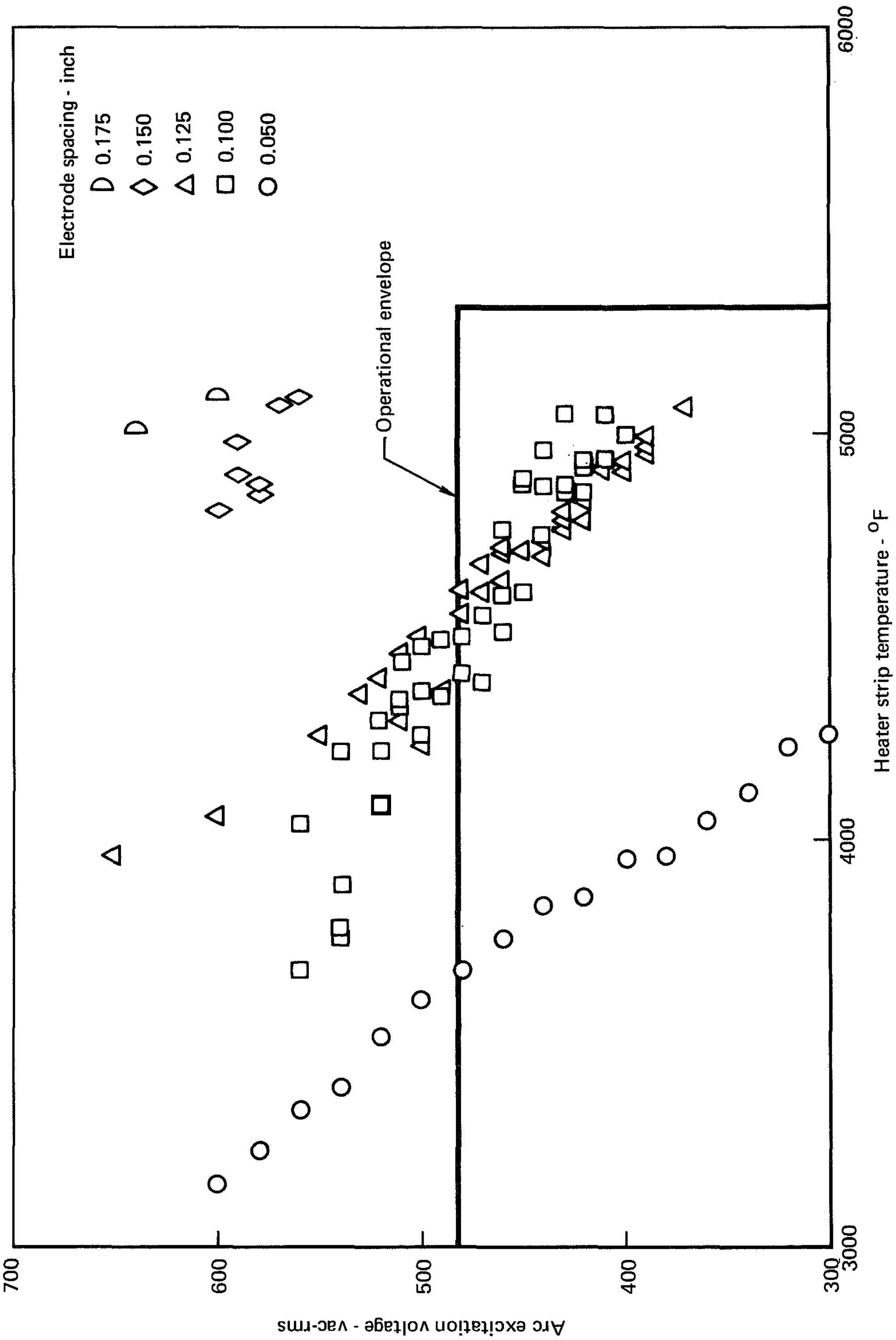

Figure 6 Hold-Off Voltage as a Function of Temperature, Strip-to-Strip Geometry, Clean Environment

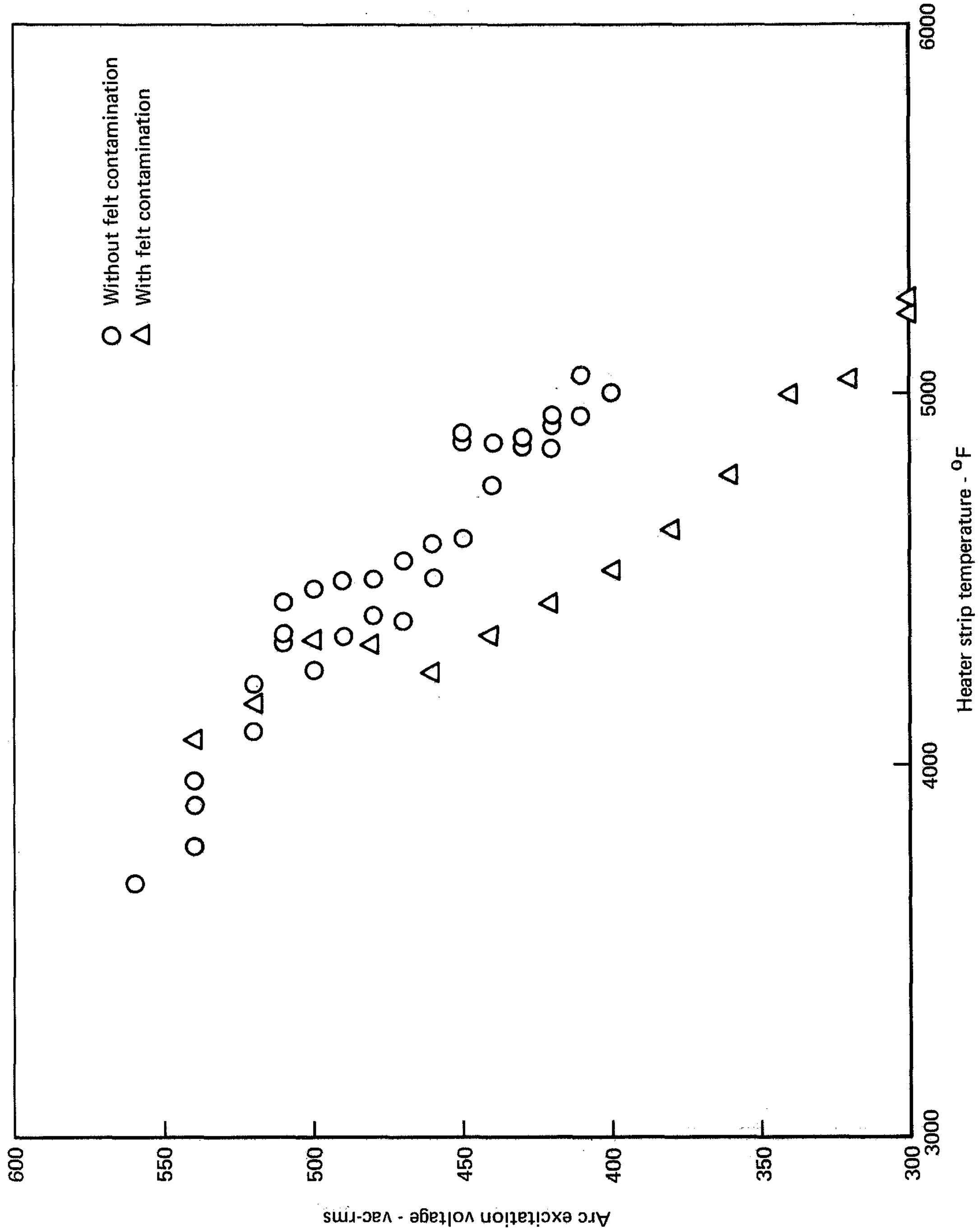

Figure 7 Effect of Graphite Felt on *Hold-Off Voltage* at 0.100 Inch Electrode Spacing

Another effect of felt contamination, illustrated by the small arcs shown in Figure 3, is temperature independent random arcing. This arcing is apparently produced by graphite fibers from the felt bridging the gap between the electrode and the strip. The arc shown in Figure 3 is typical and was produced by blowing on the felt enclosure while 500 volts were applied between the electrode and the strip with the entire apparatus at room temperature.

The apparatus illustrated in Figure 4 was utilized to determine what effect the smoke that is emitted from a strip in the 5200-5300°F range has on the hold-off voltage. In this test, at all temperatures below that at which smoke appeared, the gap would hold off over 550 volts, where as when smoke was visible the hold-off voltage dropped to about 200 volts. This was interpreted to be indicative of the electrically conductive nature of the smoke.

3.1.5 CONCLUSIONS. From the results of the arc investigation it may be concluded that arcing at all temperatures below the smoke emission temperature can be eliminated by making the inter-strip gap greater than 0.150 inch. When the graphite temperature is driven up to the smoke point, an arc will probably occur if the impressed voltage is greater than 200 volts regardless of the inter-strip gap. The use of graphite felt as a heat shield should be avoided since not only does it lower the hold-off voltage at element temperatures in excess of 4200°F but it contributes to spurious arcing at all temperatures including ambient.

3.2 CURRENT DENSITY INVESTIGATION. Since all the tests run in the arc investigation apparatus were run with graphite strips of the same cross-sectional area, the point at which smoke emission occurred was not only at a unique temperature but also at a unique current density. To decouple these two variables, a test was devised in which three graphite strips of equal cross-sectional area but different radiating areas (i.e. square or thin rectangular cross-section) would be heated to determine if the smoke point was dependent upon temperature or current density. The three strip configurations all had a cross-sectional area of 0.0376 square inch but had the following thickness and width dimensions in inches: 0.193 x 0.193, 0.080 x 0.47, and 0.040 x 0.93. Figure 8 shows the test results in terms of element temperature as a function of element current for each of the three test strips as well as the point at which smoke was detected. As can be seen, all three strips began to emit smoke at a temperature between 5200°F and 5300°F although the current densities at 5200°F varied from 12,000 to 20,600 amperes per square inch. It can be concluded from these test results that the appearance of smoke is a unique function of temperature and does not depend in any way upon current density.

3.3 EVALUATION OF SELECTIVE GRADES OF GRAPHITE. Since the arc investigation of Section 3.1 showed that the major obstruction to achieving higher heat fluxes with graphite radiant heaters was the evolution of smoke at 5200-5300°F, attention was turned to the evaluation of selective grades of graphite in an effort to find one with more desirable high-temperature properties. Five different graphite vendors were contacted and asked to supply samples of their best high-temperature graphites for evaluation. Four different grades of high-purity, fine-grained graphite were obtained along with a sample of pyrolytic graphite and one of vitreous carbon, a glass-like substance of high purity, strength, and hardness with a low permeability to both gases and liquids. These samples were all run under similar conditions in the arc investigation test apparatus to determine the temperature at which smoke emission occurred.

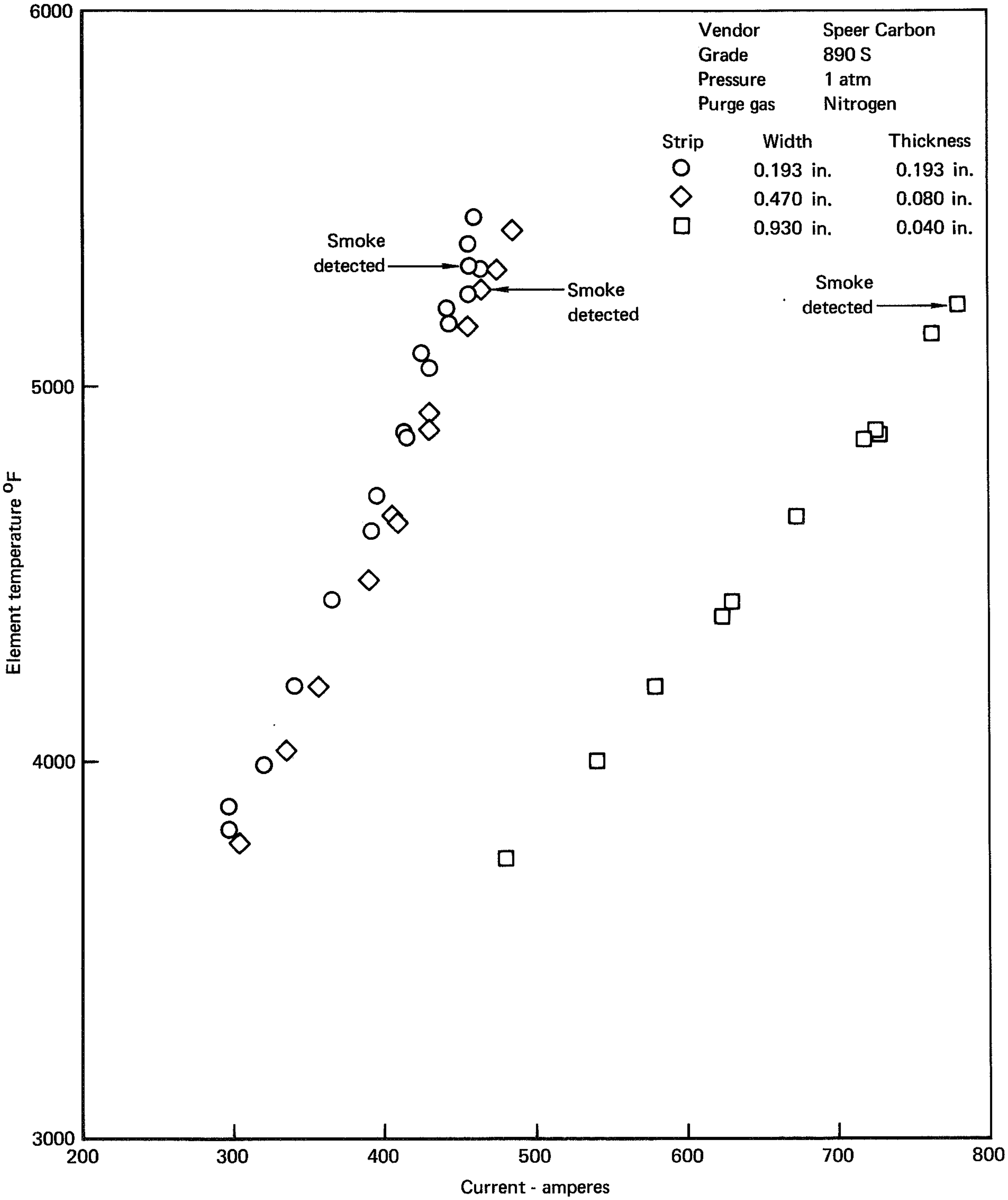

Figure 8 Current Density Tests
Element Temperature as a Function of Current

The pyrolytic graphite was tested in a manner devised to take advantage of its inherent anisotropic thermal and electrical properties. This anisotropy can be visualized by considering the pyrolytic graphite to be composed of layers, each of which has excellent thermal and electrical conductivity in plane but far less across planes. If, then, the power was put into the top plane only, this plane would become extremely hot while the rest of the strip would remain relatively cool. Actual testing showed, however, that the electrical conductivity difference was not sufficient to contain the power dissipation in a layer but rather allowed uniform cross-sectional dissipation in less than 20% of the strip length. The net effect of the thermal conductivity difference was to cause the strip to run hot down the center of the cross section and cool on the surface, opposite of what was desired. No further consideration of pyrolytic graphite was exercised after it was found that, in addition to the disadvantages described above, it exhibited a delamination problem at temperatures in excess of 4850°F. There was no significant difference in the smoke emission temperature of any of the other samples tested.

Further experiments were performed to determine the relative lifetime of these various graphites at high temperature. The procedure consisted of measuring the weight loss after a given time at or near the smoke emission temperature. Again there was no significant difference between the various samples with the exception of an extremely fine grained graphite which exhibited somewhat less weight loss. This graphite, unfortunately, had to be eliminated from consideration because it is not manufactured in large enough sizes to be used in the proposed heater design. It was concluded from this evaluation that none of the exotic graphites displayed tendencies that could not be obtained with commercial steel mill grade graphites and therefore this easily obtainable, economical grade was selected for the heater elements.

3.4 GRAPHITE COATING STUDY. The fact that many carbides have extremely high melting points indicated that the temperature limitation on the basic graphite might be raised if a method of carbide coating of the elements were devised. The carbides of interest were tantalum carbide which melts at 7010°F and a complex tantalum-zirconium carbide which melts at 7110°F. Two techniques of application were attempted; plasma spraying of tantalum metal and physical application of various powders and cement combinations including tantalum powder, graphite cement, and zirconia cement. After coating the sample strips, a reaction cycle at 4000°F was performed, the purpose of which was to react the graphite strip with the coating to obtain the desired carbide. The plasma sprayed samples failed during the reaction cycle when, apparently, the difference in thermal expansion between the graphite and the tantalum coating caused the coating to flake off. The other samples, being coated with a powder-like coating did not flake during the reaction cycle but when taken up in temperature, they emitted smoke at 5200°F the same as bare graphite.

Based upon these experiments it was concluded that, although both attempts failed, a possibility exists that a carbide coating could substantially increase the capability of graphite as a radiant heater, but that the extensive coating investigation required was beyond the scope of this program.

3.5 PURGE GAS EVALUATION. To determine the effect of purge gas composition on the smoke emission temperature, a graphite strip was operated in the arc investigation apparatus utilizing several different purge gases. These gases included nitrogen, argon, carbon dioxide, carbon monoxide, helium, difluorodichloromethane and a mixture of 25% carbon dioxide and 75% argon. The procedure was to purge the bell jar thoroughly with the selected gas, operate the graphite element at the smoke emission point and record the element temperature at this point. The carbon dioxide and the carbon dioxide-argon mixture both caused the element to emit smoke and coat all the cooled surfaces in the apparatus with a dense black film at an element temperature of approximately 3600°F. The results with difluorodichloromethane were spectacular, in that when the element temperature was increased above 3000°F, a gas separation occurred centered around the reflector plate under the heater (Figure 1). Below the reflector the gas was clear; but above the reflector around the element, the gas changed to a black smoke so dense as to nearly obscure the hot element from view. The smoke emission temperature with argon and helium was not significantly different than with nitrogen, the gas normally used for purge. The carbon monoxide, despite its obvious disadvantages of being both a toxic and a combustible gas, demonstrated an ability to suppress the smoke emission at temperatures in excess of 5600°F.

It can be concluded from this evaluation that difluorodichloromethane, carbon dioxide, and carbon dioxide mixtures are unsuitable as purge gases, while argon, helium and nitrogen have about the same potential performance. Carbon monoxide, on the other hand, demonstrates the possibility of a 20% increase in radiant heat flux because of its ability to suppress smoke emission at higher temperatures.

3.6 EMITTANCE ENHANCEMENT. Total emittance data for the graphite grade to be used for radiant heaters is a necessity for design calculations and for reduction of performance data. Complete emittance data for the Airco Speer

Carbon Co. grade 890S material was not available, however, some data at lower temperatures was available from the Defense Materials Information Center (DMIC). Supplementary data at temperatures up to 5600°F was obtained from 890S graphite using a total normal emissometer. The emissometer used for this determination has been verified against National Bureau of Standard secondary emittance standards and platinum standard specimens. The 890S graphite data, shown in Figure 9, agrees with the DMIC data and qualitatively with most other graphite emittance data available independent of grade.

When the apparent upper temperature limit for operation of a graphite radiant heater was encountered, ways were considered to increase the heat flux radiated to a test specimen for a given element temperature. Increasing the heater element emittance was an obvious method; and, considering the data in Figure 9, a considerable amount of improvement seemed possible.

Two approaches to increasing the heater element emittance were evident; coating the graphite with a high emittance material, or forming blackbody cavities in the element surface by machining. Various surface coatings to increase the emittance of graphite at high temperatures were tested; however emittance data on these coatings indicated that, as the temperature increased, the emittance of the coated sample approached that of bare graphite material. This was not considered surprising since most black coating systems able to withstand high temperature used carbon particle pigments. When the binders burnt away and the carbon particles were free to be modified by the high temperature, the coating emittance begins to approach that of the particle material (carbon).

Since coatings did not appear feasible, the alternate approach, forming blackbody cavities in the element, was chosen. Longitudinal grooving of the

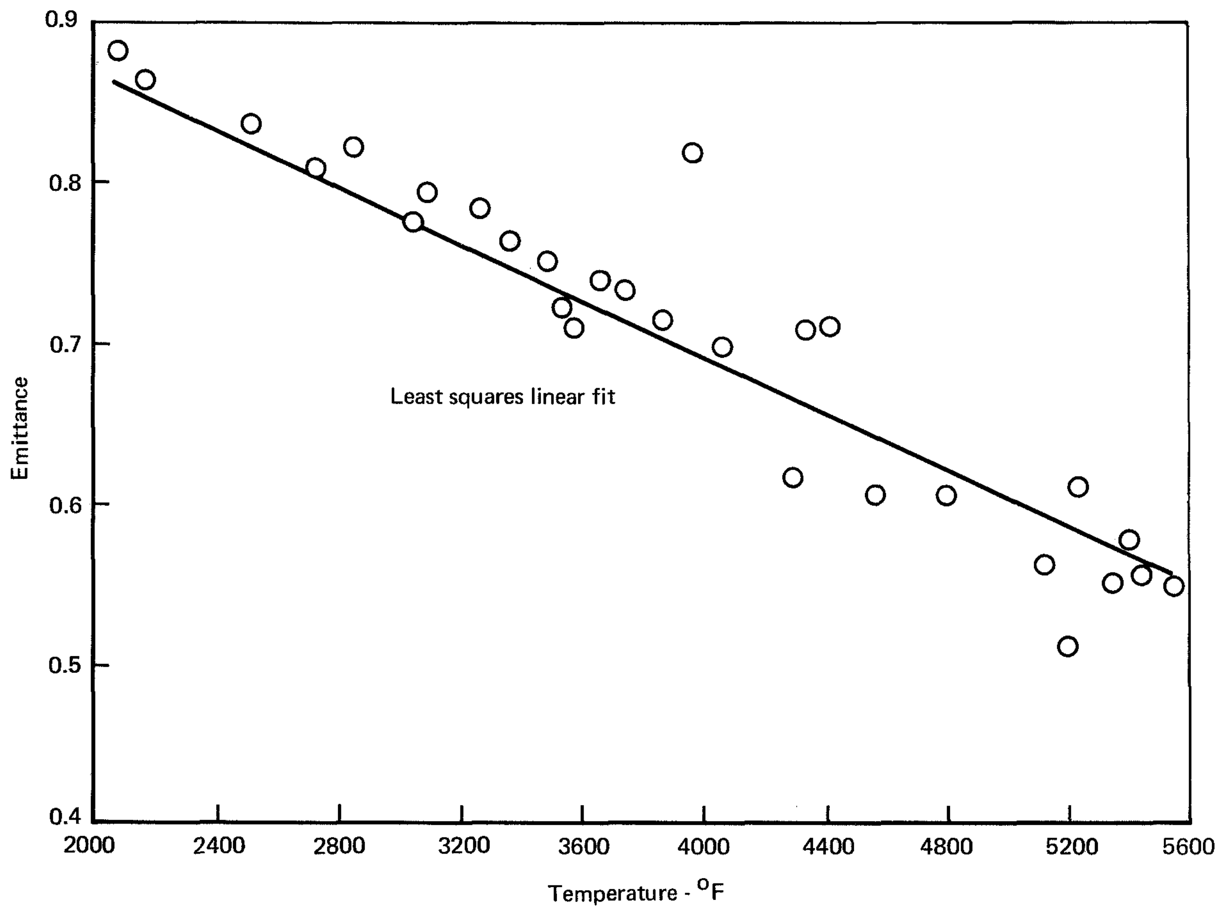

Figure 9 Total Normal Emittance - 890S Graphite

heater strip was selected as the most promising geometry since transverse or cross-hatched grooves seemed likely to produce large nonuniformities in temperature because they interrupted electrical flow through the strip. Isolated cavities in the heater strips suffered from the same objectives as cross-hatching and, in addition, appeared difficult to fabricate. The longitudinal groove profile to be evaluated, a 30-degree included angle v-groove, was choosen by the NASA contract monitor. Using this groove profile, heater element configuration was designed having the same cross-sectional area per-unit-width as a plain rectangular strip cross section 0.080 inch thick. Graphite heater strips, shown in Figure 10, were fabricated using the grooved configuration to fit in the arcing test setup described in section 3.1. A cross section of the grooved heater strip is shown in Figure 11.

A special test apparatus, fitting in the arcing test setup, was required to evaluate the emittance of grooved heater elements. The emissometer used for measurements on plain and coated graphite samples observed too small an area on the specimen surface to be used with the grooving profile selected. RF-heating used in the emissometer would also not reproduce temperature gradients caused by nonuniform electrical current flow.

The test apparatus constructed for emittance evaluation used two heat flux sensors to compare the emittance of the grooved and plain sides of a heater strip. As shown in Figure 12, one heat flux sensor views the plain side of the strip and receives a heat flux q_1 related to the view of the heater strip at the sensor F_1 and to the strip emittance ϵ_1 by

$$q_1 = \epsilon_1 F_1 q_b$$

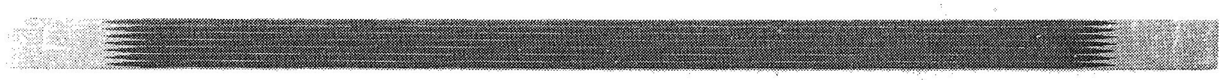

Figure 10 30° Included Angle V - Groove Graphite Strip

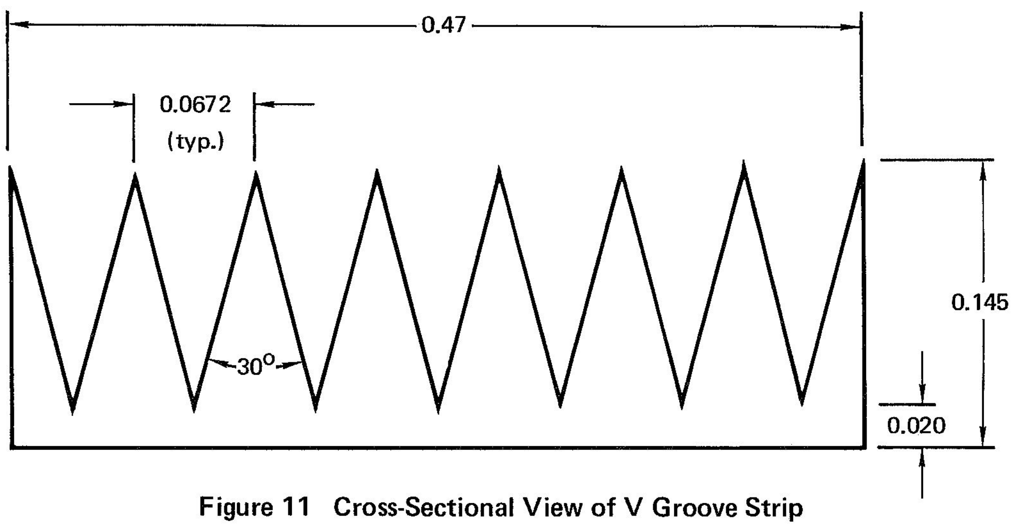

Figure 11 Cross-Sectional View of V Groove Strip

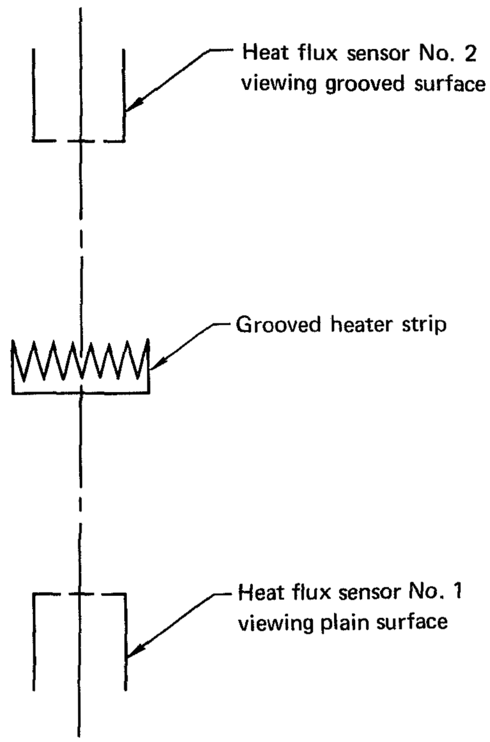

Figure 12 Test Setup to Evaluate Grooved Strip

where q_b is the radiation emitted by a blackbody at the heater strip temperature. Similarly, a second heat flux sensor views the grooved side of the heater strip and receives a heat flux q_2 given by

$$q_2 = \epsilon_2 F_2 q_b$$

where F_2 is the view factor of the strip at the second sensor and ϵ_2 is the emittance of the grooved surface. The output voltage of each heat flux sensor V is related linearly to the heat flux q received by some sensitivity S. So the output voltages of the two sensors are

$$V_1 = \epsilon_1 F_1 S_1 q_b$$

and

$$V_2 = \epsilon_2 F_2 S_2 q_b$$

The ratio of the emittance of the plain and grooved graphite surfaces is therefore linearly related to the ratio of the output voltages of the two heat flux sensors by

$$\epsilon_2/\epsilon_1 = \left(\frac{F_1 S_1}{F_2 S_2}\right) V_1/V_2$$

If the axis connecting the two heat flux sensors passes perpendicularly through the center of the heater strip, F_1 is the same as F_2 and a further simplification results.

$$\epsilon_2/\epsilon_1 = {}^{S_1}/_{S_2} \; {}^{V_1}/_{V_2}$$

The design of the test apparatus is based on this equation.

Development of a Graphite Radiant Heater

Figure 13 shows the actual test apparatus, in which two water-cooled radial-gradient Hycal heat-flux sensors were mounted in a water-cooled brass "C"-shaped block. To eliminate the effects of convection, the heater strip was mounted with the grooved face in a vertical plane using "L"-shaped graphite adapter blocks on the two electrodes of the arcing test setup. The threaded steel stem of the block fitted into an adapter which mounted to the base reflector. Water connections from the heat-flux sensors were brazed into the brass block which, in turn, had internal water-cooling passages and two AN flare fittings for connection to the water supply. Electrical leads from the two sensors went through a multi-pin electrical connector in the bell jar base-plate of the arcing test setup to a double-pole, double-throw pinch switch connecting one or the other of the sensor wire pairs to a Biddle-Gray manual potentiometer. Strip temperatures were measured with a Leeds and Northrup manual optical pyrometer viewing the plain side of the heater strip. The remainder of the apparatus was as described for the arcing tests.

It was found necessary to connect the two calorimeters so that the differential could be read directly rather than obtained from the subtraction of two absolute values. This reduced the data scatter markedly. Figure 14 shows the results of several runs and indicates that the improvement in emissivity due to grooving the strip is of the order of 4%.

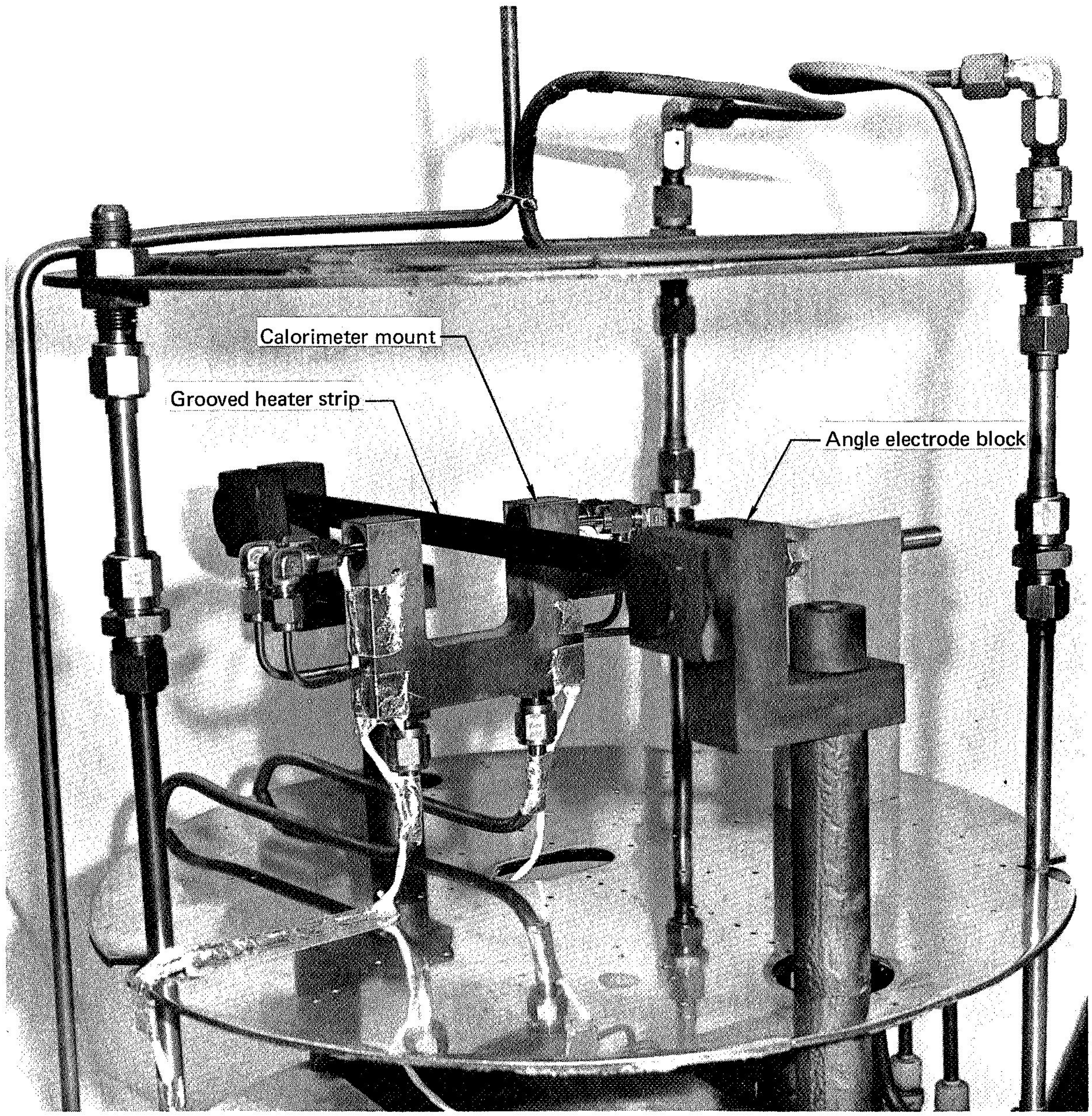

Figure 13 Test Apparatus for Evaluation of Grooved Graphite Strip

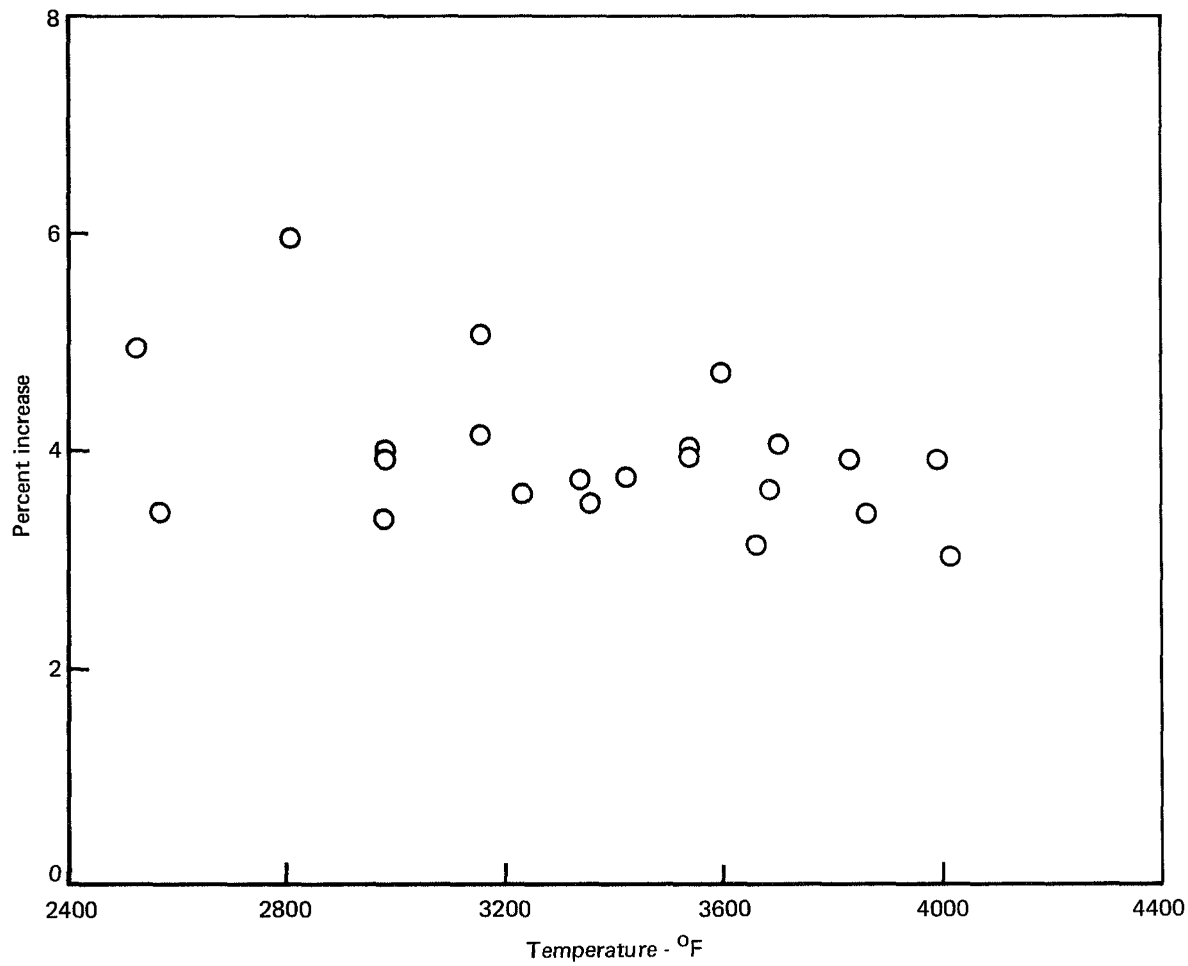

Figure 14 Emittance Improvement Data - Grooved Strip

4.0 PROTOTYPE HEATER ASSEMBLY

A prototype graphite heater assembly, shown in Figure 15, was constructed to test design concepts and components before beginning to fabricate the full-scale, end-item graphite heater. Retrofits to improve the performance or to eliminate faulty components could more easily be made on a small prototype, and repair of the damage inevitable in high heat flux heater development would be simple and inexpensive. The prototype had to be large enough, however, to permit reproduction of all the phenomena likely to be encountered. A "slice" of the larger heater, containing two separate heater elements was the size chosen. The prototype used the same end blocks, heater elements, bus bars, and side reflectors envisioned for the full-scale heater. The manifold blocks, and bottom and end reflectors differed from those of the proposed full-scale heater design only in length. Use of two elements was necessary to permit investigation of arcing between elements operating on different phases of the 3-phase AC supply.

4.1 LONG ELEMENT FEASIBILITY STUDY. In the interest of greater uniformity, a study was made to determine if a heater assembly could be constructed using elements that would bridge the entire test zone. A simple test was considered the best for determining the feasibility of using full length (26-inch) elements. The basic criteria for feasibility were element sag and expansion, plus high temperature creep. The study was essentially a "go no-go" test intended to reveal any potential problems and did not go into such detailed embellishments as end connector design or overall system configuration.

Figure 16 shows the test specimen, a hairpin heater made up of two 26-inch long, 0.8-inch x 0.050-inch graphite strips with both electrical connections at

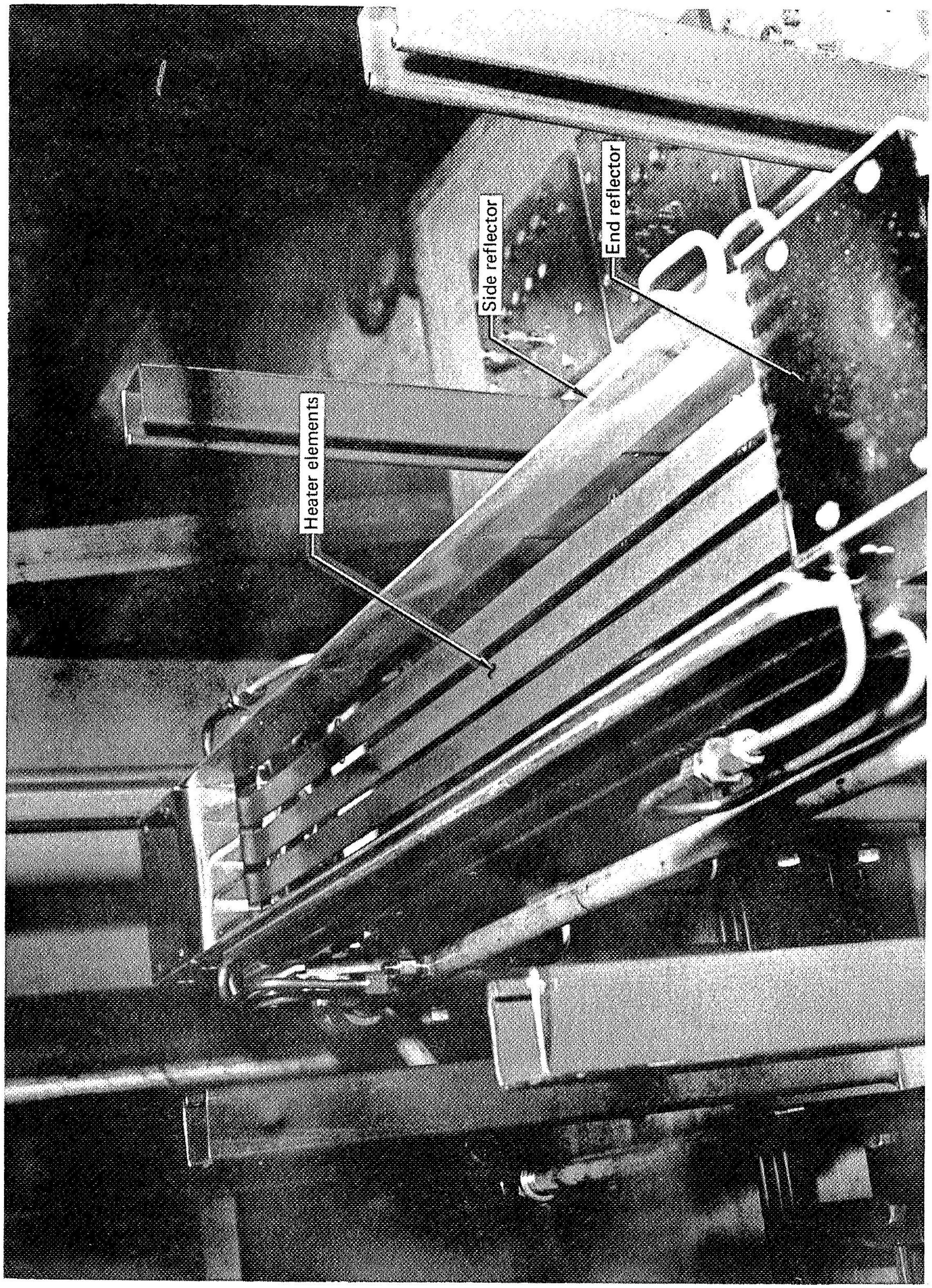

Figure 15 Prototype Graphite Heater Assembly

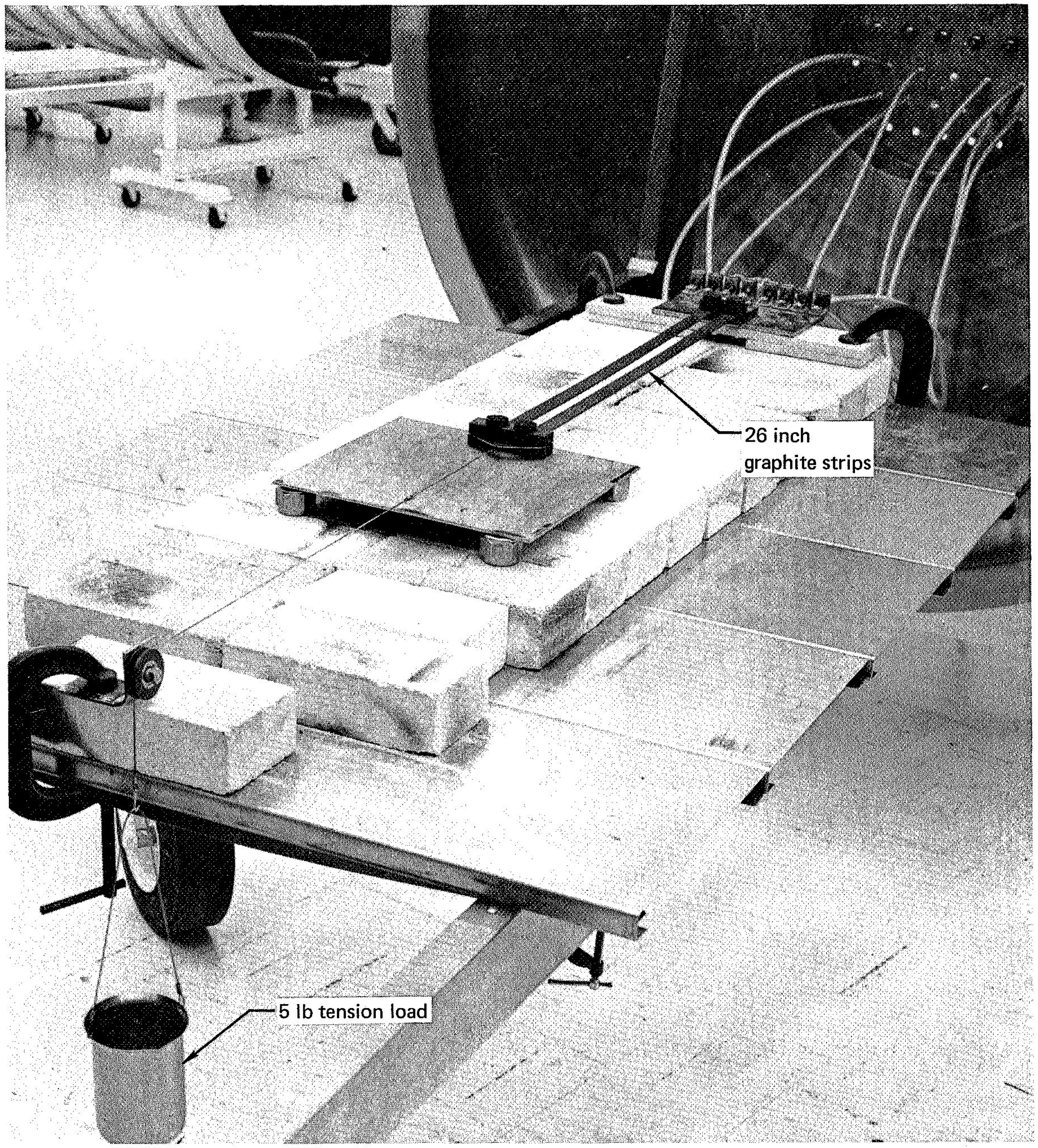

Figure 16 Test Setup - Long Element Feasibility Study

one end and a tension loaded clamp block at the other. A weight of 5 pounds was used to tension the elements and reduce the sag to less than 1/8 inch, as compared to the free element sag of approximately 1 inch. The heater assembly was mounted on a firebrick base and installed in a nitrogen purged chamber with a relatively large observation port.

At 4630°F, the heater exhibited no increased sag, but a length increase of approximately 1/4 inch. The heater returned to its original length after cooldown. The preliminary nature of the test prevented runs longer than 3 to 5 minutes duration, but none of the characteristic creep indications were noted. Testing indicated that tension was definitely necessary to eliminate sag and that no "taffy-like" creep tendencies were apparent. Spurious vibration of the elements through an amplitude up to ± 1/2 inch was also noted. This was probably due to a combination of 60 Hz electrical forces and the natural frequency of the elements used.

4.2 ELEMENT DESIGN. The heater elements for the prototype graphite radiant heater shown in Figure 17 consisted of two 26.5-inch long, 0.80-inch wide, 0.080-inch thick heater strips, connected electrically in series and were machined from a single piece of graphite to form a two-pass hairpin-type element. At the ends of the hairpin, where electrical connection is made, the strips are thickened to 0.375 inch to avoid excessive heat load to the electrode end blocks. The bend of the hairpin, connected to the graphite expansion-takeup slider, is similarly 0.375 inch thick to protect the expansion end block and to avoid excessive heating produced when the electrical current flows from strip to strip through a thin section. The heater elements were machined from Airco Speer grade 890S material; an extruded artificial graphite having an average grain size of about 0.008 inch.

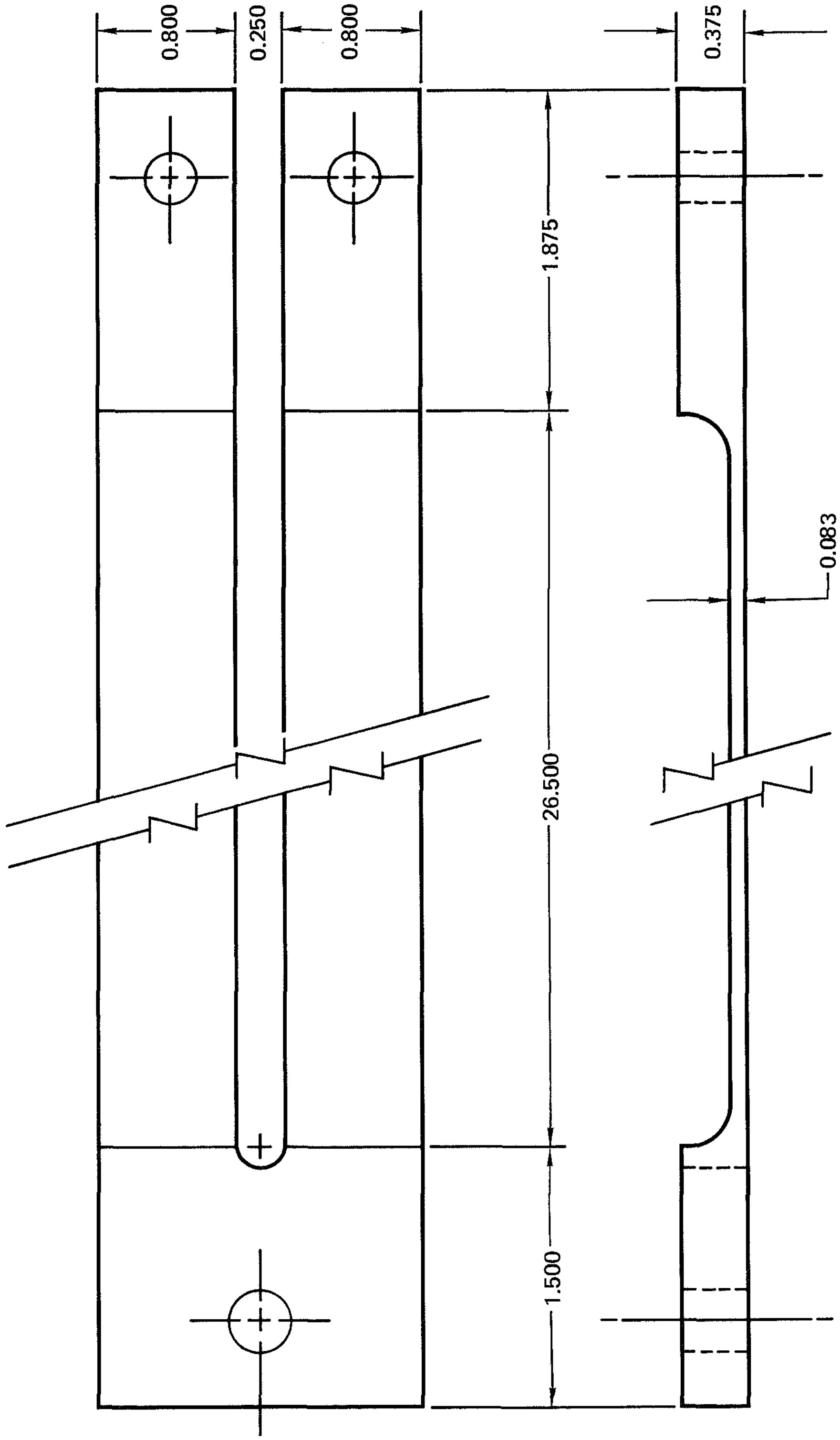

Figure 17 Graphite Heater Element

4.3 REFLECTOR DESIGN. The prototype heater assembly mechanical design defined the size and location of the reflectors and the thermal design was conducted using these geometrical constraints. For various reasons, including cost, fabricability, and developmental flexibility, it was decided to fabricate the prototype reflectors of copper plate with tubing serpentines brazed on. To this end, a heat load analysis of the reflectors was performed at a heat flux level of 250 Btu/ft^2-sec. A generalized computer program was used for these computations. The reflector array for the prototype assembly consisted of three circuits; the bottom reflector, and two others each of which comprises one side and one end and are identical. These two circuits were analyzed to produce the results illustrated in Figure 18, which are plots of the various performance parameters as a function of flow rate. The concept of pressure suppression of local boiling was used as can be readily seen in the curves by the upswing of the feed pressure at the lowest flow rate.

4.4 END BLOCK DESIGN. End blocks to support the graphite heater element, to conduct electrical power to the element, and to allow for the thermal expansion of the element are a vital part of heater design. Three problems often having mutually exclusive solutions complicate the design of the end blocks; dissipation of the heat load on the block, electrical insulation, and allowance for heater element thermal expansion.

Considerable heat is conducted into an end block from the attached graphite heater element; is radiated to the block from the element through unavoidable gaps in the reflectors; and, in the case of a current-carrying electrode block, is generated by ohmic heating in the bulk material of the block and at the joint between the electrode block and the heater element. Unless this heat load is

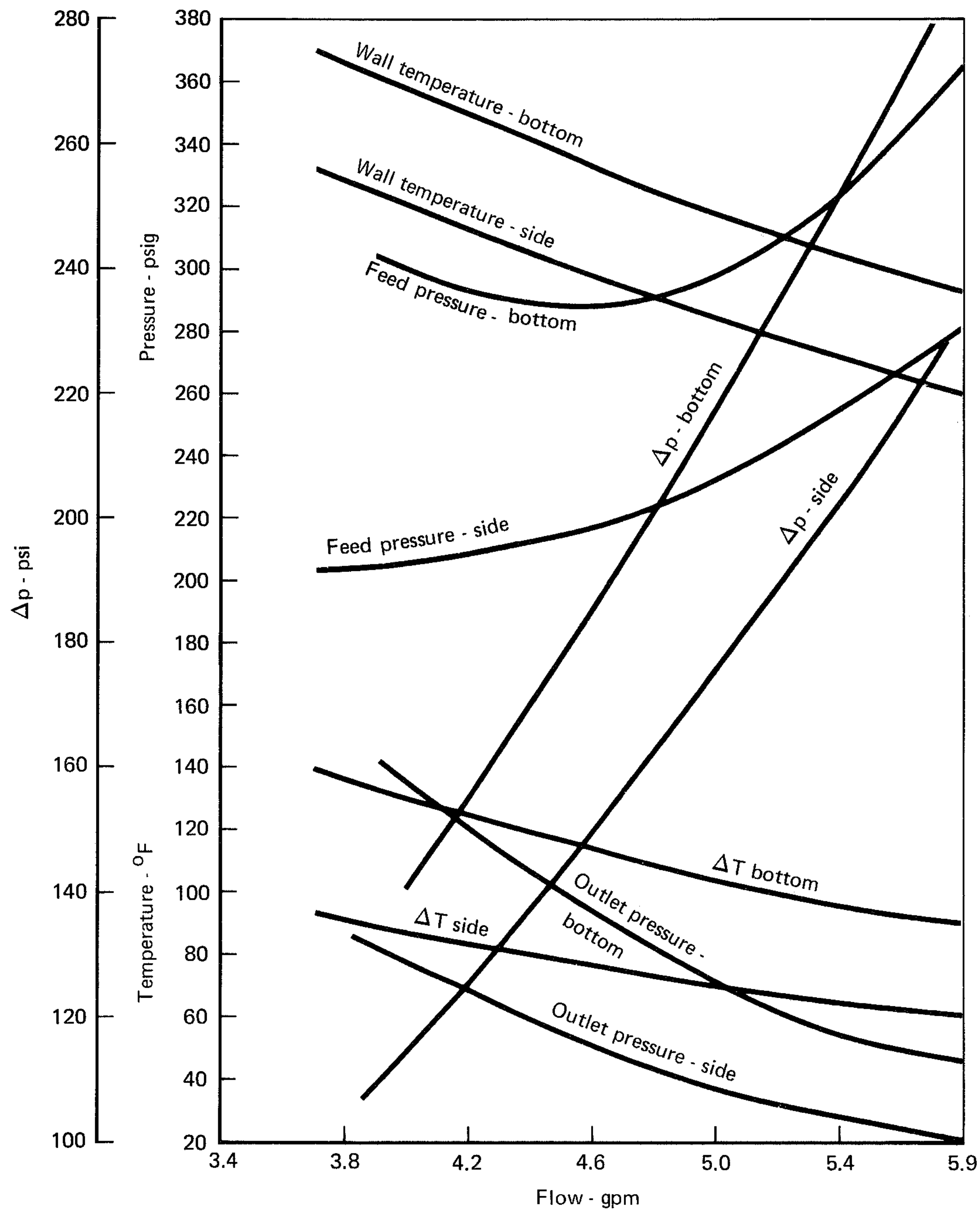

Figure 18 Reflector Performance

250 BTU/Ft^2 - Second

removed, the block temperature will increase until failure occurs. Passive cooling of blocks has been unsatisfactory in previous designs. Convection or radiation cooling requires too high a block temperature to dissipate the required amount of heat and, in addition, dissipates this heat behind the heater assembly reflectors complicating the design of other components. Active cooling of the end blocks with circulating water has been the only satisfactory design.

Electrical insulation of the end blocks from the heater assembly frame supporting the blocks is an obvious requirement. Insulation in the lines carrying water to and from water-cooled end blocks must also be provided. Most electrical insulators, however, are also thermal insulators. Without adequate shielding and intimate connection with the water-cooling system, radiative heat inputs raise the surface temperature of the insulation material to failure.

At least one end of a graphite heater element must be allowed to move to avoid element bowing from thermal expansion. In addition, when long heater elements are used, some form of positive tensioning must be used to prevent sag. Allowing for movement and tension complicates water cooling and electrical insulation.

The prototype radiant heater has two brass water manifolds, one at each end, to supply cooling to the end blocks. Two 0.75-inch diameter holes for water supply and for water drain were drilled through each manifold. Brass end plates, with brazed-on 37-degree flare fittings, were sealed to the ends of each manifold with O-rings and connected the supply and drain holes in the manifolds to external piping.

The two electrode-end blocks, connected to the legs of the hairpin-shaped graphite heater element to be used on the prototype heater, carry current to the element and, because of the large currents, are most conveniently fixed. The block fastened to the bend of the hairpin must provide for thermal expansion and element tensioning.

The graphite heater element was pinned to a graphite slider block grooved in the bottom to slide over a fixed water-cooled brass end block. For element tensioning, a compression spring was retained by a graphite nut on a graphite rod extending through the water-cooled end block into the graphite slider. The portion of graphite rod sliding through the water-cooled brass would transfer heat conducted from the slider into the end block and protect the compression spring further along on the rod. A model of this design with the graphite parts sliding on an uncooled aluminum block verified that the idea was mechanically sound, but the chief concern, thermal protection of the compression spring, could only be evaluated when the design was incorporated in the prototype heater assembly.

Early in initial testing of the heater, it was discovered that the music-wire element tensioning compression springs had overheated and spring tension had been lost. Inconel-wire compression springs were wound and installed to increase the spring temperature resistance. This modification eliminated heater element tension loss from spring relaxation.

The design of the electrode and expansion end blocks, Figure 19 and 20, employed a single stud without water passages, and at the electrode end, the stud was intentionally made large in area to avoid ohmic heating problems. A Teflon sleeve separated each stud from the manifold through which it extended.

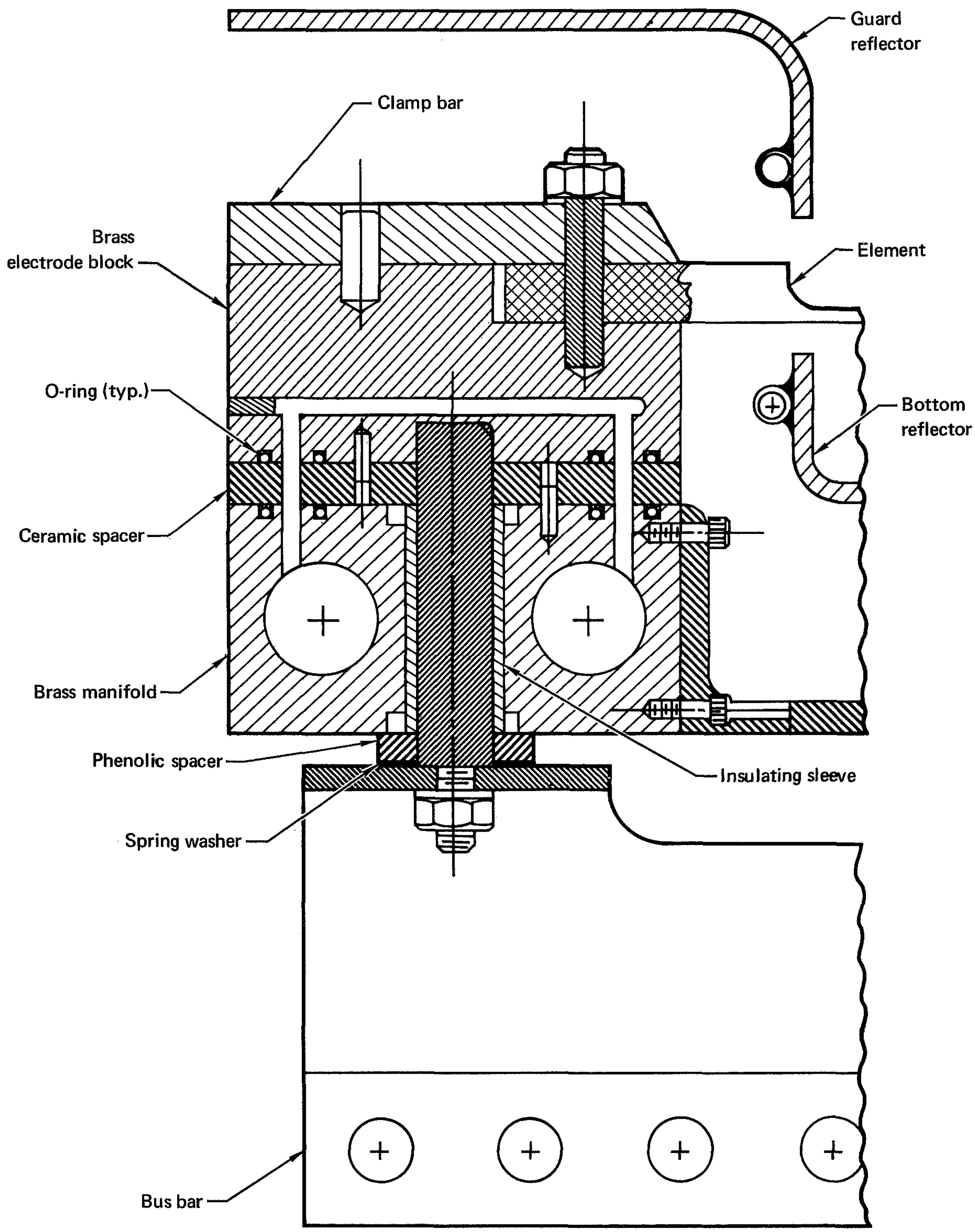

Figure 19 Full Scale Heater Assembly Electrode End Block

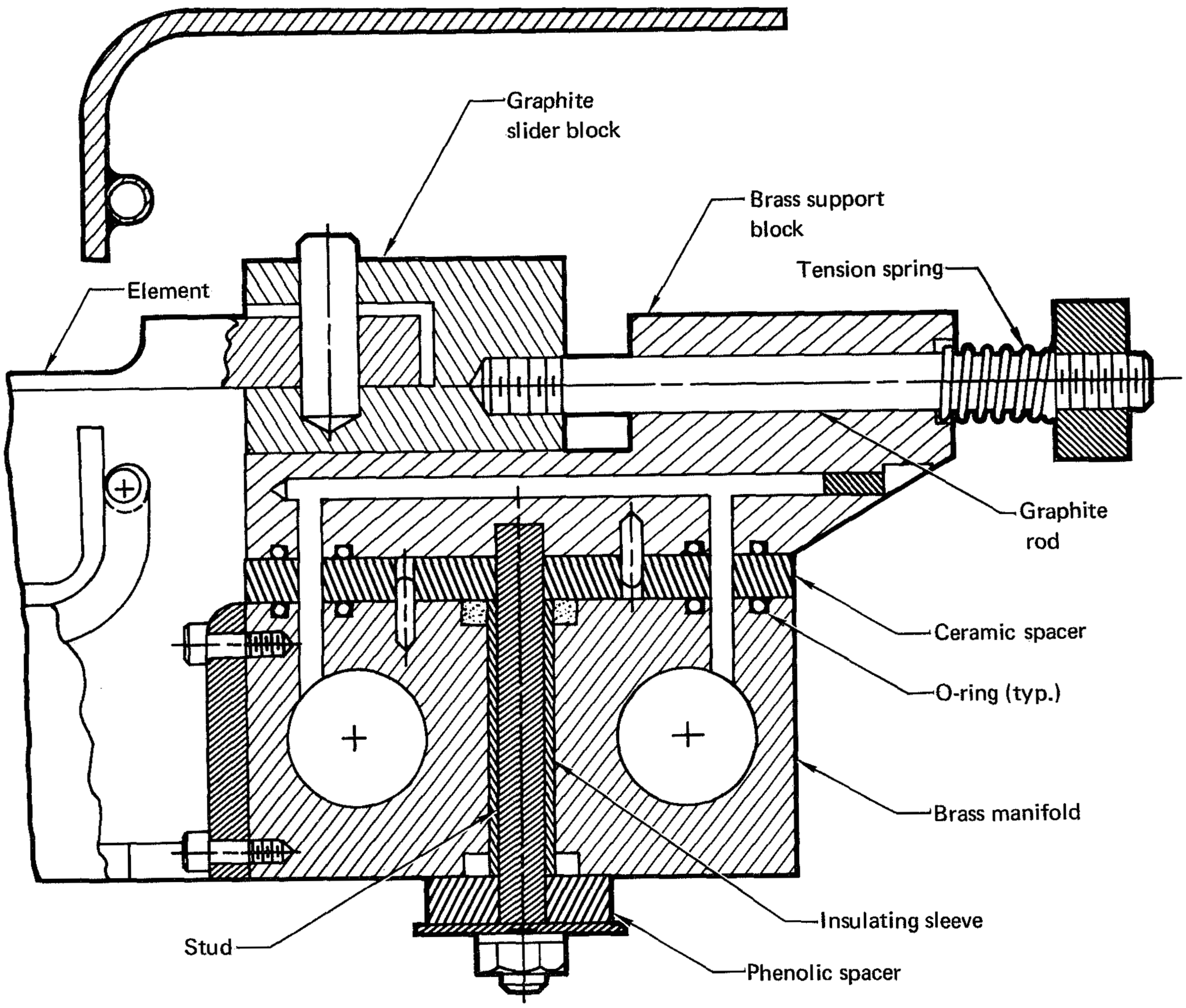

Figure 20 Full Scale Heater Assembly Expansion End Block

The upper face of the brass manifolds was insulated from the end blocks by a 0.25-inch thick machinable ceramic spacer having a maximum temperature endurance of 1,000°F in the unfired state used. Cooling water for the end blocks circulates from the supply bores of the manifolds up through the ceramic insulator through the block cooling passages, and back down through the ceramic insulator into the manifold drain bore. Conventional O-rings, located in the grooves in the end blocks and the manifolds, seal between the brass and the ceramic insulator. Water absorption by the ceramic is prevented by a silicone resin impregnation. On the electrode block end, clamp-up of the assembly is provided by a spring washer bearing on a phenolic spacer slipped over the portion of the stud extending through the brass manifold. The bus bar, clamped against a shoulder on the stud, retains the spring washer. At the expansion end, a phenolic spacer is used with a simple nut and washer to provide tension on the O-rings.

Aluminum restrictor plugs were added to the outlet of the drain bores in both manifolds to restrict flow through the manifold-end block system and to raise the pressure drop to a level compatible with that of the three reflector circuits.

The bus bars, for electrical connection to the prototype radiant heater, were 0.125-inch thick copper sheet with tabs to fasten at one end to the bottom of the studs extending through the water manifold from the electrode end blocks, and to fasten at the other end to a 0.250-inch thick plate of grade GSG silicone-resin glass-cloth laminate. Each bus bar had holes for bolting four L250-angle electrical connectors to the plate to attach four 1/0 wires. Holes were staggered on adjacent plates for clearance.

5.0 PROTOTYPE HEATER TESTING - ATMOSPHERIC PRESSURE

5.1 TEST OBJECTIVES. The prototype heater test was intended to prove the design concepts, enhance the analyses used in design, determine system limitations, and to provide data necessary to successfully design the full scale assembly. In the course of this testing, the ultimate system limitations could be approached and the performance limiting component be determined. Further, the test apparatus was extensively instrumented to provide data with which to determine a total system heat balance, the knowledge of which is invaluable in the design of heater systems. The overall objectives of all of the above is to provide experience, data, and a good general knowledge of the prototype system thereby enabling the full scale system to be designed with a high degree of confidence in its ability to perform up to expectations.

5.2 TEST PLAN. In order to fulfill the objectives, the prototype tests were conducted at steady state, with extensive data taken at each performance point. The absorbed heat flux was gradually increased until some anomaly would take place, whereupon the run was terminated, the heater examined, and the data reviewed in an effort to determine the reason for the anomaly. This was to be continued until such time that the system reliability was high enough to perform endurance tests to determine the effects of relatively long times at a constant high heat flux.

5.3 TEST APPARATUS FOR ATMOSPHERIC PRESSURE TESTING. The prototype graphite radiant heater was tested at atmospheric pressure in an inert-gas test enclosure shown in Figure 21. This test fixture maintains an inert atmosphere of nitrogen gas inside a 3.0-ft x 5.0-ft x 4.0-ft volume enclosed by

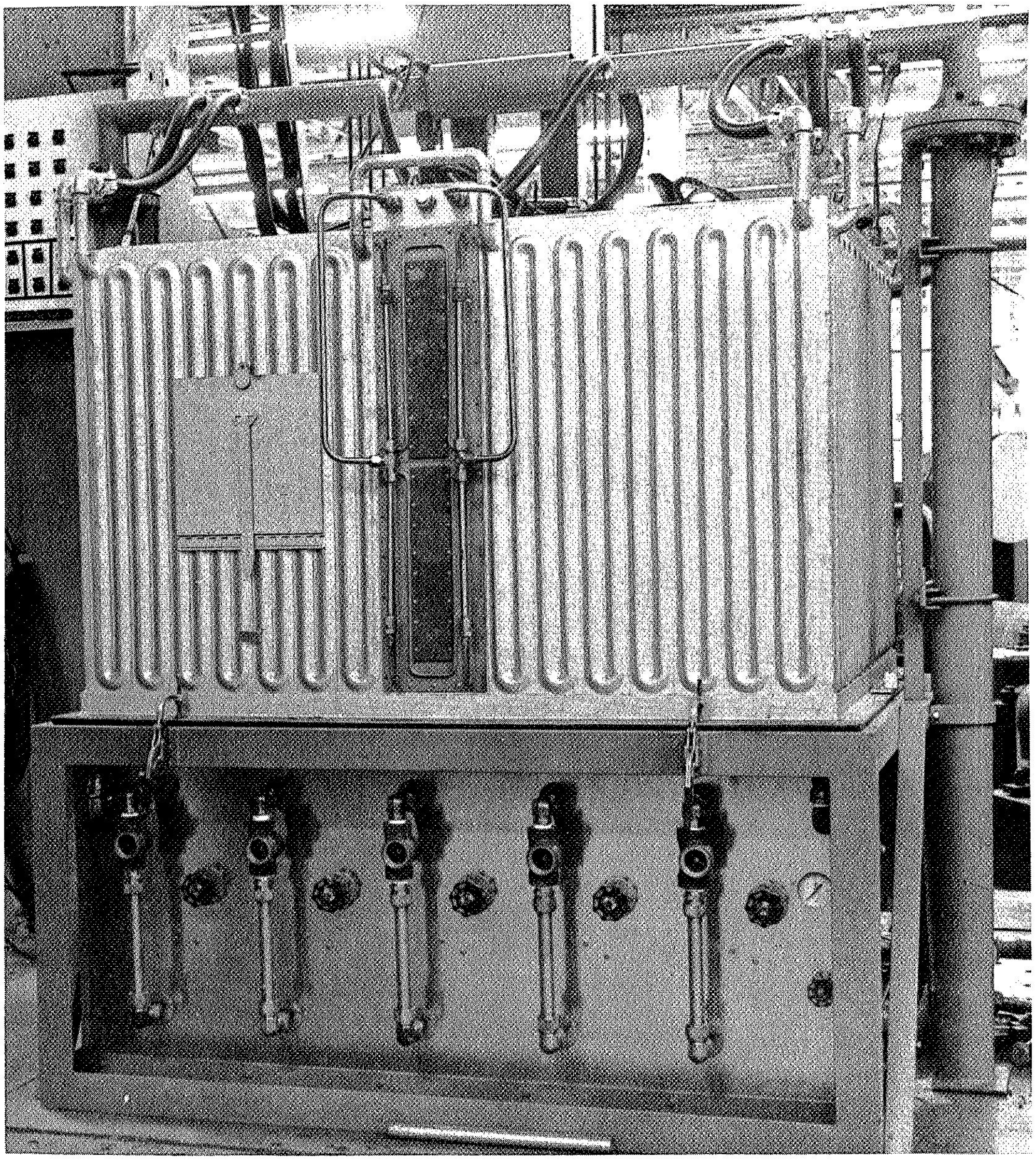

Figure 21 Water Cooled Inert Atmosphere Enclosure

water-cooled mild steel panels. Two water-operated hydraulic cylinders raise five sides of the enclosure to leave a flat 5.0-ft x 4.0-ft baseplate free for setup of equipment to be tested. In addition to permitting easy handling of the heavy enclosure top, the hydraulic cylinders have hollow piston rods which carry cooling water to the enclosure top without the inconvenience of large hoses. A rubber gasket and toggle clamps seal the enclosure top to the baseplate for testing. The enclosure baseplate contains passthroughs for cooling water, electrical power, nitrogen gas, and instrumentation. Four hard points are also provided on the baseplate for attaching test apparatus.

The schematic of Figure 22 illustrates the three separate supply and drain manifolds supply water to the inert gas test enclosure. Each drain manifold is provided with pressure gages and valves so that three different back pressures may be maintained on water cooled apparatus in the test enclosure. Water from any of the three supply manifolds may be connected to any of five globe-flow control valves and rotameters on the front panel of the fixture, thence to any of five 1.0-inch water inlets in the enclosure baseplate. Five 1.0-inch drain fittings are also provided in the baseplate. "Christmas-tree" manifolds adapt these 1.0-inch fitting to smaller sizes when necessary.

Power is supplied to the test enclosure from a 2,500 kva three-phase step-down transformer and three E-size ignitrons. Three independent channels of 480 V., 2000 a. power to the enclosure may be manual, feedback, or program controlled. Electrical power is connected to six water-cooled bus plates in the enclosure baseplates, which provided tapped holes for attaching lug terminals or bus bars and provide 0.375-inch fittings to connect to water cooling at the potential of the bus plate.

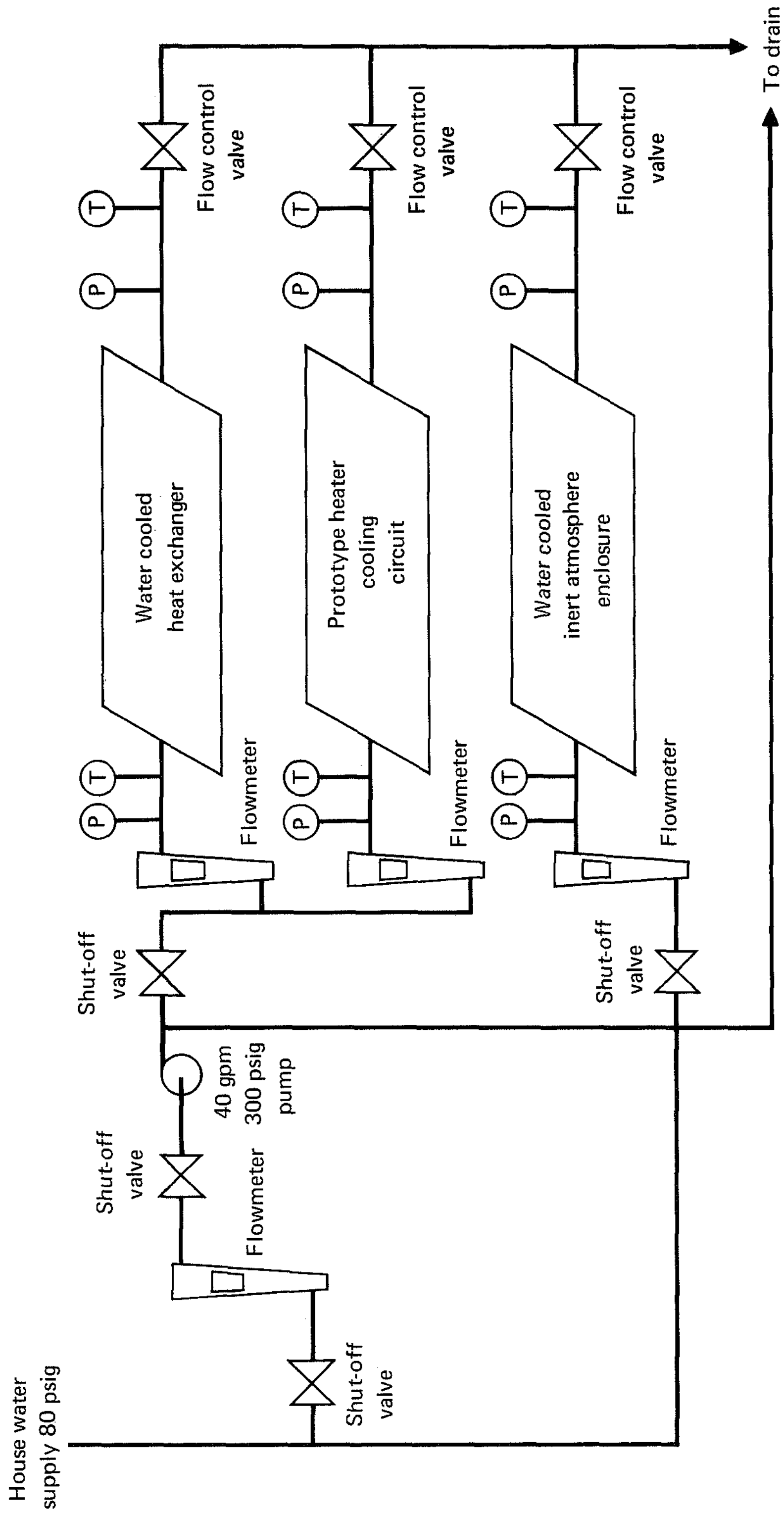

Figure 22 Cooling Water Schematic - Development Test

Nitrogen gas for purging the test enclosure is provided by vaporizing liquid nitrogen in a water-warmed heat exchanger. A valve and upstream pressure gage are used to set the desired purge rate. Other gas supplies may be easily connected to the system if desired.

Current and voltage supplied to the apparatus in the test enclosure is monitored by a true RMS digital voltmeter, wide-band current transformers, and a fuse-protected switching system. Multi-pin connectors for thermocouples on the test apparatus or other instrumentation wiring are provided in the enclosure baseplate. Instrumentation may be connected to the McDonnell Transient Heat Facility recording system.

The most severe test for a graphite radiant heater is radiating its maximum heat flux at maximum input power to a cooled test specimen capable of absorbing all the incident energy. Such a condition is also representative of the expected use of the delivered full-scale radiant heater. A water-cooled heat exchanger, shown in Figure 23 was designed and fabricated, as described in Appendix A, for testing the prototype radiant heater to reproduce this worst-case condition.

5.4 INSTRUMENTATION. The determination of the heater system energy balance requires the measurement of the water flow rate and temperature rise of each significant water circuit. The water temperature rise is measured directly by connecting a thermocouple in the inlet of a system to one in the outlet in such a manner that the millivolt output is proportional to the temperature difference. This output is directed from each circuit to a thermocouple switch and finally to a Biddle-Gray potentiometer for readout. Figure 24 shows the location of the thermocouples measuring the water temperature. The water flow rate is measured with Fischer-Porter flowmeters of a nominal rating of 12 gpm

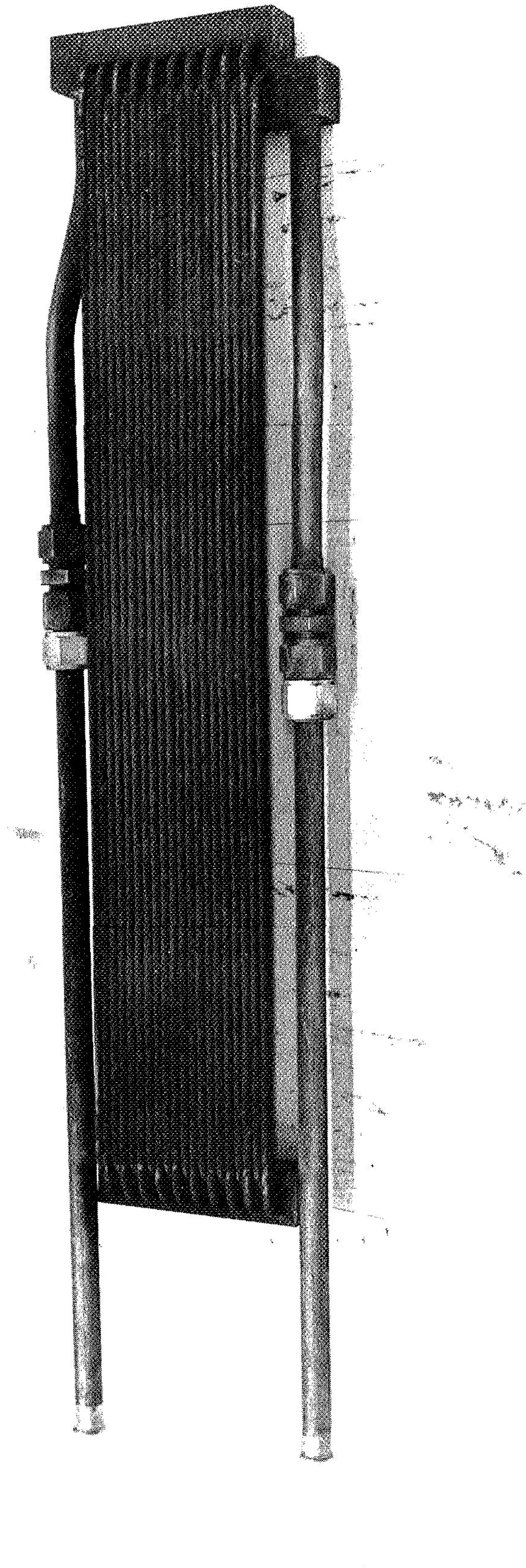

Figure 23 Water-Cooled Heat Exchanger for Prototype Heater Assembly

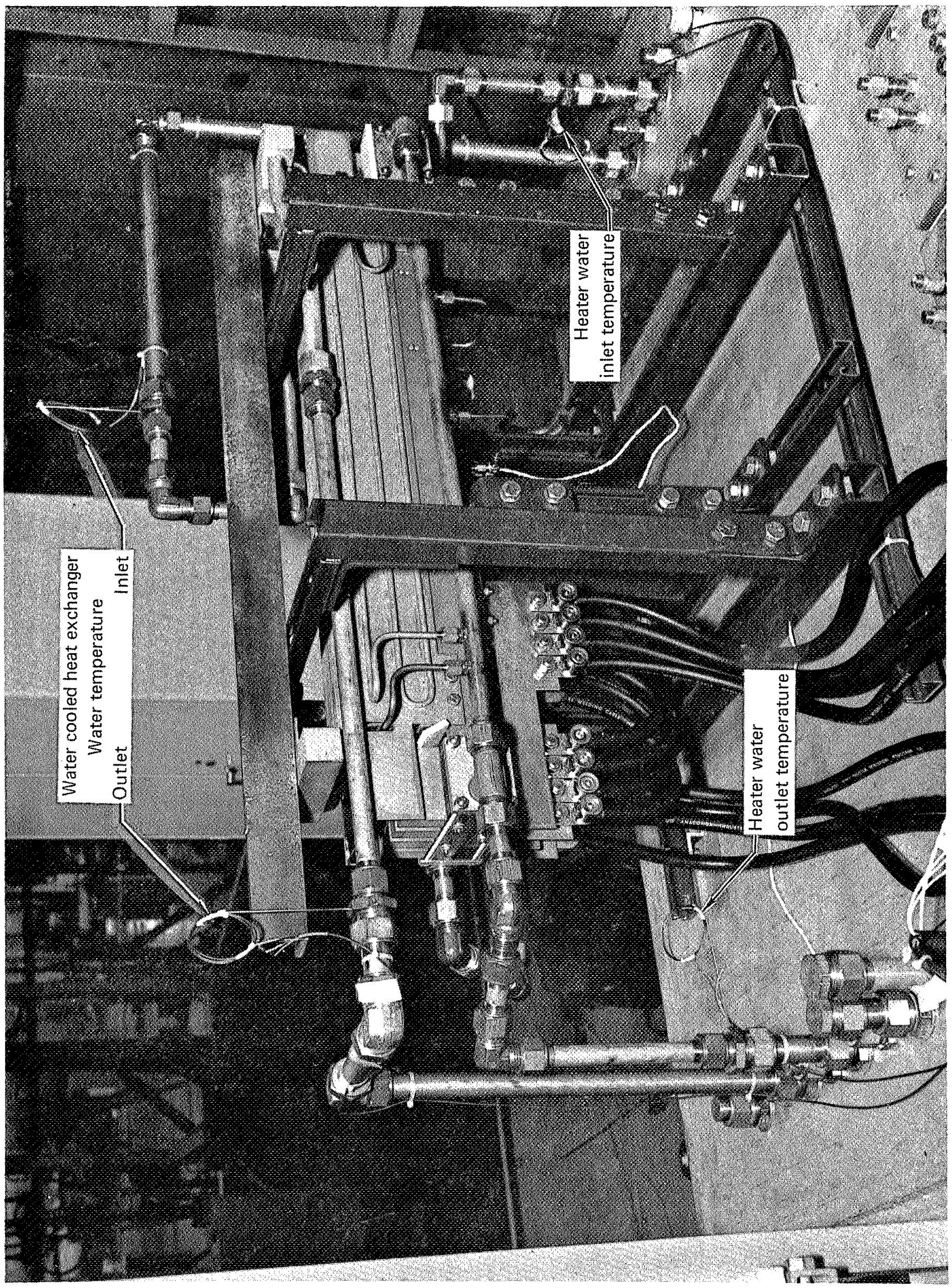

Figure 24 Prototype Heater Test Setup Instrumentation

each. A parallel connection of three flowmeters, monitors the flow through the water cooled heat exchanger while two are used for the heater assembly. This arrangement was made necessary by the unavailability of accurate large flowmeters.

Due to the nature of the wave-form of ignitron controlled power, true RMS instruments are required for voltage and current measurement. The voltage was measured directly on a true RMS voltmeter while the current was measured by means of a current transformer connected to a true RMS voltmeter.

The heat flux was measured by recording the output of a Hy-Cal radial gradient calorimeter on a standard millivolt strip chart recorder.

Various pressures were measured throughout the water system but these were mainly operational and used for the initial system settings and were therefore not usually recorded.

5.5 RESULTS AND DISCUSSION. The initial shakedown testing of the prototype heater assembly revealed only minor hardware problems and attention was concentrated on other developmental problems. One persistently puzzling problem was the difference between the calorimeter flux and the absorbed flux. Theoretically there should be a difference because the calorimeter has a different view factor for the heater than does the water-cooled heat exchanger. However, this difference is geometrically dependent and thus the ratio of absorbed to calorimeter flux should be constant and not depend upon power setting. The fact is, though, that the ratio does vary as shown in Figure 25. It must be remembered that the calorimeter is essentially a point receiver and is also closer to the heater than the water-cooled heat exchanger. For this reason, the heat absorbed by the heat exchanger is more dependent on the condition of the reflectors than

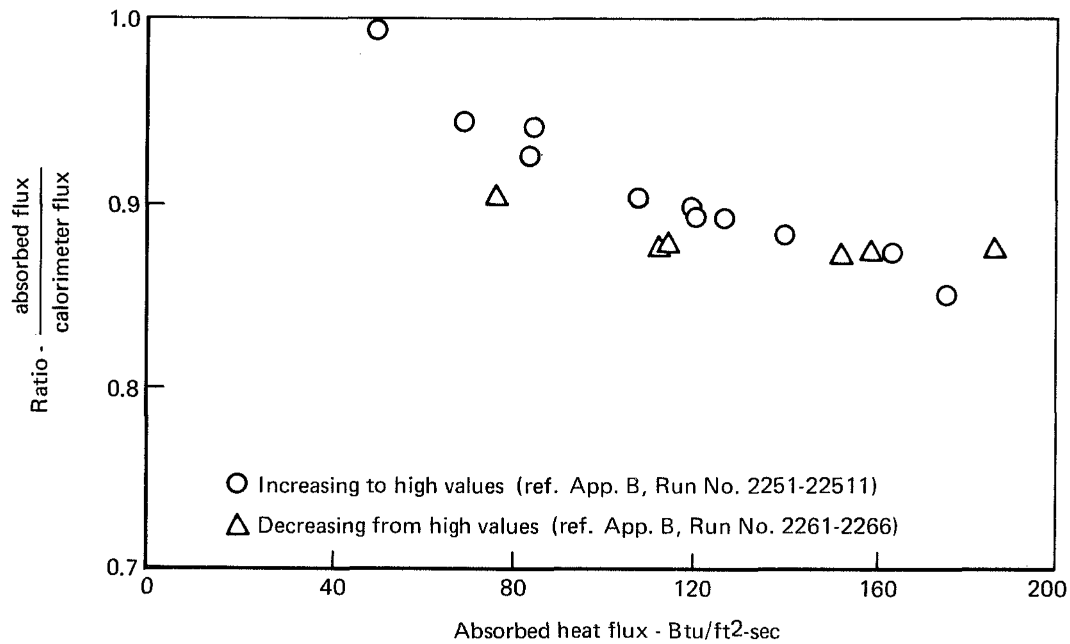

Figure 25 Variation of Flux Ratio with Power Level

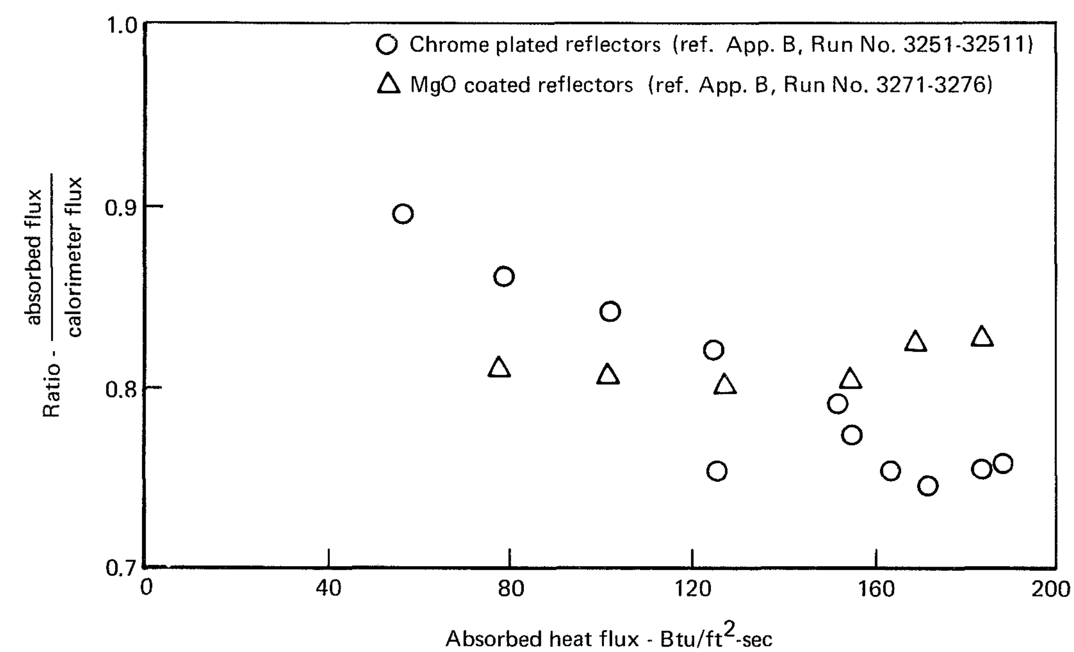

Figure 26 Effects of Reflector Surface Material

is that absorbed by the calorimeter and hence a change in the reflectance characteristics will cause a change in the ratio. One probable cause for a reflectance change is the spectral variation in the reflectivity of the plating which, like the typical shiny metal surface, decreases with decreasing wavelength with a characteristic dip somewhere near the visible portion of the spectrum. Also the variation has to do with the darkening of the reflectors by condensed carbon vapors which causes a decrease in the reflectivity. Figure 25 shows one set of data taken while increasing the power level with time and another set of data taken while decreasing the power level with time. This shows the basic trend for the reflectivity to decrease with increasing power because of the spectral characteristics as well as the effects of carbon contamination. The data taken while decreasing the power shows the effect of contamination by giving about the same values at high power and correspondingly lower values at lower power levels. This is because the carbon vaporization is a strong function of element temperature, and by operating at the higher power levels first, the reflector is contaminated so that at the lower power points the ratio is lower than it would be where the reflector would be uncontaminated at the lower levels.

The effects of reflector condition on the ratio of heat flux absorbed by the heat exchanger to that measured by the calorimeter are further illustrated by comparing the ratios presented at corresponding heat flux levels in Figure 25 and 26. The distinct drop is caused by an arc occurring during Run 2267 (reference Appendix B) which degraded the reflector surface making the reflectors absorb more of the input power. To investigate further the effects of reflector surface condition, it was decided to smoke the reflectors with magnesium oxide since magnesium oxide has a high diffuse reflectivity that is spectrally flat out to quite a long wavelength. It was expected that the ratio decrease with increasing heat flux would disappear. Figure 26 shows that, although the reflectivity of the magnesium oxide is not as high initially as the plating, its curve is indeed quite flat and crosses over the plating curve in the high flux region. No further work was done with magnesium oxide coatings because of the difficulty of application and the fragile nature of the coating which wipes off at the slightest touch.

Two 1-hour endurance tests were performed; one at a nominal calorimeter indication of 200 Btu/ft^2-sec (reference Appendix B, Run 3261-3267) and the other at 225 Btu/ft^2-sec (reference Appendix B, Run 4021-4027). However, an arc occurred during an intervening test (reference Appendix B, Run 3276) which was between these two, further degrading the reflectors. The results of this degradation can be seen in the data (reference Appendix B); that is, the 200 Btu/ft^2-sec run had an absorbed flux of 163 Btu/ft^2-sec and the 225 Btu/ft^2-sec run had 157 Btu/ft^2-sec absorbed. Figure 27 illustrates the carbon deposition degradation during a 1-hour test. The power had to be increased throughout the test to force the heat flux to remain constant.

One thing further was noted during this phase of the testing. When a new set of graphite elements was installed in the assembly, an arc would result if the power was increased suddenly upon initial operation. It was found that a bake-out of about 4000°F for 15 to 20 minutes was desirable to "cook-out" volatiles and other debris from the elements before serious testing was commenced.

5.6 CONCLUSIONS. After some minor modifications of the original design, the prototype heater assembly operated in an entirely satisfactory manner. It was reliable, leak free, and rugged enough to stand several arcing situations

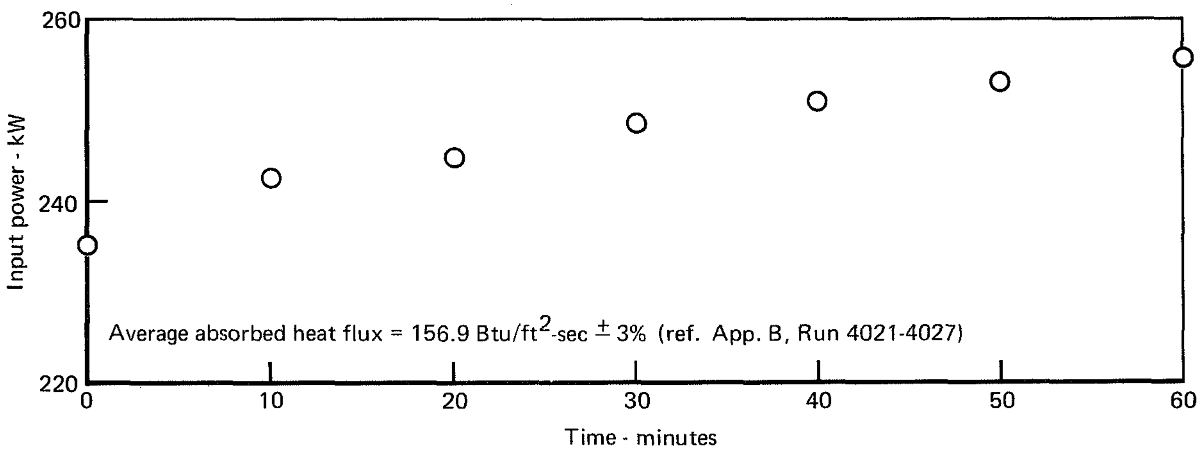

Figure 27 Power Variation During One-Hour Test

with only superficial damage. The input power to the assembly is essentially all absorbed into either the water cooled heat exchanger or the reflectors and the losses to the purge gas and other external equipment is negligible (reference Appendix B).

The maximum attainable heat flux at atmospheric pressure seems to be in the 200-250 Btu/ft^2-sec range as indicated with the calorimeter and about 180 Btu/ft^2-sec absorbed into the water cooled heat exchanger (reference Appendix B). It appears that this limitation is placed on the heat flux by both darkening of the reflectors and arcing, both of which are the result of carbon vaporization which becomes excessive at the very high temperature required to produce the heat flux.

The performance of the heater assembly is quite sensitive to the condition of the reflectors. Spectral reflectivity changes are easily noticed from the decrease of absorbed heat flux as are the changes produced by reflector degradation from condensed carbon vapor. Further, arcs, discoloration, and other such degradation seriously degrade the efficiency and, hence, the maximum performance capability of the heater.

6.0 PROTOTYPE HEATER TESTING - ELEVATED PRESSURE

6.1 PRESSURE VESSEL. The pressure environment for the prototype heater test is a pressure vessel 12 inches in diameter and 36 inches long mounted on a monorail so that the end plate with the heater assembly, water piping, instrumentation, and wiring is fixed and the vessel moves out of the way. The vessel was designed and constructed in accordance with the ASME Unfired Boiler Code and is rated at 300 psi and 650°F. The end plate is drilled and fitted with provisions for eight 250-amp electrical power passthroughs, a purge inlet and outlet, two cooling water inlets and outlets, and an instrumentation passthrough. The entire setup is housed in a steel enclosure and operated from a remote console for maximum personnel safety in the event of catastrophic failure. Pressurization with nitrogen gas is provided by a NASA furnished vaporizer - LN_2 trailer via a liquid-gas heat exchanger and suitable valving to control both the flow rate and pressure. Figure 28 is a photograph of the pressure vessel while Figure 29 shows the prototype heater installed, and Figure 30 is a flow schematic for the cooling water and high pressure nitrogen purge gas.

6.2 INSTRUMENTATION. Instrumentation used for the pressure environment test was the same as for the atmospheric testing with the addition of a tank pressure gage, a purge flowmeter, and a number of thermocouples to measure internal gas temperature, nitrogen return line temperature, and vessel wall temperature at various locations.

6.3 TEST OBJECTIVES. The objectives of the prototype heater test in a pressurized environment are essentially the same as those described for the atmospheric pressure tests with the additional objective of determining the

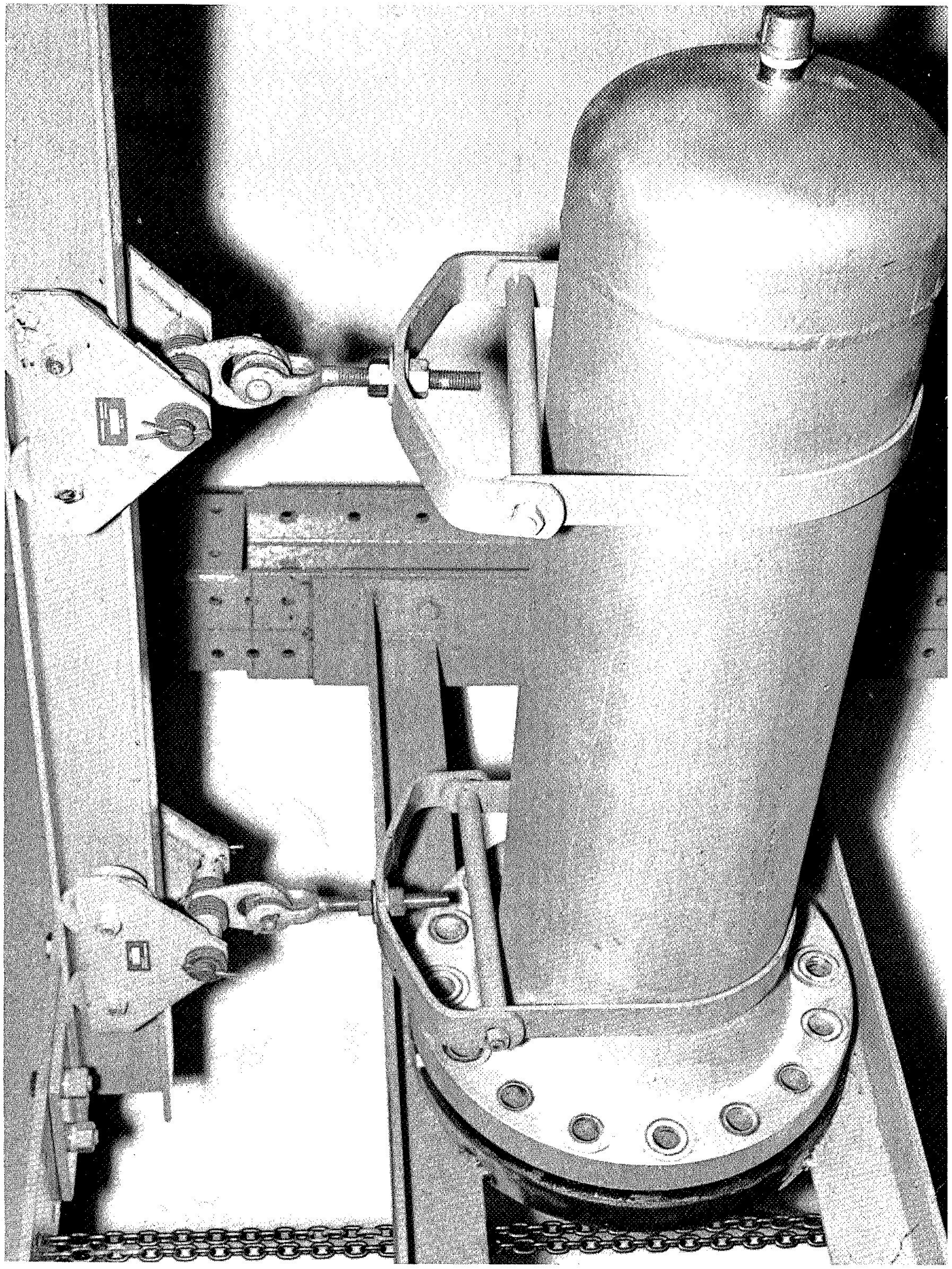

Figure 28 High Pressure Qualification Pressure Vessel

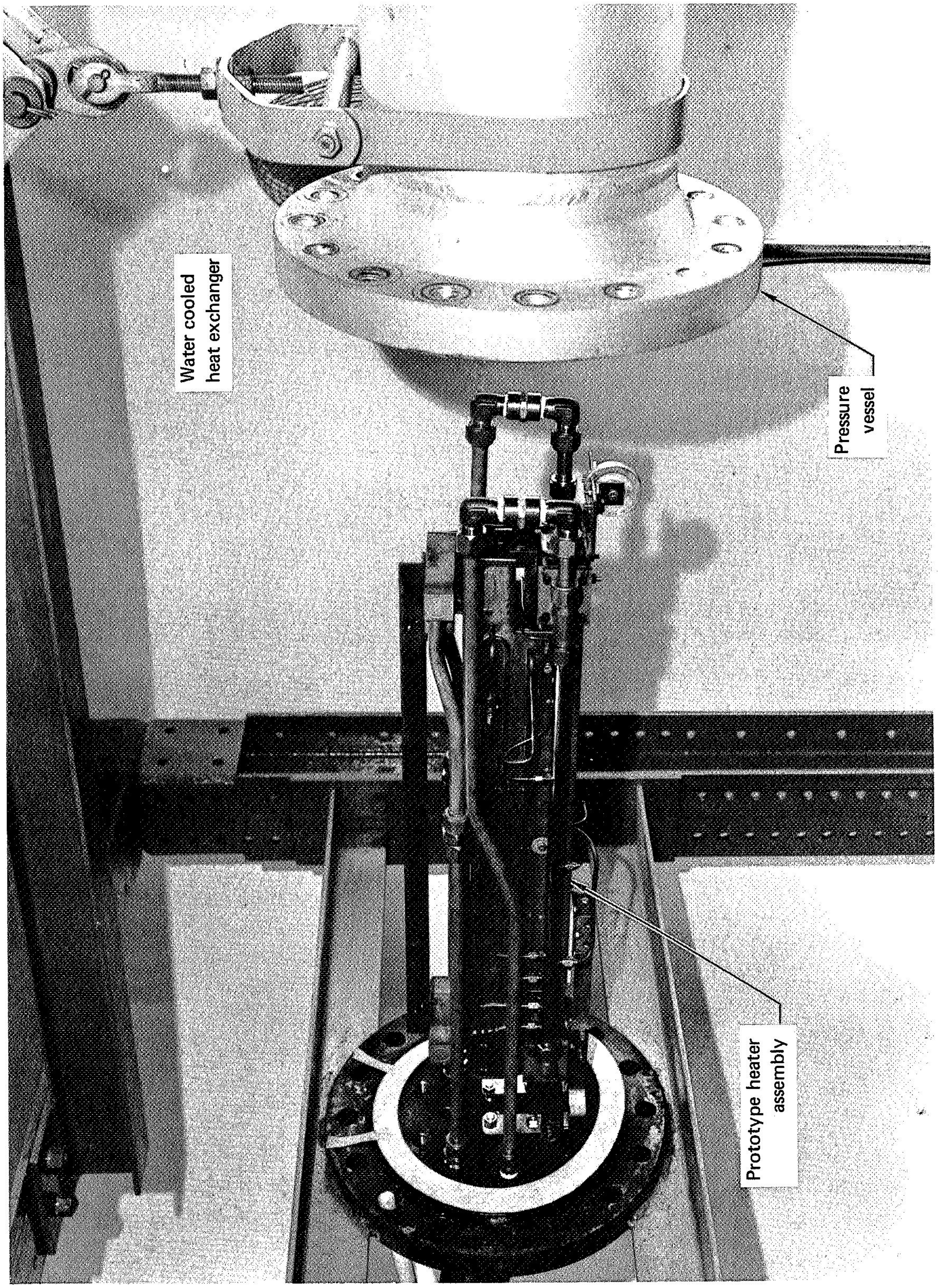

Figure 29 Prototype Heater High Pressure Test Setup

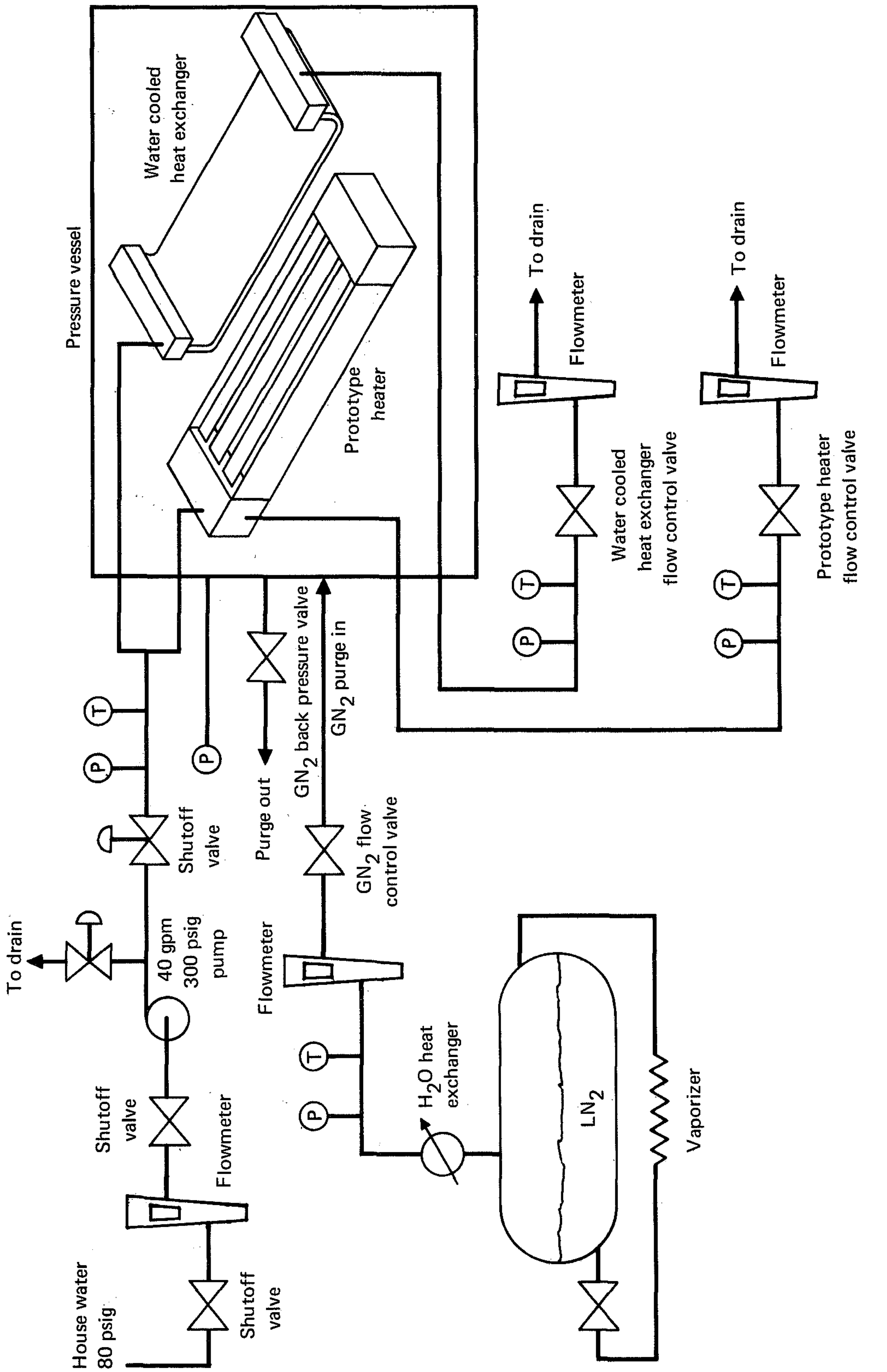

Figure 30 High Pressure Qualification Tests Schematic

effect of the increased pressure on the operation and performance of the heater. It was expected that the increased pressure would drastically affect the convection in the vessel and therefore an additional test objective was to determine the magnitude of these changes both from the standpoint of heater losses and vessel temperature.

6.4 TEST PLAN. From a hardware qualification standpoint, the test plan for the elevated pressure test is essentially the same as that for the atmospheric test. Two plans were used in an effort to determine the performance envelope and maximum performance capability of the prototype heater assembly in the pressurized environment. The first, consisted of operating the heater at its expected peak heat flux while varying the performance-affecting parameters one at a time and recording fail or no-fail data. This would establish a locus of failure points which would comprise the boundary of the performance envelope. The second method involved operation at somewhat less than the expected peak heat flux over a relatively long time while recording degradation data. Although this method does not define the absolute fail boundary it does, by increasing the heat flux level slightly in each succeeding test and observing the degradation rate with time, define a fail-free performance-time envelope.

6.5 RESULTS AND DISCUSSION. Initial shakedown testing of the prototype heater assembly in the pressure vessel indicated that the purge flow rate and the pressure might have considerable affect on the performance of the heater. It was decided, according to the first plan mentioned above, that the means by which to investigate this possibility was to operate the heater at the threshold of failure while varying the purge flow rate and pressure. Data would consist of the points of failure while varying purge at constant pressure or varying pressure at constant purge, all of which was to take place at constant heat flux. The result expected was to establish a performance envelope boundary beyond which one may not venture without disastrous results. Since it was obvious that if the power level was not sufficiently high, no failure would occur, it was necessary, during this set of tests, to operate the heater at 250-270 Btu/ft^2-sec indicated on the calorimeter and greater than 200 Btu/ft^2-sec absorbed in the dummy heat exchanger (reference Appendix C, Run 5041-5123). Four tests were performed in which an attempt was made to vary the tank pressure from 100 psig to 0 psig at constant purge and heat flux. Heater element failure occurred in each attempt, badly damaging the bottom reflector. Due to economic and time considerations, the reflector was subjected to a "quick fix" each time but unfortunately the reflector was in such bad shape that the repairs were marginal at best. None of the expected results were obtained from any of the tests because the heater was run at a power level high enough to cause failure to occur randomly instead of with any regard to the variable parameters. The final test of this series rendered the bottom reflector unusable and the assembly was removed and rebuilt with a new bottom reflector.

By the time the prototype heater assembly was refurbished, the pressure vessel had been reworked to provide two-phase electrical power and 250 psig pressure capability. Initial shakedown tests at 250 psig revealed that the increased convection caused by the high pressure resulted in considerable heating of the pressure vessel. A liberal quantity of thermocouple instrumentation was installed inside and on the shell of the pressure vessel and more checkout tests were run. It was found that the vessel temperature was somewhat insensitive to a heater power level above 70-100 Btu/ft^2-sec. This is probably because the convective heating is a linear function of the heater element temperature while the radiant power delivered is a fourth power function of temperature. The vessel heating was, however, rather intimately tied to the purge flow rate and by reducing this rate the maximum temperature of the vessel was held within acceptable limits. During this check out of the facility, a few random arcs were experienced, all of which occurred in and around the brass hardware rather than in the element-reflector area. Also some in-leakage of purge gas to the water system was noted. The heater assembly was again torn down and received extensive dielectric work and a new set of O-rings. A checkout run showed the heater assembly to perform in an acceptable manner at 250 psig up to a heat flux of 225 Btu/ft^2-sec as indicated on the calorimeter and 181 Btu/ft^2-sec absorbed into the dummy heat exchanger (reference Appendix C, Run 9085). Two endurance qualification tests of 1-hour duration were then performed; the first at a starting absorbed flux of 185 Btu/ft^2-sec (reference Appendix C, Run 9106-91010) and the second starting at 214 Btu/ft^2-sec absorbed (reference Appendix C, Run 9184-9187). The first test was shut down at 60 minutes, while in the second, an element failure occurred at 51 minutes. During the performance of both these tests, the eroding of the elements was noticeable by the steady decrease of current at constant voltage plus the necessity of an upwards voltage adjustment in an attempt to hold the input power constant. In addition, the effects of the power decrease along with the darkening of the reflectors was noted by observing the temperature change of the cooling water decrease in the heat exchanger and increase in the reflectors. These effects are shown in Figure 31 where the percent decrease in both the heat flux and input power is plotted against time. Since the decrease in heat flux is a combination of the reflector darkening and the power decrease, this plot shows that both effects are contributing with the darkening being the most serious. This plot also shows that the heater assembly

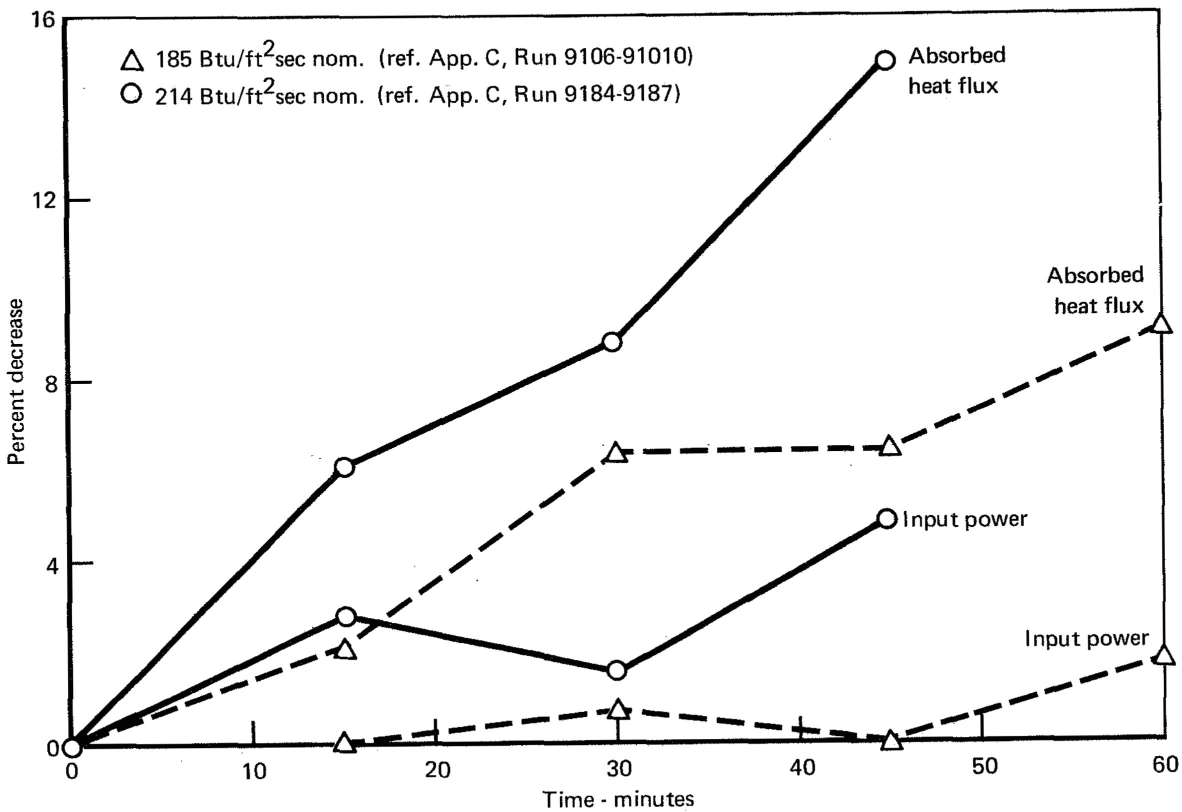

Figure 31 Loss Summary - Endurance Tests

life is extremely sensitive to the heat flux level when the upper limits are approached. This effect would be even more pronounced if an attempt were made to eliminate the decrease by constant adjustment of the power input. This would accelerate the element erosion and more rapidly degrade the reflectors such as to produce what could probably be described as a runaway to failure condition.

6.6 CONCLUSIONS. From an operational standpoint the prototype heater assembly is well suited to a 250 psig external pressure environment. Its lack of elastomers and other perishables allow it to exist without problems in a rather severe convective environment. Also, for this particular application there seemed to be no pronounced difference between single phase operation and that with two-phase power. It should be pointed out, however, that considerable care should be exercised in the routine maintenance of the heater assembly in order to assure acceptable high-performance operation. This is especially true when arcing has taken place on preceding runs. All carbon tracks, arc marks, water, and debris must be carefully removed or further spurious arcing is almost a certainty.

The performance of the prototype heater assembly in the 250 psig environment indicates that the pressure has some effect on the maximum heat flux level that can be achieved. In testing at atmospheric pressure, the maximum flux absorbed by the heat exchanger was 188 Btu/ft^2-sec (reference Appendix B, Run 32511) while in the pressure vessel at 250 psig, the maximum was 214 Btu/ft^2-sec (reference Appendix C, Run 9184) indicating an increase of approximately 14%. However, at this high flux level, the absorbed heat flux can be expected to fall off 10 to 15% in the course of a 1-hour test (reference Figure 31). During an extended test for this particular configuration, the data (reference Appendix C, Run 9184-9187) shows that the reflectors start out a run absorbing about 40% of the input power, and after nearly an hour, are absorbing almost 50% of the power. This percentage is likely to be lower on the full scale assembly since it has a higher ratio of heater element area to reflector area.

The technique of operating just under the expected limit over relatively long times to establish degradation rate trends which can be interpreted to obtain a reasonable performance envelope is more informative than the costly, time-consuming, and frustrating method of "backing into" the performance envelope by recording failure points, even though this method will, in theory, establish an absolute performance envelope.

Convection at the 250 psi level in a pressure vessel could constitute a serious problem in certain applications. Although convective losses from the heater assembly range from only 2 to 3% at low power levels to a negligible percentage at high power levels, this amount of waste power is enough to seriously overheat ancillary equipment and components in an experimental setup. In general, it can be said that a problem could exist and that the lowest possible purge rate is desirable to minimize local heat transfer coefficients.

7.0 FULL-SCALE HEATER DESIGN

The design of the reflectors for the full scale heater assembly is essentially the same as that for the prototype heater assembly. The side reflectors are identical with the exception of a three-bolt mounting to eliminate the bowing caused by thermal expansion. The end reflectors are also the same as in the prototype except for slotted out mounting holes to allow for expansion take-up. The bottom reflector is made up of five separate pieces, the long axis of which is positioned perpendicular to the elements. The use of a multiple piece reflector was predicated by the ease of fabrication and minimum replacement cost in the event of catastrophic failure. Each of the five pieces is fitted with a five pass serpentine of 1/4-inch copper tubing so that when mounted crosswise, the hookup to the inlet and outlet manifolds is convenient and neat. The bottom reflector panels at each end are turned up and the last pass of tubing runs along the edge to provide adequate cooling to this edge. Each reflector panel is fastened down with eight screws to prevent bowing from thermal expansion. The fabrication technique used for these reflectors was the same as that used for those on the prototype heater assembly.

The brass water distribution manifolds on both the electrode end and the support end are of the same general configuration as those used on the prototype heater assembly except that they are designed smaller, lighter, and more compact in cross section. The through holes were specified at 3/4-inch diameter to provide equal distribution of water to all of the blocks. Restrictors are threaded into the outlet ends of each manifold to provide a pressure drop equivalent to that in the reflectors at the desired flow rate. Electrical insulation is enhanced by the addition of counterbores on each end of the holes that accept the block holding stud. The top counterbores are filled with RTV-102 to prevent the entry of water, dirt, debris, and other spurious matter.

The electrode blocks are also essentially the same as those in the prototype. The changes include moving the water inlet and outlet holes further apart to cool the ends better and the addition of roll-pin locators to provide for positive rotary location of the block and insulator on the manifold. The phenolic and spring washer arrangement on the mounting stud was modified slightly with the addition of a wood washer to ease assembly.

The support blocks incorporate a longer back end to move the springs back to a cooler area in addition to moving the water holes farther apart and providing roll-pin locators. Other than this they are like the one designed for the prototype.

The water requirements for the full-scale heater assembly were calculated using the generalized computer program and were found to be in the 30 to 40 gpm range at about 300 psig back pressure. Tubular inlet and outlet water manifolds are provided with fittings for two 1-inch lines each, to allow for minimum pressure drop in the supply system. For purposes of uniform distribution of water to all the parallel circuits, the tubular manifolds were specified at 2 inches in diameter.

Water management is rather critical in an assembly that contains nine parallel circuits. If any circuit has significantly less resistance to flow than the others, it will use more than its share of the available water thereby starving the other circuits and possibly causing reflector failure. In the full-scale assembly, all five-bottom manifolds have identical water passages while the side reflectors are each connected in series to one of the end reflectors. From the water balance with the prototype where the end reflectors were short and the bottom reflector had only four passes, it can be seen that the extra length of the end reflector almost exactly balances the fifth pass in each bottom reflector. As described above, the brass manifolds are fitted with downstream restrictors to cause their flow-pressure drop characteristics to match those of the reflectors. The full scale graphite heater assembly is shown in Figure 32.

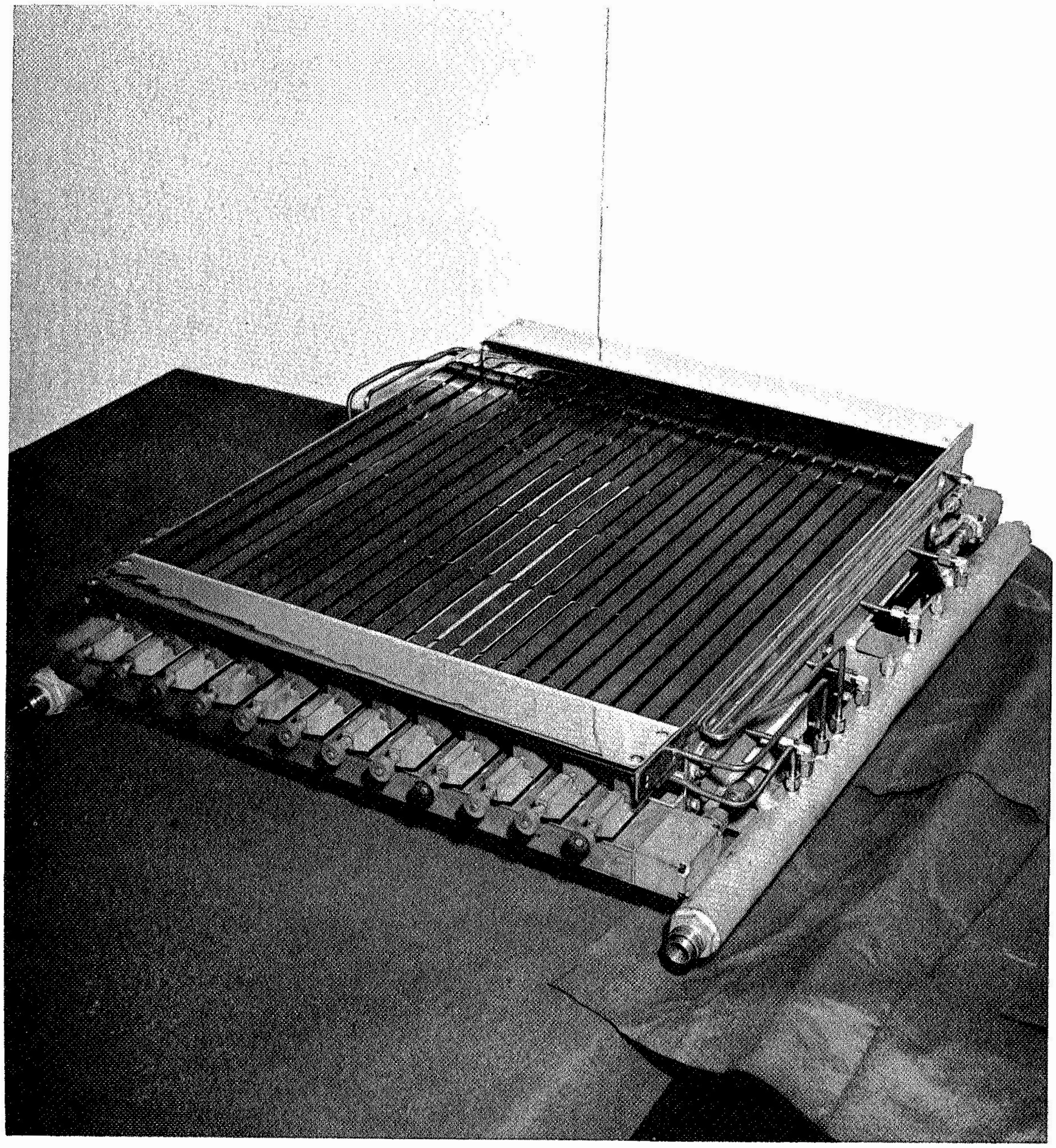

Figure 32 Full-Scale Graphite Heater Assembly

8.0 RECOMMENDATIONS

The performance of the graphite radiant heater developed under this contract is limited to about 220 Btu/ft^2-sec. The heater performance, however, can be extended by using carbon monoxide as a purge gas, graphite elements with emittance enhancing grooves, and reflectors plated with silver, gold, or barium sulfate. Heat flux levels in the range of 250-300 Btu/ft^2-sec could possibly result from these improvements.

An alternate approach would be to consider a heater system that utilizes low voltage, high current power by making the graphite elements relatively thick. Despite the massive power supply and cable requirements, this approach would allow the generation of extremely high temperatures with the arcing problem alleviated by the low voltage and the degradation rate slowed by the small percentage change in cross section from evaporation of the thick elements. Based upon experience with small cylindrical heaters operating on low-voltage high-current power, heat flux levels up to 500 Btu/ft^2-sec are attainable for test durations up to approximately 10 minutes.

A feasibility study to investigate the merits of a low-voltage high-current graphite radiant heater, including development of electrodes, expansion slide blocks, and other necessary ancillary equipment for operation at 500 Btu/ft^2-sec, is recommended.

9.0 CONCLUDING REMARKS

The graphite radiant heater concept described herein provides a unique heating system for thermostructural tests, which is compatible with ignitron power supplies and will deliver heat flux levels approximately twice that available with quartz lamp systems.

A prototype of the full-scale heater was fabricated and tested with the results indicating that a maximum heat flux of 188 Btu/ft^2-sec absorbed into a water-cooled heat exchanger could be reliably achieved at a pressure of one atmosphere. At a pressure of 250 psig a heat flux of 218 Btu/ft^2-sec was obtained. Examination of the data from these prototype tests indicated that the performance limitation realized was a direct result of the inability to operate graphite elements in excess of 5200-5300°F without the emission of relatively large quantities of smoke. This smoke, being somewhat electrically conductive, causes arcing between the elements even when the element spacing is sufficient to hold off the maximum power supply voltage if smoke were not present. Experimentation with various grades of graphite and a number of different purge gases showed little improvement in the maximum operating temperature with the exception of carbon monoxide purge gas which demonstrated the ability to suppress the smoke emission at temperatures up to 5600°F, thereby indicating that about a 20% increase in heat flux could be realized.

APPENDIX A

WATER COOLED HEAT EXCHANGER

PROTOTYPE DESIGN. The design selected for the prototype water cooled heat exchanger consisted of a bank of 1/4-inch diameter copper tubes arranged one immediately next to the other to form a solid wall of tubes not unlike the "water walls" often seen in high performance steam boilers. The water-flow configuration has the inlet and outlet manifolds on the same end with a jumper manifold on the other end so that the typical water-flow path is "down and back." This arrangement is able to generate a large heat transfer film coefficient with a modest pressure drop and relatively low flow rates, all of which contributes to efficient use of the water available.

To compute the heat transfer characteristics of the water cooled heat exchanger, the same generalized computer program used for the reflectors was employed. An analysis was carried out to determine the performance at a heat flux level of 250 Btu/ft^2-sec. The results of this analysis are presented in Figure A-1, showing the pertinent parameters plotted versus water flow rate.

FULL-SCALE WATER COOLED HEAT EXCHANGER. A large water-cooled heat exchanger changer similar to that used with the prototype radiant heater was designed and fabricated for use with the full-scale heater. As on the small test panel, the cold surface of the large water-cooled heat exchanger was constructed of closely spaced 0.250-inch diameter x 0.030-inch wall copper tubes through which water flowed. The tubes were arranged in eight groups of thirteen tubes, each group being connected to a brass supply manifold at one end and to a brass drain manifold at the other end. In contrast to the prototype heat exchanger, water flows in only one direction in the thirteen tubes of one group. Each of the groups may be replaced independently of the others so that damage to the test specimen can be repaired without massive rework. Four of the eight tube groups are connected

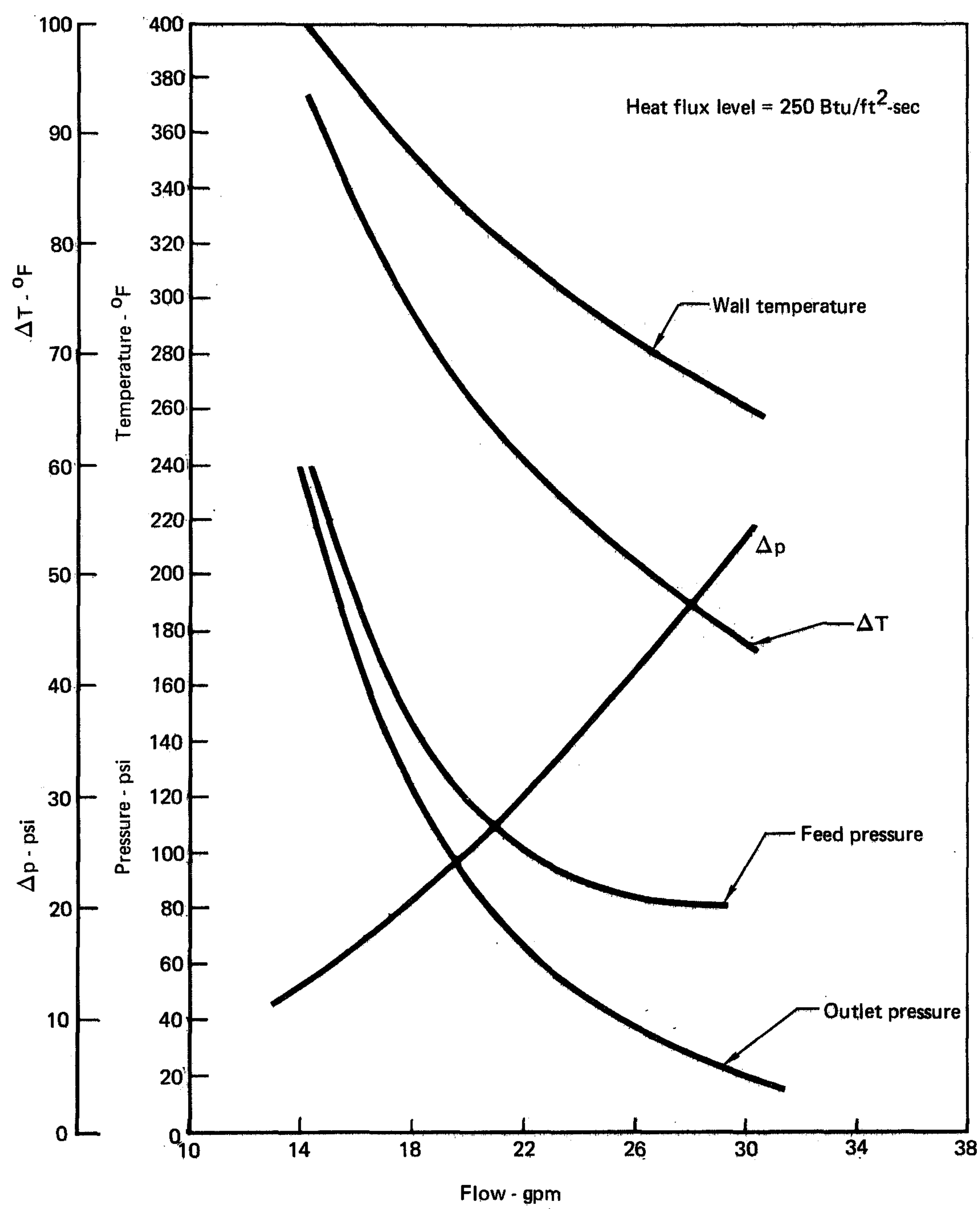

Figure A-1 Prototype Water-Cooled Heat Exchanger Performance by standard tubing and AN flare fittings to a large supply manifold at one end of the unit and to a common manifold at the other end. The remaining four tube groups are similarly connected from the common manifold to a drain manifold located adjacent to the supply manifold. The full scale water cooled heat exchanger is shown in Figures A-2 and A-3. The water requirements for this heat exchanger were computed at a heat flux level of 250 Btu/ft^2-sec and the result is presented in Figure A-4.

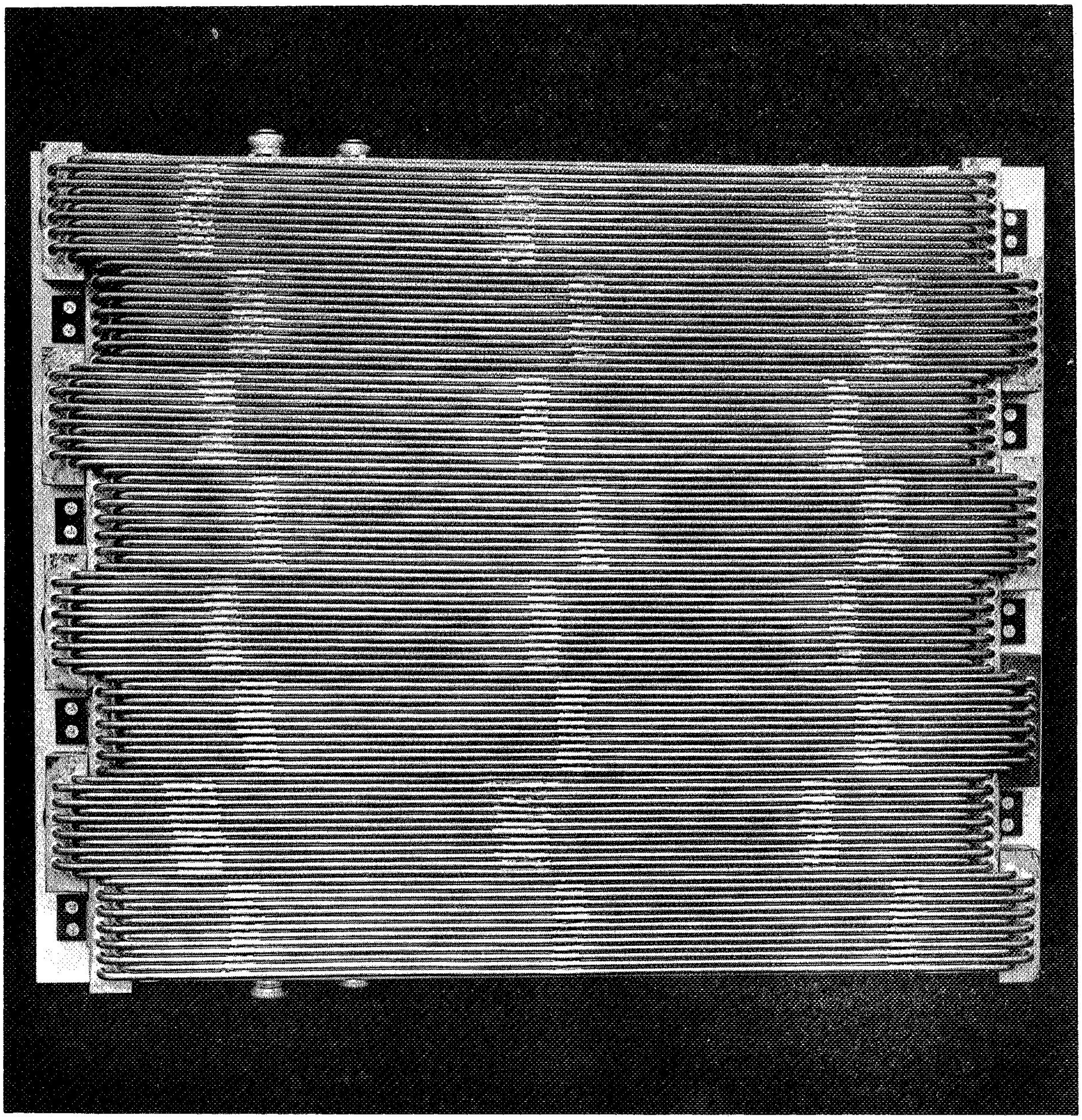

Figure A-2 Full-Scale Water Cooled Heat Exchanger - Front Side

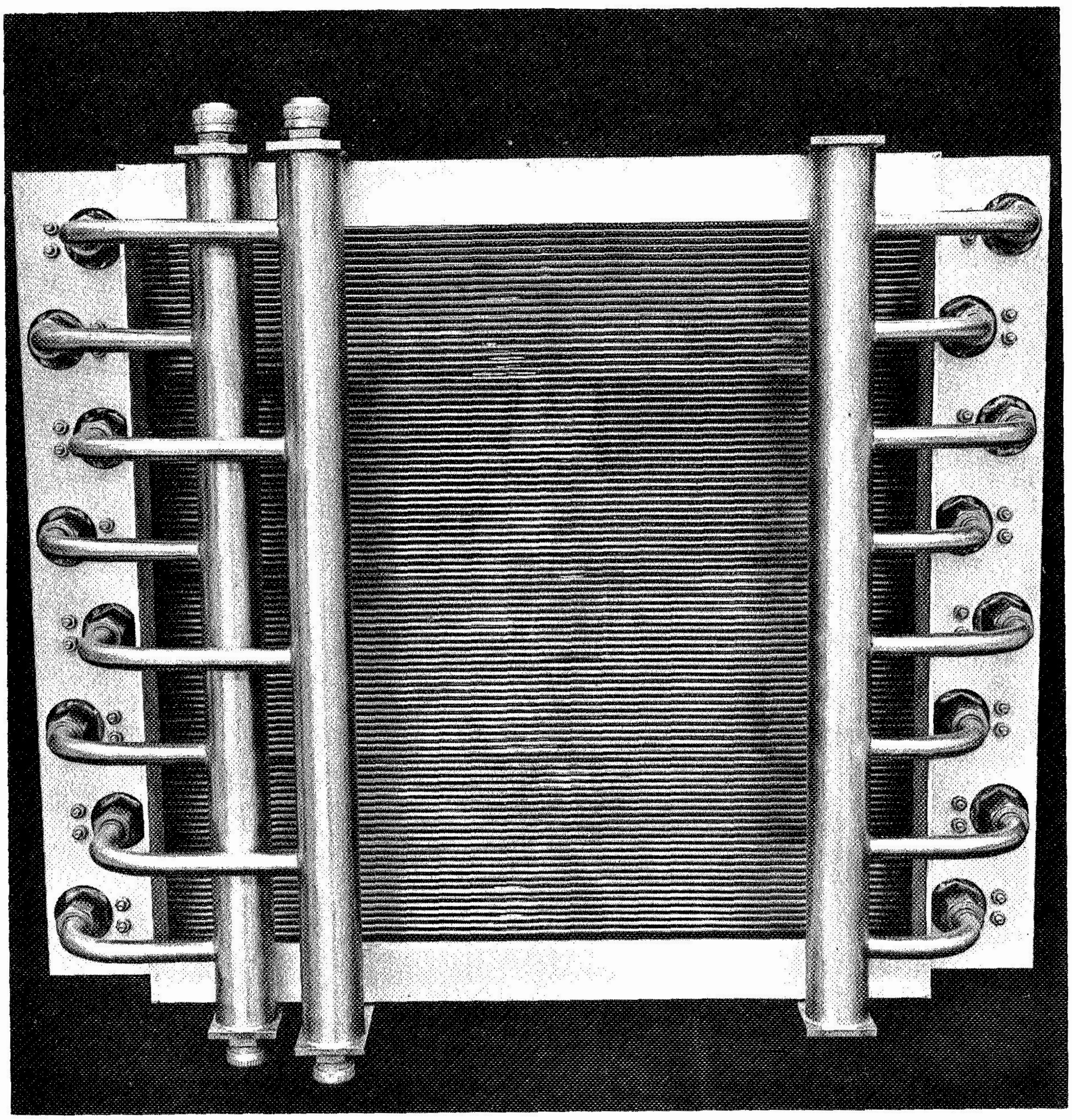

Figure A-3 Full-Scale Water Cooled Heat Exchanger - Back Side

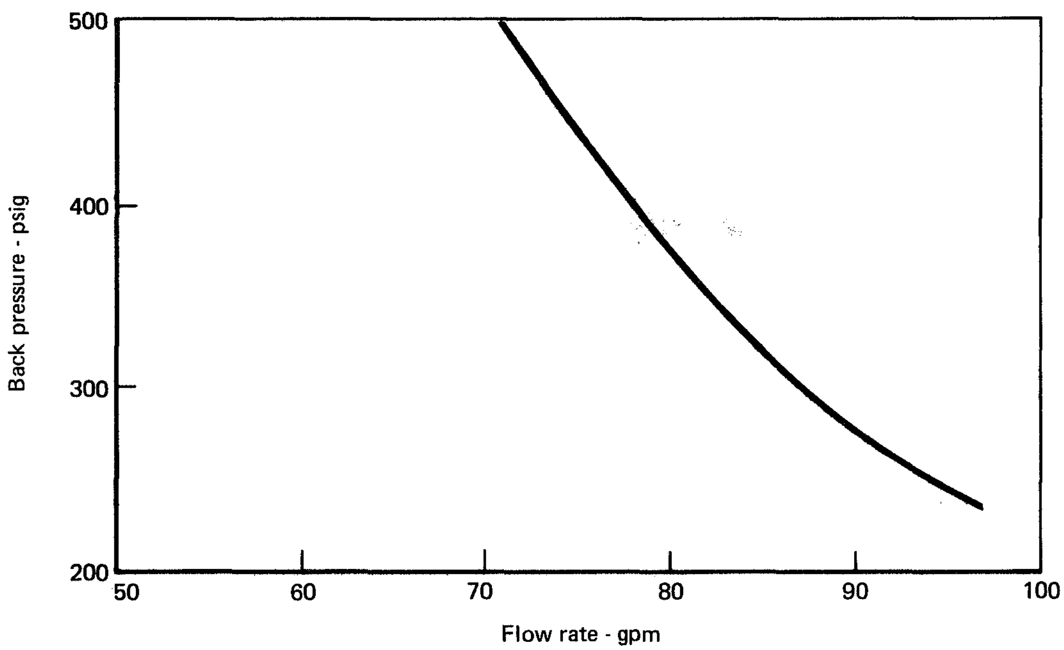

Figure A-4 Water-Cooled Heat Exchanger Requirements - Full Scale Assembly at 250 Btu/Ft^2-Second

APPENDIX B

PROTOTYPE HEATER DEVELOPMENT TEST RESULTS

TEST RUNS 2172-21712

Purpose: Initial Prototype shakedown at low level with heat balance determination.

Run No.	Volts	Amps	Run Time min:sec.
2172	165	286	
2173	124	224	
2174	167	283	
2175	220	353	
2176	163	271	88:20
2177	218	330	
2178	220	328	
2179	241	353	
21710	260	375	
21711	280	395	
21712	300	418	

Results: Successful operation, all heat accounted for in water cooled heat exchanger and heater assembly with negligible percentage to water cooled test enclosure.

WATER COOLED HEAT EXCHANGER

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
2172	11.7	16.3	26.6	59.3
2173	12.1	9.4	15.8	59.9
2174	12.1	16.8	28.4	63.1
2175	12.0	26.9	45.2	61.2
2176	11.5	16.3	26.4	62.8
2177	11.3	26.0	41.1	60.0
2178	11.4	25.1	40.1	58.3
2179	11.1	30.5	47.3	58.4
21710	11.7	33.7	55.0	59.2
21711	11.5	39.1	63.2	60.0
21712	11.5	44.1	70.8	59.2

HEATER ASSEMBLY

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
2172	6.1	17.7	15.1	33.7
2173	5.9	10.7	8.9	33.8
2174	6.0	19.1	16.0	35.5
2175	6.0	32.3	27.1	36.6
2176	11.4	9.4	14.9	35.4
2177	11.5	16.3	26.4	38.5
2178	11.5	15.4	24.7	36.0
2179	11.7	18.6	30.4	37.6
21710	11.2	22.8	35.6	38.3
21711	11.4	26.0	41.5	39.4
21712	11.4	29.2	46.6	39.0

RUN NO.	HEAT FLUX, BTU/SQ.FT.-SEC: Q_C, CALORIMETER	Q_A, HEAT EXCHANGER	Q_A/Q_C	INPUT POWER KW
2172	38.6	32.5	.84	41.7
2173	22.5	19.3	.86	27.7
2174	36.8	34.6	.94	47.2
2175	63.7	55.2	.87	77.6
2176	35.1	32.2	.92	44.1
2177	57.9	50.1	.87	71.9
2178	57.6	48.9	.85	72.1
2179	67.2	57.6	.86	85.0
21710	78.0	67.1	.86	97.5
21711	88.7	77.0	.87	110.6
21712	101.2	86.3	.85	125.4

TEST RUNS 2241-2245

Purpose: Further shakedown of prototype at higher heat flux levels.

Run No.	Volts	Amps	Run Time min:sec.
2241	192	317	
2242	231	423	
2243	260	466	28:30
2244	299	518	
2245	328	557	

Results: Successful operation

WATER COOLED HEAT EXCHANGER

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
2241	16.0	19.1	42.6	62.8
2242	15.8	26.0	57.1	61.3
2243	15.7	31.9	69.8	60.5
2244	15.3	41.3	88.1	59.7
2245	15.2	48.9	103.4	59.4

HEATER ASSEMBLY

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
2241	11.3	16.8	26.5	39.0
2242	11.5	22.3	35.7	38.4
2243	11.7	27.3	44.5	38.5
2244	12.0	35.5	59.2	40.1
2245	12.1	41.3	69.6	40.0

	HEAT FLUX, BTU/SQ.FT.-SEC			INPUT POWER
RUN NO.	Q_C, CALORIMETER	Q_A, HEAT EXCHANGER	Q_A/Q_C	KW
2241	53.0	52.0	.98	71.2
2242	72.6	69.6	.96	97.7
2243	89.8	85.1	.95	121.2
2244	119.1	107.4	.90	154.9
2245	142.3	126.0	.88	182.7

TEST RUNS 2251-22511

Purpose: Investigation of the variation of the ratio of absorbed flux to calorimeter flux with increasing power level.

Run No.	Volts	Amps	Run Time min:sec.
2251	187	361	
2252	233	424	
2253	261	458	
2254	301	512	41:45
2255	332	553	
2256	261	446	
2257	331	528	
2258	332	528	
2259	362	563	
22510	401	608	
22511	435	638	

Results: Data showed a decrease in the ratio with increasing power level. Further discussion of these results is presented in Section 5.5 and illustrated in Figure 25.

WATER COOLED HEAT EXCHANGER

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
2251	16.4	18.1	41.6	64.6
2252	16.2	25.5	57.7	61.4
2253	16.2	31.4	70.9	62.2
2254	15.8	39.9	88.2	60.1
2255	15.7	47.5	104.1	59.5
2256	16.1	30.5	68.6	61.8
2257	15.8	44.9	99.0	59.3
2258	20.1	35.0	98.2	58.8
2259	19.8	41.3	114.4	58.9
22510	19.5	49.3	134.5	57.9
22511	19.2	53.7	144.2	54.5

HEATER ASSEMBLY

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
2251	11.0	16.3	25.2	39.1
2252	11.2	23.6	37.1	39.4
2253	11.3	30.5	48.3	42.4
2254	11.5	36.8	59.3	40.4
2255	11.6	44.4	72.2	41.3
2256	11.4	29.1	46.4	41.9
2257	11.5	43.5	70.1	42.0
2258	15.6	32.7	71.2	42.7
2259	15.8	38.6	85.3	43.9
22510	15.9	46.6	103.4	44.5
22511	16.1	54.2	121.9	46.1

	HEAT FLUX, BTU/SQ.FT.-SEC			INPUT POWER
RUN NO.	Q_C, CALORIMETER	Q_A, HEAT EXCHANGER	Q_A/Q_C	KW
2251	50.8	50.7	.998	67.6
2252	74.4	70.4	.946	98.7
2253	91.5	86.4	.943	119.5
2254	118.7	107.5	.905	154.1
2255	142.3	126.9	.892	183.5
2256	90.1	83.6	.927	116.4
2257	135.1	120.7	.893	175.2
2258	133.4	119.7	.897	175.2
2259	157.7	139.5	.885	203.8
22510	187.7	163.9	.874	243.8
22511	206.6	175.8	.851	277.5

TEST RUNS 2261-2267

Purpose: Investigation of the variation of the ratio of absorbed flux to calorimeter flux while decreasing the power from an initial high level.

Run No.	Volts	Amps	Run Time min:sec.
2261	433	632	
2262	396	596	
2263	359	553	
2264	329	516	23:5
2265	328	514	
2266	259	431	
2267	433	623	

Results: Data showed a decreased in the ratio with increasing power level. Further discussion of these results is presented in Section 5.5 and illustrated in Figure 25. An arc occurred in Run No. 2267.

WATER COOLED HEAT EXCHANGER

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
2261	17.7	62.1	152.9	58.6
2262	18.1	51.5	130.5	58.0
2263	18.4	42.8	109.8	58.1
2264	18.6	36.3	94.3	58.3
2265	16.2	41.3	93.2	58.0
2266	16.3	27.6	63.2	59.4
2267	22.6	47.0	147.5	56.2

HEATER ASSEMBLY

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
2261	16.1	47.5	107.0	41.0
2262	16.0	43.3	96.8	43.0
2263	15.9	36.6	81.5	43.1
2264	15.7	31.1	68.3	42.2
2265	11.2	42.9	67.0	41.7
2266	10.9	28.5	43.6	41.0
2267	16.7	48.9	113.7	43.3

	HEAT FLUX, BTU/SQ.FT.-SEC			INPUT POWER
RUN NO.	Q_C, CALORIMETER	Q_A, HEAT EXCHANGER	Q_A/Q_C	KW
2261	213.1	186.4	.875	273.6
2262	182.3	159.1	.873	236.0
2263	153.4	133.9	.871	198.5
2264	130.9	115.0	.879	169.7
2265	130.1	113.6	.871	168.5
2266	85.1	77.0	.905	111.6
2267	211.3	179.8	.852	

TEST RUNS 3251-32511

Purpose: Investigation of the possibility of obtaining an absorbed heat flux of 250 Btu/ft^2-sec by gradually increasing the power level.

Run No.	Volts	Amps	Run Time min:sec.
3251	199	382	
3252	242	445	
3253	282	501	
3254	320	533	
3255	361	604	46:40
3256	372	617	
3257	319	541	
3258	375	606	
3259	392	623	
32510	410	642	
32511	420	652	

Results: No problems occurred, maximum flux achieved was 188 Btu/ft^2-sec absorbed.

WATER COOLED HEAT EXCHANGER

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
3251	19.2	17.5	47.0	64.9
3252	19.0	24.4	64.8	63.2
3253	18.7	31.9	83.4	62.0
3254	18.5	39.9	102.8	61.0
3255	18.2	49.3	124.8	60.1
3256	18.0	50.6	127.3	58.2
3257	20.0	37.1	103.5	62.9
3258	19.5	49.2	134.3	62.1
3259	24.1	42.0	141.0	60.6
32510	24.0	45.0	150.7	60.1
32511	24.1	46.0	154.3	59.1

HEATER ASSEMBLY

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
3251	15.3	13.9	29.7	41.1
3252	15.5	19.7	42.5	41.5
3253	15.6	25.7	55.9	41.5
3254	15.8	32.0	70.4	41.8
3255	16.1	39.6	89.3	43.0
3256	16.1	43.1	97.1	44.4
3257	16.9	28.2	66.4	40.4
3258	17.3	37.7	91.2	42.2
3259	14.8	47.6	98.7	42.4
32510	14.8	52.0	107.7	43.0
32511	14.8	55.3	114.1	43.7

RUN NO.	HEAT FLUX, BTU/SQ.FT.-SEC Q_C, CALORIMETER	Q_A, HEAT EXCHANGER	Q_A/Q_C	INPUT POWER KW
3251	64.0	57.3	.895	76.0
3252	91.7	79.0	.862	107.7
3253	120.6	101.7	.842	141.3
3254	152.7	125.3	.820	176.7
3255	192.7	152.2	.790	217.8
3256	200.6	155.2	.774	229.4
3257	167.8	126.2	.753	172.5
3258	216.9	163.7	.753	226.9
3259	230.3	171.9	.745	244.2
32510	243.8	183.7	.755	263.0
32511	246.2	188.1	.763	273.8

TEST RUNS 3261-3267

Purpose: Performance of a 1-hour test at a constant nominal heat flux rate of 200 Btu/ft^2-sec as indicated with the calorimeter.

Run No.	Volts	Amps	Run Time min:sec.
3261	382	596	
3262	380	589	
3263	386	593	
3264	385	591	60
3265	387	592	
3266	390	594	
3267	394	604	

Results: Successfully accomplished.

WATER COOLED HEAT EXCHANGER

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
3261	18.5	52.1	134.6	62.0
3262	18.6	51.3	133.0	62.4
3263	18.6	51.8	134.3	61.6
3264	18.6	51.4	133.2	61.5
3265	18.5	51.8	133.7	61.3
3266	18.6	51.5	133.5	60.4
3267	18.5	51.7	133.6	59.1

HEATER ASSEMBLY

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
3261	15.8	40.6	89.4	41.2
3262	15.7	40.3	88.3	41.4
3263	15.7	40.9	89.6	41.1
3264	15.6	41.1	89.9	41.5
3265	15.7	42.0	92.2	42.3
3266	15.7	43.1	94.5	42.8
3267	15.8	44.4	97.6	43.2

	HEAT FLUX, BTU/SQ.FT.-SEC			INPUT POWER
RUN NO.	Q_C, CALORIMETER	Q_A, HEAT EXCHANGER	Q_A/Q_C	KW
3261	202.2	164.1	.81	227.9
3262	198.2	162.1	.817	223.5
3263	200.6	163.7	.815	228.6
3264	198.6	162.4	.817	227.4
3265	199.0	163.0	.816	228.9
3266	199.4	162.7	.814	231.7
3267	201.0	162.9	.810	237.3

TEST RUNS 3271-3276

Purpose: Investigation of the effect of a magnesium oxide reflector coating on the variation of the ratio of absorbed flux to calorimeter flux.

Run No.	Volts	Amps	Run Time min:sec.
3271	249	415	
3272	290	466	
3273	332	516	37:40
3374	370	557	
3275	395	585	
3276	430	622	

Results: Data showed a difference in the results with the magnesium oxide coated reflector when compared with a polished chrome plated reflector. Discussion of these results is presented in Section 5.5 and illustrated in Figure 26. An arc occurred in Run 3276.

WATER COOLED HEAT EXCHANGER

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
3271	17.7	25.9	64.1	65.2
3272	17.3	34.3	82.9	64.4
3273	16.8	44.4	104.4	64.0
3274	18.5	48.9	125.9	64.1
3275	18.2	54.5	138.3	62.9
3276	22.9	47.0	150.1	58.9

HEATER ASSEMBLY

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
3271	16.2	17.3	39.3	40.0
3272	16.5	21.8	50.4	39.1
3273	16.9	27.1	63.8	39.1
3274	15.5	35.4	76.9	39.1
3275	15.7	40.2	88.1	40.0
3276	14.3	53.6	106.9	41.9

	HEAT FLUX, BTU/SQ.FT.-SEC			INPUT POWER
RUN NO.	Q_C, CALORIMETER	Q_A, HEAT EXCHANGER	Q_A/Q_C	KW
3271	96.5	78.1	.81	103.2
3272	125.4	101.1	.805	135.1
3273	159.0	127.3	.800	171.3
3274	191.1	153.5	.803	206.1
3275	204.6	168.6	.824	230.9
3276	222.4	183.0	.825	267.4

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APPENDIX C

HIGH PRESSURE QUALIFICATION TEST RESULTS

TEST RUNS 4021-4027

Purpose: Performance of 1-hour test at a constant nominal heat flux rate of 225 Btu/ft^2-sec as indicated with the calorimeter.

Run No.	Volts	Amps	Run Time min:sec.
4021	410	574	
4022	419	579	
4023	422	579	
4024	428	581	60
4025	430	580	
4026	435	582	
4027	439	582	

Results: Successfully accomplished.

WATER COOLED HEAT EXCHANGER

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
4021	22.9	40.9	130.7	58.3
4022	22.9	40.4	129.1	55.8
4023	23.0	40.0	128.5	55.2
4024	23.1	40.0	128.8	54.4
4025	23.1	40.0	129.2	54.3
4026	23.0	39.7	127.1	52.7
4027	23.0	39.7	127.3	52.3

HEATER ASSEMBLY

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
4021	14.8	48.2	99.5	44.4
4022	14.7	52.1	106.6	46.1
4023	14.6	53.7	109.3	46.9
4024	14.6	55.3	112.7	47.6
4025	14.8	55.6	114.7	48.2
4026	14.8	57.1	117.8	48.8
4027	14.7	59.0	120.6	49.6

	HEAT FLUX, BTU/SQ.FT.-SEC			INPUT POWER
RUN NO.	Q_C, CALORIMETER	Q_A, HEAT EXCHANGER	Q_A/Q_C	KW
4021	222.4	159.3	.715	235.1
4022	224.0	157.4	.704	242.6
4023	222.4	156.6	.704	244.4
4024	223.2	157.0	.705	248.4
4025	222.4	157.5	.707	249.6
4026	223.2	155.0	.695	253.1
4027	222.4	155.2	.696	255.4

TEST RUNS 4061-4142

Purpose: Determination of the effects of two-phase operation. (Runs 4061-4066). Determination of the effect of the installation of a new calorimeter with an unaltered surface coating upon the ratio of absorbed flux to calorimeter flux. (Run 4141-4142).

Run No.	Volts		Amps		Run Time
	Phase 1	Phase 2	Phase 1	Phase 2	min:sec.
4061	80	77	277	255	8:30
4062	121	137	372	396	6:30
4063	158	159	459	445	10:40
4064	178	179	504	485	8:40
4065	202	201	553	529	8:50
4066	211	210	571	545	4:40
4141	235	223	561	570	12:10
4142		NO DATA			0:40

Results: Two-phase operation had no apparent effect on operation. Results of Run 4141 showed that adjustment of calorimeter calibration was required for data reduction analysis. An arc occurred in Run 4142.

WATER COOLED HEAT EXCHANGER

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
4061	17.1	11.5	27.6	69.3
4062	16.8	25.7	60.2	63.7
4063	16.6	36.9	85.4	62.4
4064	20.6	36.2	103.9	61.6
4065	20.4	44.7	127.2	61.3
4066	22.9	42.9	137.0	61.2
4141	22.6	48.6	152.9	62.1

HEATER ASSEMBLY

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
4061	11.3	9.6	15.2	38.2
4062	11.6	23.3	37.8	40.0
4063	11.8	32.7	53.8	39.3
4064	15.0	32.5	68.2	40.4
4065	15.3	40.0	85.2	41.0
4066	14.5	46.4	94.1	42.1
4141	14.6	52.4	106.6	43.3

	HEAT FLUX, BTU/SQ.FT.-SEC			INPUT POWER
RUN NO.	Q_C, CALORIMETER	Q_A, HEAT EXCHANGER	Q_A/Q_C	KW
4061	40.6	33.6	.828	41.8
4062	91.7	73.3	.800	99.2
4063	135.3	104.1	.77	143.5
4064	165.0	126.7	.766	176.9
4065	204.6	155.1	.758	217.9
4066	223.6	167.0	.748	234.9
4141	195.9	186.4	.953	258.6

TEST RUNS 4271-4276

Purpose: Initial shakedown in pressure vessel at low heat flux levels.

Run No.	Volts	Amps	Run Time min:sec.
4271	155	318	15:50
4272	197	389	8:00
4273	200	391	9:10
4274	252	467	5:20
4275	300	533	6:00
4276	351	598	5:50

Results: Successful operation.

WATER COOLED HEAT EXCHANGER

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
4271	17.0	12.6	30.1	64.5
4272	17.0	19.2	45.7	62.7
4273	20.4	16.5	47.1	63.4
4274	20.3	24.6	69.8	62.2
4275	20.3	33.0	93.7	61.6
4276	20.4	43.0	122.1	61.1

HEATER ASSEMBLY

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
4271	11.1	13.0	20.2	43.2
4272	11.1	20.1	31.3	42.9
4273	13.7	16.3	31.2	42.0
4274	13.7	24.7	47.3	42.2
4275	13.9	33.1	64.5	42.4
4276	13.8	43.9	84.4	42.2

	HEAT FLUX, BTU/SQ.FT.-SEC			INPUT POWER	TEST VESSEL PRESSURE PSIG
RUN NO.	Q_C, CALORIMETER	Q_A, HEAT EXCHANGER	Q_A/Q_C	KW	
4271	41.9	36.7	.88	49.1	0
4272	65.3	55.7	.893	76.4	0
4273	62.3	57.5	.923	78.0	100
4274	92.6	85.1	.92	117.7	100
4275	126.4	114.2	.903	159.6	100
4276	167.0	148.9	.89	209.7	100

TEST RUNS 5041-5044

Purpose: Further shakedown in pressure vessel at higher heat flux levels.

Run No.	Volts	Amps	Run Time min:sec.
5041	203	375	5:00
5042	306	512	5:00
5043	399	625	5:00
5044	NO DATA		

Results: Successful operation to an absorbed heat flux of 175.2 Btu/ft^2-sec.

Element broke and arcing occurred in Run 5044.

TEST RUNS 5071-5073

Purpose: Investigation of the effect of reducing pressure, in steps, upon arcing at high heat flux levels.

Run No.	Volts	Amps	Run Time min:sec.
5071	416	712	6:00
5072	410	699	7:00
5073	416	702	8:15

Results: An arc occurred and reflector damage resulted.

WATER COOLED HEAT EXCHANGER

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
5041	22.1	14.3	44.3	61.1
5042	22.1	29.7	91.6	61.4
5043	21.8	47.2	143.7	60.5
5071	23.0	51.0	163.7	58.0
5072	23.0	49.8	159.6	58.5
5073	22.9	49.8	159.2	57.2

HEATER ASSEMBLY

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
5041	14.2	13.1	26.0	35.9
5042	14.2	28.8	57.1	38.2
5043	14.5	48.0	97.4	41.0
5071	13.8	65.7	126.0	44.6
5072	13.8	64.6	124.0	45.4
5073	13.8	66.6	128.4	46.1

	HEAT FLUX, BTU/SQ.FT-SEC			INPUT POWER	TEST VESSEL PRESSURE PSIG
RUN NO.	Q_C, CALORIMETER	Q_A, HEAT EXCHANGER	Q_A/Q_C	KW	
5041	65.3	54.0	.852	76.1	100
5042	128.0	111.7	.872	156.6	100
5043	195.5	175.2	.895	249.3	100
5071	274.7	199.6	.727	296.1	100
5072	267.1	194.6	.728	286.5	80
5073	274.7	194.1	.707	292.0	60

TEST RUNS 5081-5083

Purpose: Investigation, with a repaired reflector, of the effect of reducing pressure, in steps, upon arcing at high heat flux levels.

Run No.	Volts	Amps	Run Time min:sec.
5081	421	705	5:30
5082	439	720	3:40
5083	438	714	3:30

Results: An arc occurred and reflector damage resulted.

TEST RUNS 5121-5123

Purpose: Determination of the heat flux level at which arcing occurs at atmospheric pressure.

Run No.	Volts	Amps	Run Time min:sec.
5121	306	533	4:10
5122	404	655	3:40
5123	440	695	4:00

Results: An arc occurred in Run 5123 and the reflector was destroyed.

WATER COOLED HEAT EXCHANGER

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
5081	23.8	51.9	172.1	60.9
5082	23.6	54.5	179.1	59.5
5083	23.7	52.5	173.7	58.3
5121	22.4	32.3	100.9	64.9
5122	22.4	49.8	155.8	61.8
5123	22.5	53.2	166.0	57.2

HEATER ASSEMBLY

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
5081	13.9	60.7	117.4	41.5
5082	13.9	66.7	129.0	42.8
5083	13.8	69.3	133.5	44.8
5121	13.2	34.3	63.0	40.5
5122	13.3	57.4	106.4	42.2
5123	13.3	72.5	134.7	46.2

	HEAT FLUX, BTU/SQ.FT.-SEC			INPUT POWER	TEST VESSEL PRESSURE PSIG
RUN NO.	Q_C, CALORIMETER	Q_A, HEAT EXCHANGER	Q_A/Q_C	KW	
5081	252.9	209.8	.829	296.8	100
5082	264.0	218.3	.829	316.0	100
5083	262.1	211.8	.812	312.7	80
5121	134.2	123.0	.916	163.0	0
5122	215.8	189.9	.880	264.6	0
5123	238.0	203.2	.852	305.8	0

TEST RUNS 6191-6194

Purpose: Shakedown test with two-phase power at 250 psig nominal vessel pressure.

Run No.	Volts Phase 1	Volts Phase 2	Amps Phase 1	Amps Phase 2	Run Time min:sec.
6191	141	142	500	535	
6192	159	157	548	572	16:50
6193	178	177	600	625	
6194		NO DATA			

Results: Random arcing occurred in and around brass hardware. Water leakage and dielectric breakdown were the probable cause. Vessel heating due to increased convection was noted.

WATER COOLED HEAT EXCHANGER

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
6191	24.6	24.9	85.4	61.2
6192	24.5	30.0	102.8	61.0
6193	24.6	36.7	126.2	60.9
6194	24.5	43.7	149.0	60.1

HEATER ASSEMBLY

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
6191	12.6	31.5	55.5	39.8
6192	12.7	38.3	68.1	40.4
6193	12.7	48.6	86.3	41.7
6194	12.7	58.7	104.2	42.0

	HEAT FLUX, BTU/SQ.FT.-SEC			INPUT POWER	TEST VESSEL PRESSURE PSIG
RUN NO.	Q_C, CALORIMETER	Q_A, HEAT EXCHANGER	Q_A/Q_C	KW	
6191	104.5	104.2	.995	146.4	250
6192	126.7	125.3	.990	176.9	250
6193	160.1	153.9	.958	217.4	250
6194	197.2	181.6	.919	260.0	250

TEST RUNS 7171-7245

Purpose: Investigation of the convective pressure vessel heating to ensure that safe operation was possible at high heat flux levels and 250 psig.

Run No.	Volts		Amps		Run Time
	Phase 1	Phase 2	Phase 1	Phase 2	min:sec.
7171	123	131	472	500	20
7231	126	130	480	495	7
7232	159	163	565	582	7
7233	176	179	612	625	12
7241	131	131	483	489	10
7242	162	161	560	563	8
7243	177	180	600	612	8
7244	196	198	645	653	7
7245	210	211	670	682	6

Results: Low purge rates kept maximum pressure vessel temperature within acceptable limits. Further discussion of these results are presented in Section 6.5 and 6.6.

WATER COOLED HEAT EXCHANGER

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
7171	25.3	18.9	67.0	56.9
7231	25.4	20.7	73.4	61.7
7232	25.2	30.7	108.1	61.4
7233	25.3	35.3	124.4	59.5
7241	25.9	20.1	73.0	60.2
7242	25.9	28.3	102.4	59.3
7243	25.9	33.9	122.5	59.4
7244	25.7	39.8	142.8	58.6
7245	25.8	43.7	156.8	57.8

HEATER ASSEMBLY

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
7171	12.6	31.5	55.5	39.8
7231	12.4	26.0	45.0	37.8
7232	12.4	40.6	70.6	40.1
7233	12.5	48.5	84.5	40.4
7241	12.4	26.0	45.2	37.2
7242	12.5	38.2	67.0	38.8
7243	12.6	47.0	82.7	40.1
7244	12.9	56.0	100.5	41.2
7245	12.9	62.4	111.8	41.2

	HEAT FLUX, BTU/SQ.FT.-SEC			INPUT POWER	TEST VESSEL PRESSURE PSIG
RUN NO.	Q_C, CALORIMETER	Q_A, HEAT EXCHANGER	Q_A/Q_C	KW	
7171	80.4	81.6	1.019	123.5	253
7231	84.1	89.5	1.066	124.8	250
7232	128.6	131.7	1.025	184.7	250
7233	156.4	151.7	0.968	219.5	253
7241	87.0	89.1	1.025	127.3	249
7242	126.7	124.8	0.984	181.3	249
7243	154.6	149.4	0.965	216.3	249
7244	185.3	174.1	0.939	255.7	249
7245	205.4	191.2	0.931	284.6	249

TEST RUNS 9081-9085

Purpose: Further shakedown testing with two-phase power at 250 psig nominal vessel pressure and higher heat flux levels.

Run No.	Volts		Amps		Run Time
	Phase 1	Phase 2	Phase 1	Phase 2	min:sec.
9081	131	134	440	450	13:00
9082	158	155	505	505	6:00
9083	180	181	555	562	7:30
9084	199	199	585	592	6:00
9085	220	220	621	622	3:15

Results: Successfully accomplished.

WATER COOLED HEAT EXCHANGER

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
9081	23.4	20.4	66.7	59.4
9082	23.3	27.1	88.2	58.8
9083	23.5	34.1	111.9	58.3
9084	23.3	39.7	128.9	57.7
9085	23.3	45.8	148.8	57.1

HEATER ASSEMBLY

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
9081	12.6	24.3	42.8	38.1
9082	12.7	33.8	59.9	39.9
9083	12.6	44.6	78.5	40.9
9084	13.0	51.5	93.1	41.7
9085	12.9	60.9	109.2	41.9

	HEAT FLUX, BTU/SQ.FT.-SEC			INPUT POWER	TEST VESSEL PRESSURE PSIG
RUN NO.	Q_C, CALORIMETER	Q_A, HEAT EXCHANGER	Q_A/Q_C	KW	
9081	89.6	81.3	.909	117.9	247
9082	121.2	107.5	.886	157.2	246
9083	160.1	136.5	.850	201.6	246
9084	189.8	157.1	.830	234.2	246
9085	225.0	181.5	.806	273.4	246

TEST RUNS 9101-91010

Purpose: Performance of a 1-hour test at a heat flux level approaching the maximum performance limitations.

Run No.	Volts		Amps		Run Time
	Phase 1	Phase 2	Phase 1	Phase 2	min:sec
9101	120	120	445	465	7:30
9102	140	140	500	530	4:00
9103	160	160	550	580	5:00
9104	180	180	600	630	5:00
9105	201	200	655	685	7:30
9106	208	210	665	700	
9107	210	210	665	700	
9108	210	209	660	690	60:00
9109	210	211	660	695	
91010	209	210	650	685	

Results: Successfully accomplished. Results discussed further in Section 6.5 and illustrated in Figure 31.

WATER COOLED HEAT EXCHANGER

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
9101	25.0	17.9	62.7	60.3
9102	24.9	23.3	81.0	59.0
9103	24.9	29.3	101.6	59.0
9104	24.8	35.6	122.9	58.3
9105	24.8	42.7	147.5	57.6
9106	24.8	44.2	152.5	56.1
9107	24.8	43.3	149.6	54.8
9108	24.8	41.3	142.8	53.0
9109	24.8	41.2	142.3	52.4
91010	24.6	40.3	138.5	52.0

HEATER ASSEMBLY

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
9101	12.6	22.1	39.0	37.5
9102	12.7	29.7	52.9	38.5
9103	12.6	38.5	67.8	39.4
9104	12.9	47.5	85.2	40.4
9105	12.9	59.3	106.3	41.5
9106	12.9	64.6	115.7	42.6
9107	12.9	67.3	120.6	44.1
9108	12.9	69.2	123.8	45.9
9109	12.9	71.0	127.1	46.8
91010	12.9	70.1	125.5	47.1

	HEAT FLUX, BTU/SQ.FT.-SEC			INPUT POWER	TEST VESSEL PRESSURE PSIG
RUN NO.	Q_C, CALORIMETER	Q_A, HEAT EXCHANGER	Q_A/Q_C	KW	
9101	78.5	76.5	.972	109.2	248
9102	106.3	98.8	.929	144.2	248
9103	134.2	123.9	.923	180.8	248
9104	167.5	149.8	.894	221.4	251
9105	212.1	179.8	.847	268.6	253
9106	228.8	185.9	.811	285.3	252
9107	232.5	182.4	.784	286.6	254
9108	230.6	174.1	.755	282.8	248
9109	234.3	173.5	.740	285.2	250
91010	230.6	168.8	.732	279.7	250

TEST RUNS 9181-9187

Purpose: Performance of a 1-hour test at a heat flux level approaching the maximum performance limitations closer than in Runs 9101-91010.

Run No.	Volts		Amps		Run Time
	Phase 1	Phase 2	Phase 1	Phase 2	min:sec.
9181	116	120	414	450	6:30
9182	159	160	521	550	5:00
9183	199	199	618	648	7:00
9184	232	235	680	720	
9185	230	232	670	705	
9186	233	237	668	700	51:35
9187	230	237	649	682	

Results: Element failed after approximately 51 min. of the 60 min. part of the test. Discussion of the results is presented in Section 6.5 and illustrated in Figure 31.

WATER COOLED HEAT EXCHANGER

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
9181	25.0	17.1	59.9	61.6
9182	24.9	27.4	95.3	58.6
9183	24.6	40.1	137.9	57.4
9184	24.8	50.9	175.6	56.3
9185	24.6	48.2	165.5	54.7
9186	24.8	46.2	159.5	52.1
9187	24.8	43.3	149.4	50.4

HEATER ASSEMBLY

RUN NO.	FLOW GPM	DELTA T DEG. F	ABSORBED HEAT BTU/SEC	PCT. TOTAL PCT
9181	12.9	19.7	35.3	36.4
9182	13.0	34.2	62.0	38.1
9183	13.0	52.9	95.8	39.9
9184	13.0	71.5	129.1	41.4
9185	13.1	73.8	134.5	44.4
9186	13.2	78.2	143.7	46.9
9187	13.2	78.1	143.6	48.5

	HEAT FLUX, BTU/SQ.FT.-SEC			INPUT POWER	TEST VESSEL PRESSURE PSIG
RUN NO.	Q_C, CALORIMETER	Q_A, HEAT EXCHANGER	Q_A,Q_C	KW	
9181	76.7	73.0	.953	102.0	252
9182	134.2	116.2	.865	170.8	245
9183	200.9	168.1	.835	251.9	248
9184	273.3	214.0	.785	326.9	250
9185	275.1	201.7	.732	317.6	250
9186	286.3	194.5	.680	321.5	250
9187	290.0	182.2	.628	310.9	250

Development of a Graphite Radiant Heater

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ABSTRACT

This report describes the design, development, fabrication and testing of a 4-square foot graphite radiant heater capable of delivering a heat flux in excess of 200 Btu/ft^2-sec, while operating from 480-volt ignitron power supplies. Included are detailed descriptions of component development, graphite limitations, extensive prototype testing, and the design and fabrication of the full size heater assembly.

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