REPORT MDC E0775

DESIGN, FABRICATION, TESTING, AND DELIVERY OF SHUTTLE HEAT PIPE LEADING EDGE TEST MODULES

FINAL REPORT

VOLUME II
TECHNICAL REPORT

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY • EAST

MCDONNELL DOUGLAS
CORPORATION

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20 APRIL 1973

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Saint Louis, Missouri 63166 (314) 232-0232

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CORPORATION

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Foreword

This report contains a description of work conducted for the Astronautics Laboratory of the Marshall Space Flight Center under Contract NAS8-28656, "Design Fabrication, Testing and Delivery of Heat Pipe Leading Edge Modules." The NASA Contracting Officer Representative for this study was Mr. Farouk Huneidi and the MDAC Program Manager was Mr. R. V. Masek.

Major contributions to the accomplishment of this program were made by Mr. G. A. Niblock and Mr. G. G. Graff at MDAC-E and Mr. J. S. Holmgren, Mr. P. P. King, and Mr. G. D. Johnson at MDAC-DWDL.

1. INTRODUCTION

The goal of low cost space transportation that the Space Shuttle is expected to accomplish requires highly reusable system components, especially in the orbiter. The orbiter will make about 100 flights in fulfilling its design capability. During the flights certain aerodynamic surfaces experience an extremely severe environment, notably the nose region and leading edge surfaces. Thermal protection of these regions presents a variety of problems.

A prior study, performed under contract NAS8-27708, examined the feasibility of using high temperature heat pipes and three alternate concepts for cooling nose and wing stagnation regions. The study included both the orbiter and the booster of the fully reusable Phase B configuration.

The initial analysis indicated that the booster applications showed little promise for heat pipe concepts. The orbiter leading edge application was, however, found to be feasible with respect to the heating and acceleration environments. The wing leading edge was amenable to a simple design. Cascading was not required and the shape was essentially two-dimensional, permitting an assembly of conventional high temperature heat pipes in spanwise segments. Consequently, the leading edge application was investigated in detail to allow a preliminary design.

The leading edge heat pipe design and the three alternates were examined and compared. The heat pipe version was determined to be somewhat heavier than the alternate candidates but much less expensive (as was each reusable design) than the ablative version on the basis of total program costs. Subsequent consideration of more severe entry conditions than those of the Phase B configuration and environments significantly impacted the trade study results. The hotter entry resulted in temperatures exceeding the columbium reuse temperature limit. This analysis, although qualitative, indicated that the heat pipe and carbon-carbon designs remained viable candidates.

The current contract (NAS 8-28656), reported in this document, is a follow-on to the prior study for the purpose of constructing feasibility test models of the heat pipe concept. The program included the analysis and design of the heat pipes, their integration into the test module structure, heat pipe development testing, fabrication of the test modules and facility adapter, and formulation of recommended testing conditions. The heat pipe analysis and testing were conducted at the Donald W. Douglas Laboratories (DWDL) in Richland, Washington. Structural analysis and design, fabrication of sheet metal and machined parts and final assembly were accomplished by MDAC-E in St. Louis, Missouri.

The results of the heat pipe and leading edge module thermal analysis indicate the test modules will meet their design goal; reducing the leading edge temperature at the stagnation line from 1316°C (2400°F) to less than 1010°C (1850°F). The development tests demonstrated that the model assembly could be brazed with active heat pipes, as was borne out by the subsequent successful brazing of both modules with active heat pipes loaded with sodium. Construction of the two modules in this fashion conclusively demonstrated the manufacturing feasibility of the concept.

2. HEAT PIPE ANALYSIS AND DEVELOPMENT TESTING

All analysis and testing related to heat pipe internal design, e.g., working fluid selection, wick design, and material compatibility were conducted by DWDL. Because of the advanced nature of this heat pipe application the various analyses were confirmed by development testing prior to fabrication of the deliverable hardware. Because of the high temperature operation, a major concern was compatibility between the container material, the wick, and the working fluid. The type of wick design required analysis and testing for selection of the final design. Finally, to assure a design with structural integrity for safety in handling and in testing of the hardware, several structural qualification type tests were performed.

Heat Pipe Internal Design - The Reference (1) review of heat pipe fluids and materials for Space Shuttle applications showed that sodium/Hastelloy-X might be considered for temperatures up to 1800°F. Data existing in the literature of the sodium/Hastelloy-X system are limited to a few tests conducted either in a nuclear reactor or a pumped loop. In another review, of alkali metal corrosion tests, Reference (2), data for Hastelloy-X in pumped loops were somewhat conflicting. In one case corrosive attack was reported in a 305 hour test with temperatures up to 1700°F, and in the other case there was no evidence of corrosion in a 1000 hour test with temperatures up to 1500°F.

It should be pointed out that in loop tests the Hastelloy-X would not be the only component of the loop. Other metallic materials used in the construction of the loop could affect the behavior of the Hastelloy-X. This is also in the case in the tests described in Reference (3) in which Hastelloy-X exposed to flowing sodium at 819°F to 887°F showed little evidence of attack. The Hastelloy-X was in contact with several other materials during the test period.

The compatibility of iron-, cobalt-, and nickel-base superalloys has been determined in refluxing potassium at 1800°F for times up to 2000 hours. See Reference (4). Hastelloy-X was included as one of the test materials. The results of these tests were that the cobalt and nickel-base alloys (including Hastelloy-X) appeared to have sufficient corrosion resistance to warrant consideration for use as hardware for the ground testing of design concepts for components of space power systems.

Although these tests were with potassium, it would be expected that operation with sodium should be somewhat similar. This has been essentially verified by operation of a sodium/Hastelloy-X heat pipe at 715°C (1320°F) for 20,000 hours as reported in Reference (5). The temperature is lower than the required temperature for the Shuttle application, but the very long time of the test would tend to indicate that little corrosion had occurred.

As pointed out by DeVan, Reference (6), the corrosion of materials in a polythermal all-liquid loop does not necessarily apply to a two-phase boiling system. Further, although a heat pipe is similar to a boiling system in that there is evaporation and condensation - (thus two phases) all liquid-vapor phase change occurs by surface evaporation without boiling. Somewhat better simulation can be provided by a small test system, which is essentially identical to a heat pipe, called a reflux capsule.

A reflux capsule test provides a simple method for investigating the effect of a two-phase liquid metal environment on heat pipe structural materials. The capsule, constructed of the material(s) of interest, is placed with its axis vertical. Heat is applied to the lower end, causing the liquid metal to vaporize. Condensation of the vapor occurs at the upper end and gravity returns it to the heated end. This method, reported in Reference (7), has been used successfully by DWDL to determine the compatibility of various materials at temperatures up to 1800°C (3272°F) and so was employed with the new combination of materials to assure compatibility.

Hastelloy-X tubing and bar stock were procured in accordance with AMS specifications No. 5588 and No. 5754F, respectively. Reactor grade sodium ($<$10 ppm oxygen; 32 ppm carbon) was obtained from Mine Safety Appliances Corp. After the capsule parts were machined, the parts were degreased in alcohol, cleaned in hot water and Alconox, rinsed in alcohol and finally cleaned in Freon in an ultrasonic cleaner. Then the parts were dipped into a nitric-hydrofluoric acid mixture for 3-5 minutes. After a thorough rinsing, the capsules and end plugs were TIG welded together in an inert gas glove box.

The assembled capsules were then given a heat treatment which simulates the thermal portion of the brazing cycle which is to be used in the fabrication of the leading edge segment. This consisted of heating in a vacuum to

115°C (2100°F) and holding for 15 minutes. Then the capsules were cooled to 1040°C (1900°F) and held there for three hours, followed by a furnace cool to room temperature.

Charging of the capsules was conducted in a high purity (less than 10 ppm $O_2 + H_2O$) inert atmosphere glove box to duplicate the purity level expected in the test module heat pipes. Since trace quantities of oxygen in Alkali metals can influence corrosion behavior markedly, it is imperative that a known purity level be maintained.

After sodium loading the capsules were placed in the vacuum furnace for testing. Two chromel-alumel thermocouples were spot welded to each capsule for monitoring test temperature. Desired test conditions were:

1. 985°C (1800°F) for 30 hours
2. 985°C (1800°F) for 100 hours
3. 1040°C (1900°F) for 30 hours

In addition to these three tests, one capsule contained a section of stainless steel screen. The purpose of this test was to determine if the stainless steel screen had sufficient corrosion resistance for consideration as a wicking material.

Upon completion of each test, the sodium was removed and three metallographic samples were taken from each capsule: one from the liquid zone, one from the vapor zone, and the other from the liquid/vapor interface region (top of the liquid pool). After the metallographic analysis was completed, hardness and wall thickness measurements were made on each specimen.

These examinations indicated that there was no significant corrosion of the Hastelloy-X walls or of either the Hastelloy-X or stainless steel screens. Stainless steel screens were selected for the panel heat pipes since they provided good corrosion resistance at lower cost than Hastelloy-X. These tests demonstrated that the Hastelloy-X, stainless steel screen, and sodium system should fulfill the space shuttle mission requirements.

The brazing temperature of 1052°C (1925°F) was higher than the expected operating temperature and it was planned to braze with completed (active) heat pipes. A 1.59-cm (5/8-in.) OD, 25.4-cm (10-in.) long Hastelloy-X heat pipe was brazed to a 0.51-mm (0.02-in.) thick fin to further assess compatibility with the working fluid. Figure 1 shows the fin-to-tube braze and a closeup of the tube wall. No discernible corrosive attack occurred. The tube interior surface, the stainless steel wick, and the pinch-off closure were closely examined and the results indicate compatibility was conclusively demonstrated by the test.

With material compatibility assured, the wick design proceeded with the following design criteria: (a) ability to transport the required heat flux at maximum temperature, (b) ability to operate during start-up conditions, and (c) ability to be formed into a proper contour for the leading edge segment. Previous experience with (c) essentially fixes the wick design to be either isotropic or arterial. Since the amount of Hastelloy-X tubing was quite limited, the preliminary tests were conducted with stainless steel heat pipes.

The term "isotropic wick" implies that the wicking material has uniform porosity such that the capillary radius (r_c) and permeability coefficient (K_p) are constant for the material. Maximum heat pipe performance is obtained by maximizing the capillary pumping capacity. Thus, it is desirable to have a small r_c and large K_p; however, for a isotropic material, this combination of desired properties is not obtainable. To circumvent this situation, a wick was fabricated from two types of screen material, one possessing a low r_c and the other a high K_p. This was accomplished by rolling up a sandwich structure of 100 mesh and 200 mesh screen so that the bulk of the wick consisted of alternate layers of each type and with the OD and ID surfaces covered by 200 mesh. Measurements of the permeability of this structure gave a value of 2.56 X 10^{-9} ft^2. A single layer of 100 mesh has a K_p of 3.1 X 10^{9} ft^2 and that of a single layer of 200 mesh is 6.3 X 10^{-10} ft^2. Thus, the K_p of the structure is very close to that of the 100 mesh screen. Covering the entire surface of the structure with the 200 mesh screen provides the small value of r_c. Porosity measurements of this layered wick gave a value of 0.72. This wick structure was then processed for incorporation into a heat pipe.

The other type wick structure evaluated was a special type of arterial wick. The arterial wick, because of the low pressure drop of the artery, has a substantially greater heat transfer capacity in the wick-limited operating mode. The basic arterial wick structure was the type used for the ATS-E and OWS-I heat pipes. Four small (0.037 in. OD) screen tubes were

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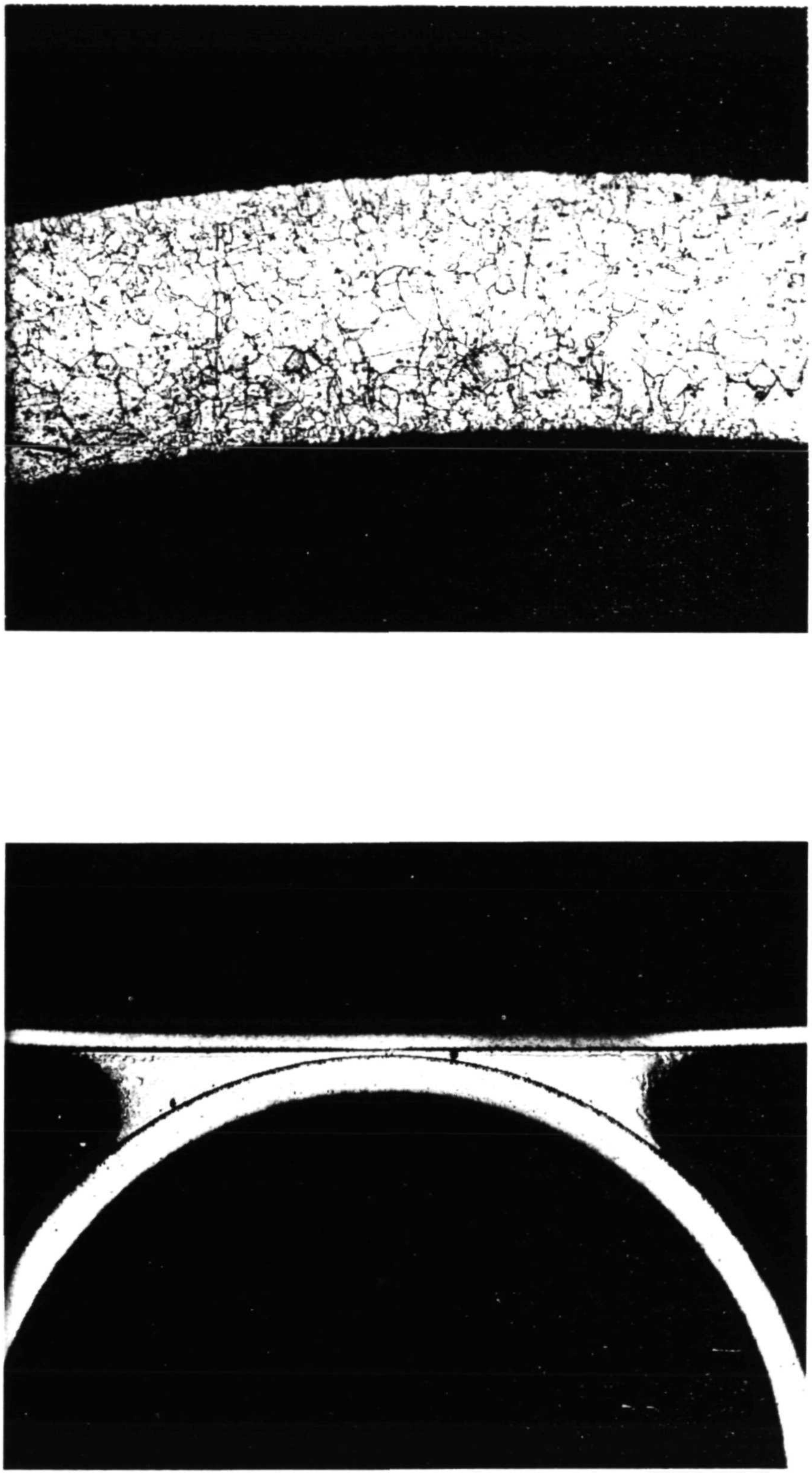
NO DISCERNABLE CORROSIVE ATTACK



TUBE WALL MAGNIFIED VIEW

FIN-TO-TUBE BRAZE JOINT

Figure 1

inserted into the main artery to create a "multiple artery" wick. This structure has been previously analyzed and characterized through lab experiments.

These two wick structures were analyzed with sodium as the working fluid. The pipes were 41.9-cm in length and 1.27-cm in diameter. Performance values as calculated with a DWDL computer program are shown in Figures 2 and 3. The envelope of operational limits is probably best described in the sonic (gas flow) and wick (liquid flow) curves since the entrainment limit (mixed flow) is somewhat arbitrary. From these curves, it can be seen that if several hundred watts were applied to either pipe at low temperatures (315^{o}C) the limit first encountered would be the sonic limit. From this one would expect possible problems during start-up.

To assess the possible start-up problem, two heat pipes, each with one type of wick (isotropic or arterial), were constructed and tested. Heat loads were applied with a Lepel radio frequency (RF) induction heating unit. Heat removal was solely by radiation. The radiated power was a calculated value based on experimental values of temperature and emissivity. Temperatures were measured with chromel-alumel thermocouples and the emissivity was determined with the use of an Ircon pyrometer. A plate voltage reading from the Lepel unit was taken for several steady state temperatures. From this a curve of plate voltage versus power radiated could be constructed for each pipe. For start-up behavior, the RF unit was set at a given value of plate voltage. It was assumed that the power input to the pipe was equal to the maximum value determined from the steady state conditions.

A typical temperature versus time relationship for start-up is shown in Figure 4 for the multiple artery heat pipe. Successful start-up occurred with both wick designs for various heat loads. This was demonstrated many times without evidence of performance limiting phenomena. The time required to heat up from room temperature to a preselected arbitrary temperature (e.g. 593^{o}C) showed good agreement with the calculated value. Some theoretical and experimental values are shown in Figure 5.

THEORETICAL PERFORMANCE
OF AN ISOTROPIC WICK HEAT PIPE

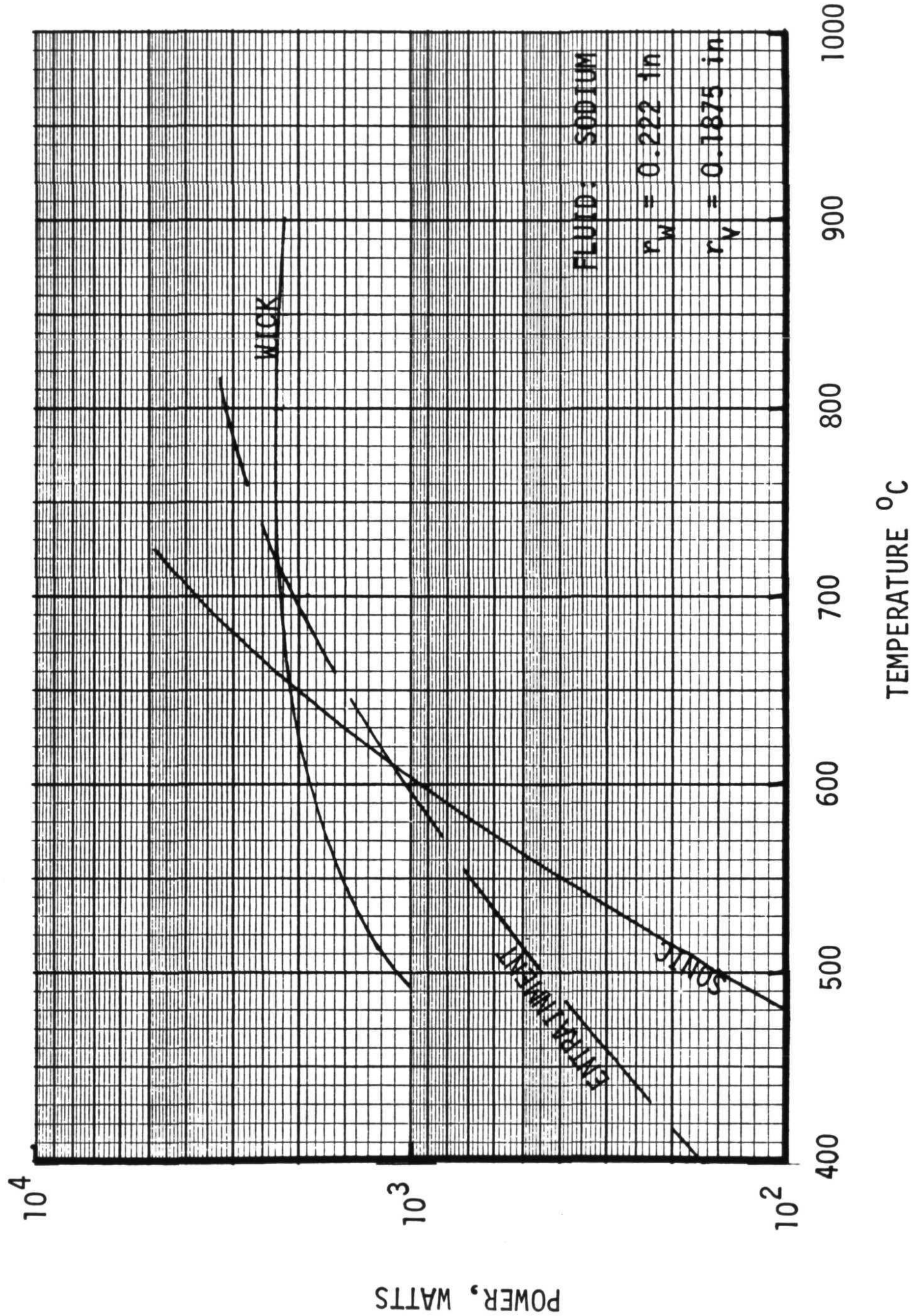


Figure 2

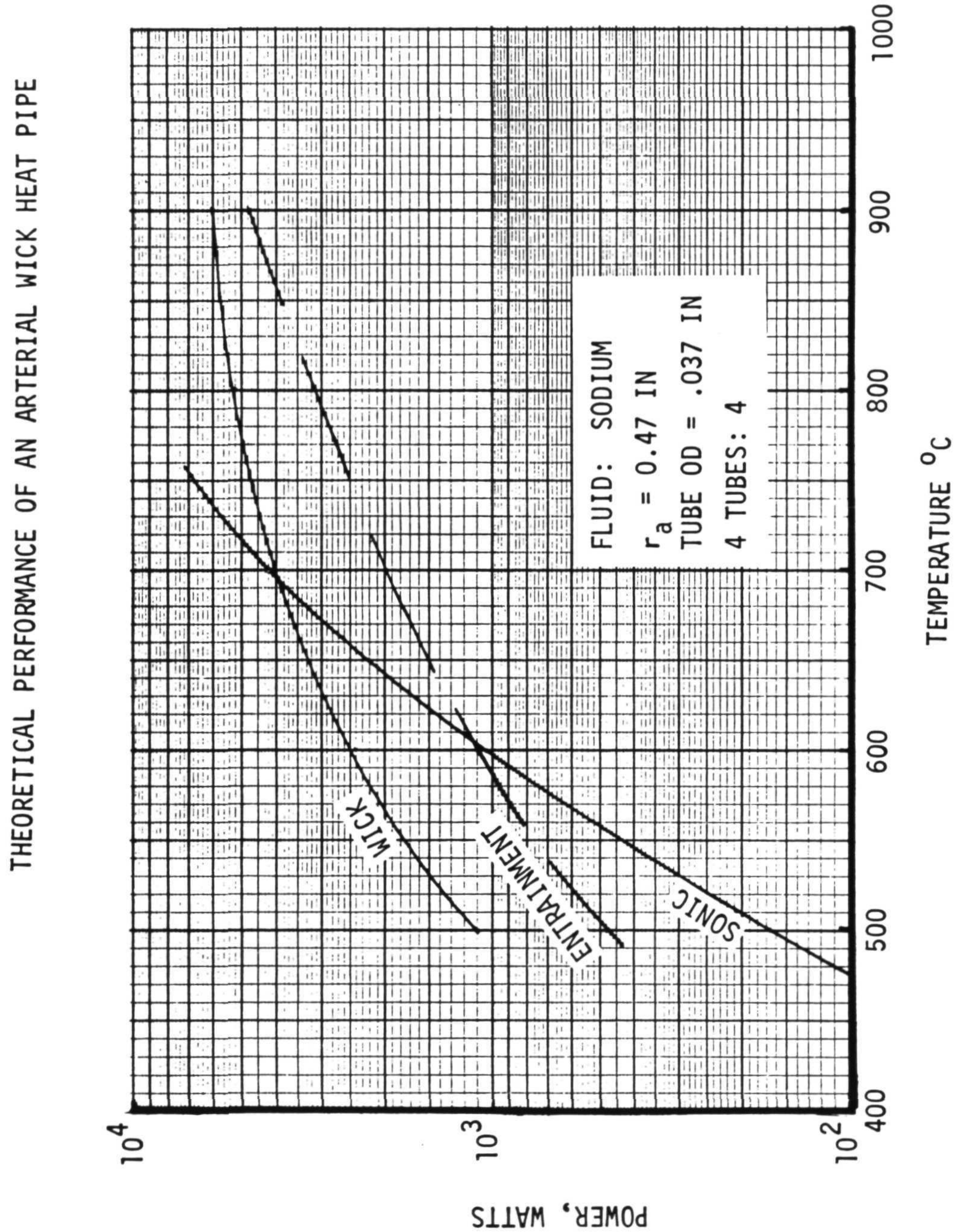

THEORETICAL PERFORMANCE OF AN ARTERIAL WICK HEAT PIPE
FLUID: SODIUM
r_a = 0.47 IN
TUBE OD = .037 IN
4 TUBES: 4
WICK
ENTRAINMENT
SONIC
10^4
10^3
10^2
POWER, WATTS
400
500
600
700
800
900
1000
TEMPERATURE °C

Figure 3

START-UP OF AN ARTERIAL SODIUM HEAT PIPE

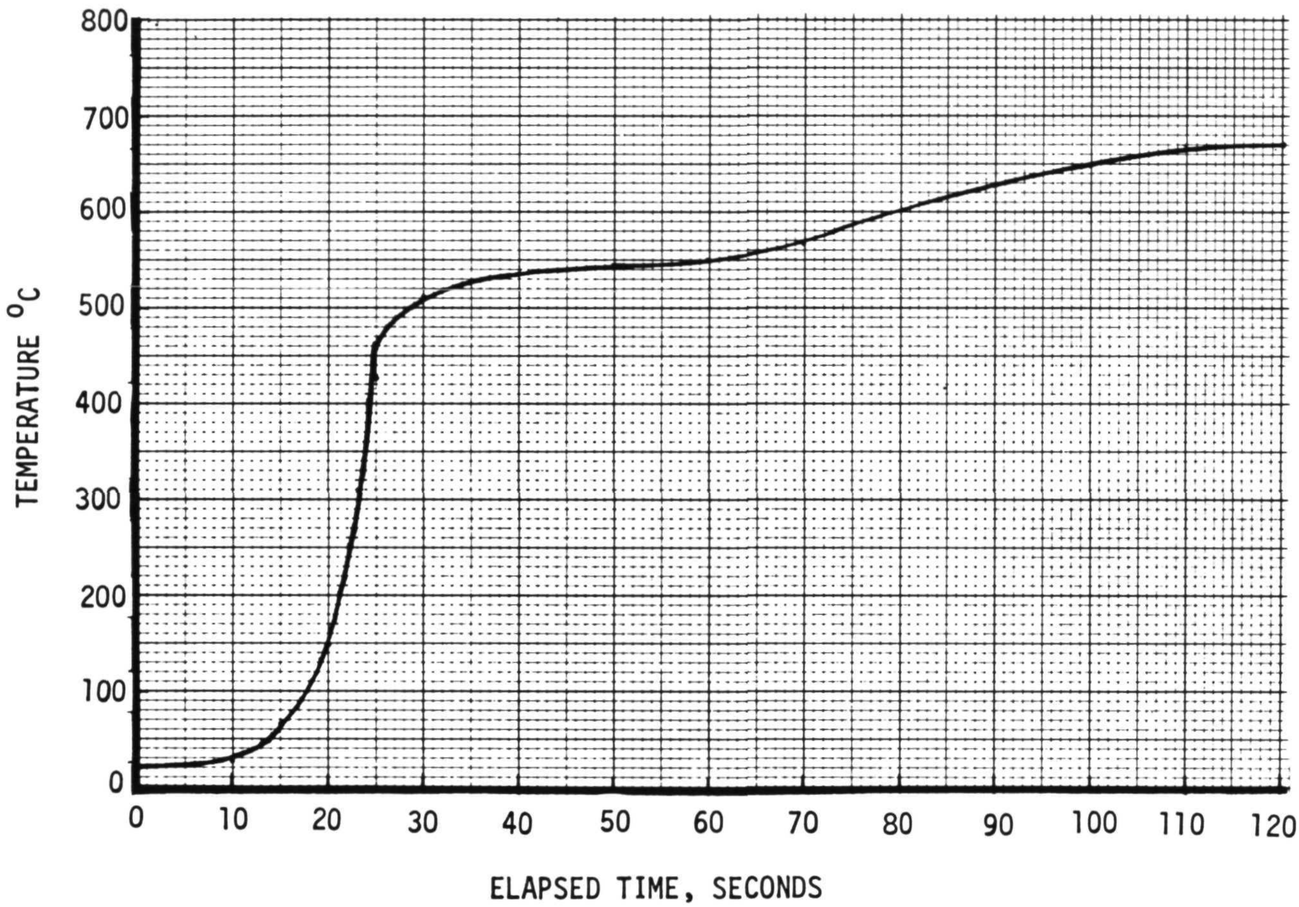


Figure 4

COMPARISON OF THEORETICAL AND EXPERIMENTAL
HEAT-UP TIMES

Heat Pipe	Input Power watts	Heat-up Time, seconds Theory	Experimental
Isotropic Wick	385	112	96
	263	162	138
	220	196	180
Multiple Artery	260	149	141

Figure 5

All of the start-up tests had been conducted with the pipe level. Since part of the leading edge will have to operate against gravity, several tests were conducted to determine if a gravity head would affect the start-up characteristics. Tests conducted with the multiple artery showed that gravity heads up to 11.7-cm (4.6-in) had no effect on starting up from room temperature. No tests were conducted beyond this value since extensive modification of the equipment would have been required to yield higher elevations and the heat pipes clearly were capable of starting against the required head.

Both wick configurations operated satisfactorily. Therefore, the isotropic wick was chosen since it was the simplest design. As a final check of the wick selection, a Hastelloy-X heat pipe containing the selected wick type was built and tested. Because of the very limited supply of 1.27-cm (0.5 in.) tubing this test pipe was constructed with 1.59-cm (5/8 in.) tubing. The heat pipe length was 45.7-cm (18 in.). The permeability of the wick was measured as 2.85×10^{-9} ft^2. Operation of the Hastelloy-X heat pipe was entirely satisfactory with no problems exhibited during start-up. The maximum temperature reached was 930°C and at this temperature the pipe was rejecting 989 watts, which is about 37% of the theoretical limit. The operation of the Hastelloy-X pipe at 37% of the wick limit was not an operational limit but was a condenser limit. The Hastelloy-X pipe, with that combination of area, temperature, and emissivity could not radiate more than 989 watts. The results of these heat pipe tests showed that the layered multiscreen wick would be entirely acceptable for use in the heat pipes for the leading edge panel.

These tests confirming wick performance then allowed a high confidence computation of the performance of the design diameter heat pipe. Performance values for the wick in the design diameter pipe were calculated and the results are summarized in Figures 6 and 7. Figure 6 shows the performance of a level pipe operating in 1-g as a function of temperature and effective length. Figure 7 shows how the performance of the same pipe is affected by imposing a tilt of 17.12 degrees. This value of gravity head represents the worst case for the leading edge. These values in Figures 6 and 7 are theoretical limits and steady state operational values are below this limit in order to ensure a reasonable safety factor.

LEADING EDGE HEAT PIPE PERFORMANCE

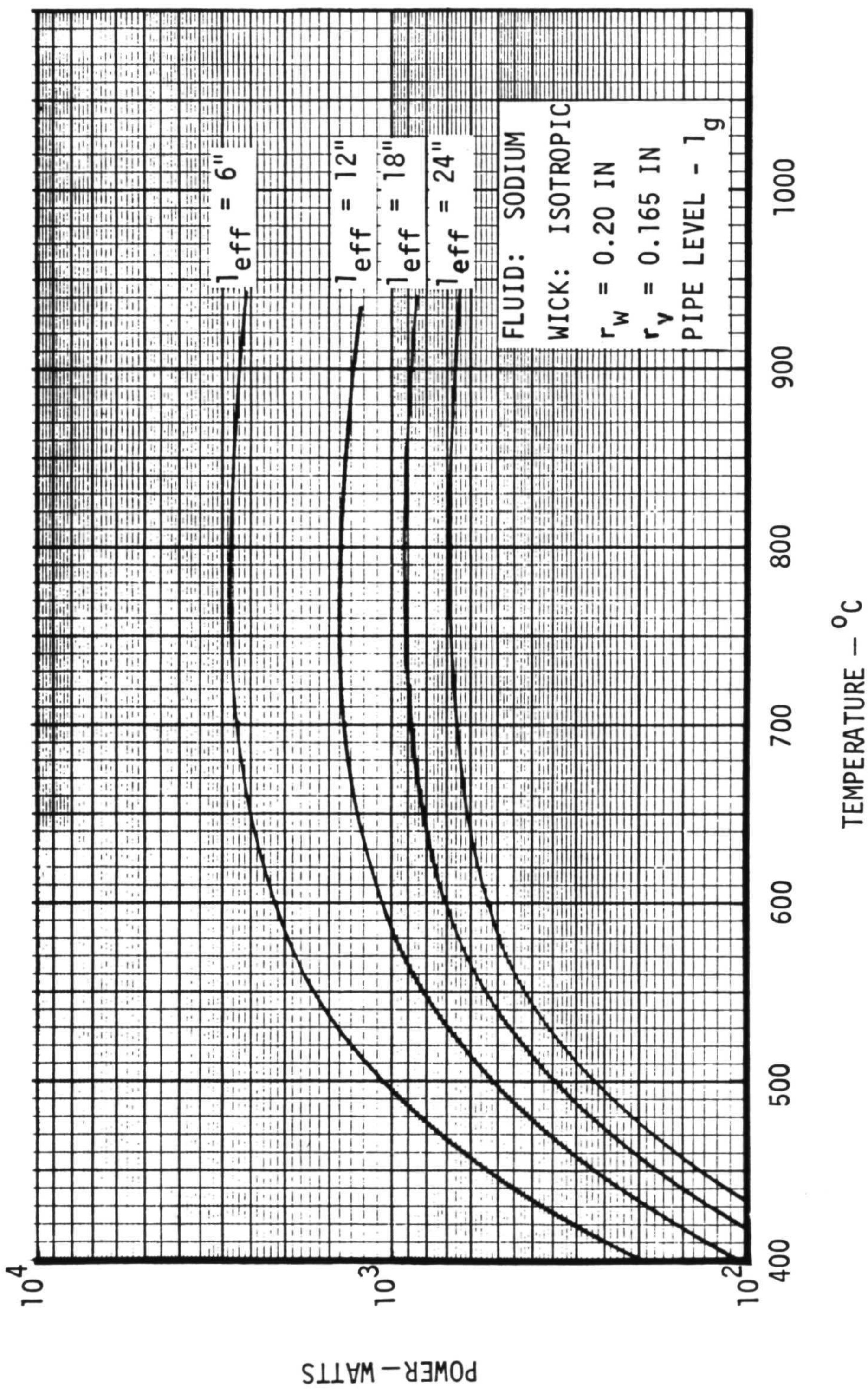


Figure 6

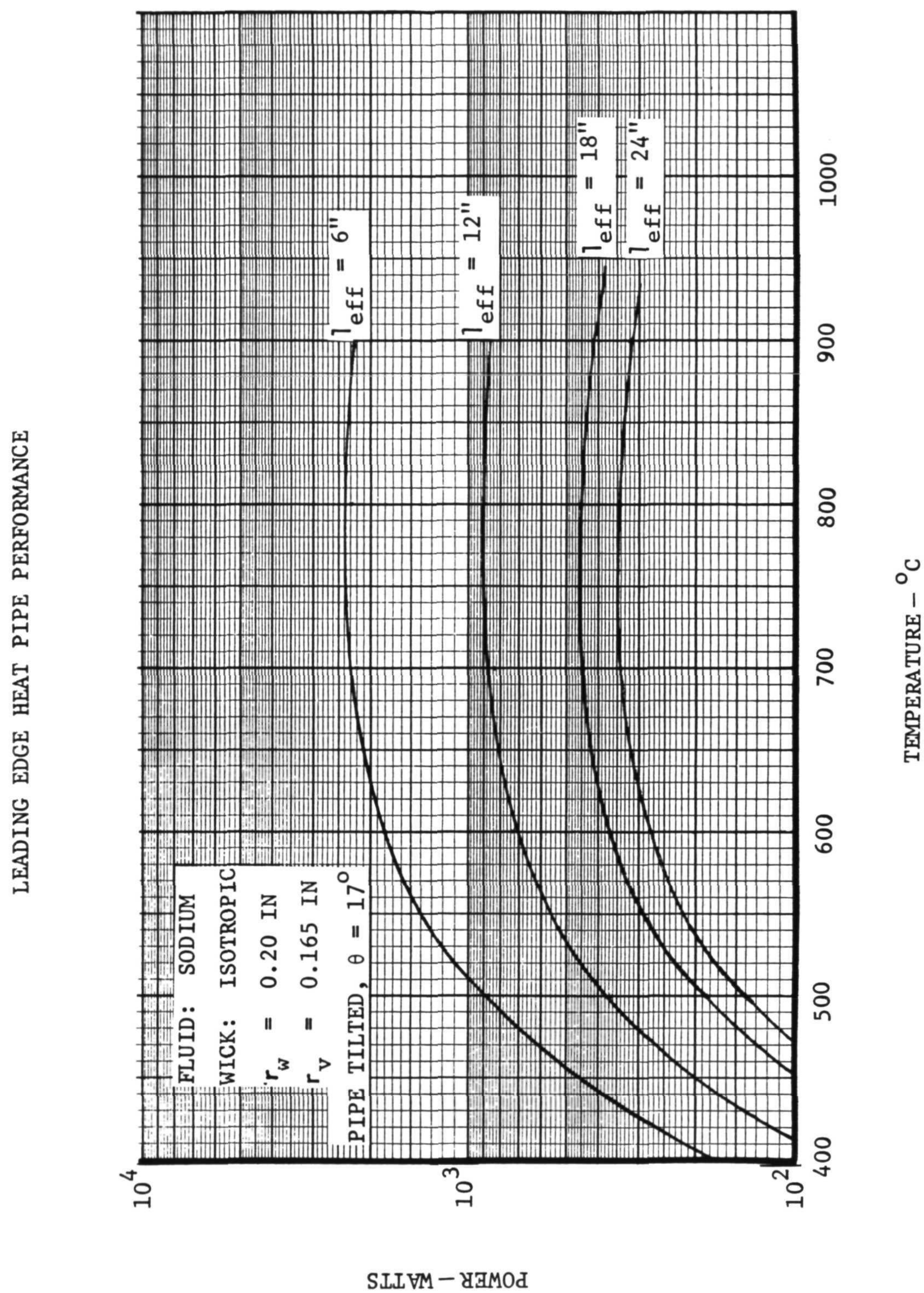

LEADING EDGE HEAT PIPE PERFORMANCE
FLUID: SODIUM
WICK: ISOTROPIC
r_w = 0.20 IN
r_v = 0.165 IN
PIPE TILTED, θ = 17°
l_{eff} = 6"
l_{eff} = 12"
l_{eff} = 18"
l_{eff} = 24"
10^4
10^3
10^2
POWER – WATTS
400
500
600
700
800
900
1000
TEMPERATURE – °C

Figure 7

Structural Tests - Two tests were performed. The first tests were to establish the strength of the tubing as a pressure vessel and to verify the end closure strength. A second test was conducted to determine the shear strength of the tube-to-skin braze joint as data on the specific alloys were not available.

Three end plug weld qualification pipes were constructed and tested. End plug external views are shown in Figure 8. The pipes were pressure tested and examined. The results indicated a very substantial strength margin. The operating internal pressure during testing will be about 4.14×10^5 N/m^2 (60 psia). The minimum burst pressure requirement at room temperature, accounting for temperature effects on the Hastelloy-X alloy strength, was established as 9.2×10^6 N/m^2 (1340 psia). The tubes were pressurized to 68.9×10^6 N/m^2 (10,000 psia) without failure and dimensional checks also indicated no yielding. The burst pressure is probably in excess of 138×10^6 N/m^2 (20,000 psia) at room temperature, a margin of safety of about 15 for internal pressure. Metallurgical evaluation subsequent to the pressure test showed high quality welds. Typical end plug-to-tube and end plug pinch-off closure welds are shown in Figure 9 (a and b respectively).

Three test specimens were prepared and tested to assess the shear strength of the Hastelloy-X and braze alloy combination. The specimens all failed in tension in the skin rather than in shear. A typical test specimen is shown in Figure 10. Skin segments were brazed to opposite sides of the tube to prevent bending loads and in this case one skin segment broke free. Two specimens failed at loads equivalent to shear stresses of 131×10^6 N/m^2 (19,000 psi) and one at 186×10^6 N/m^2 (27,000 psi). This was well in excess of expected shear stresses.

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END PLUG ASSEMBLIES

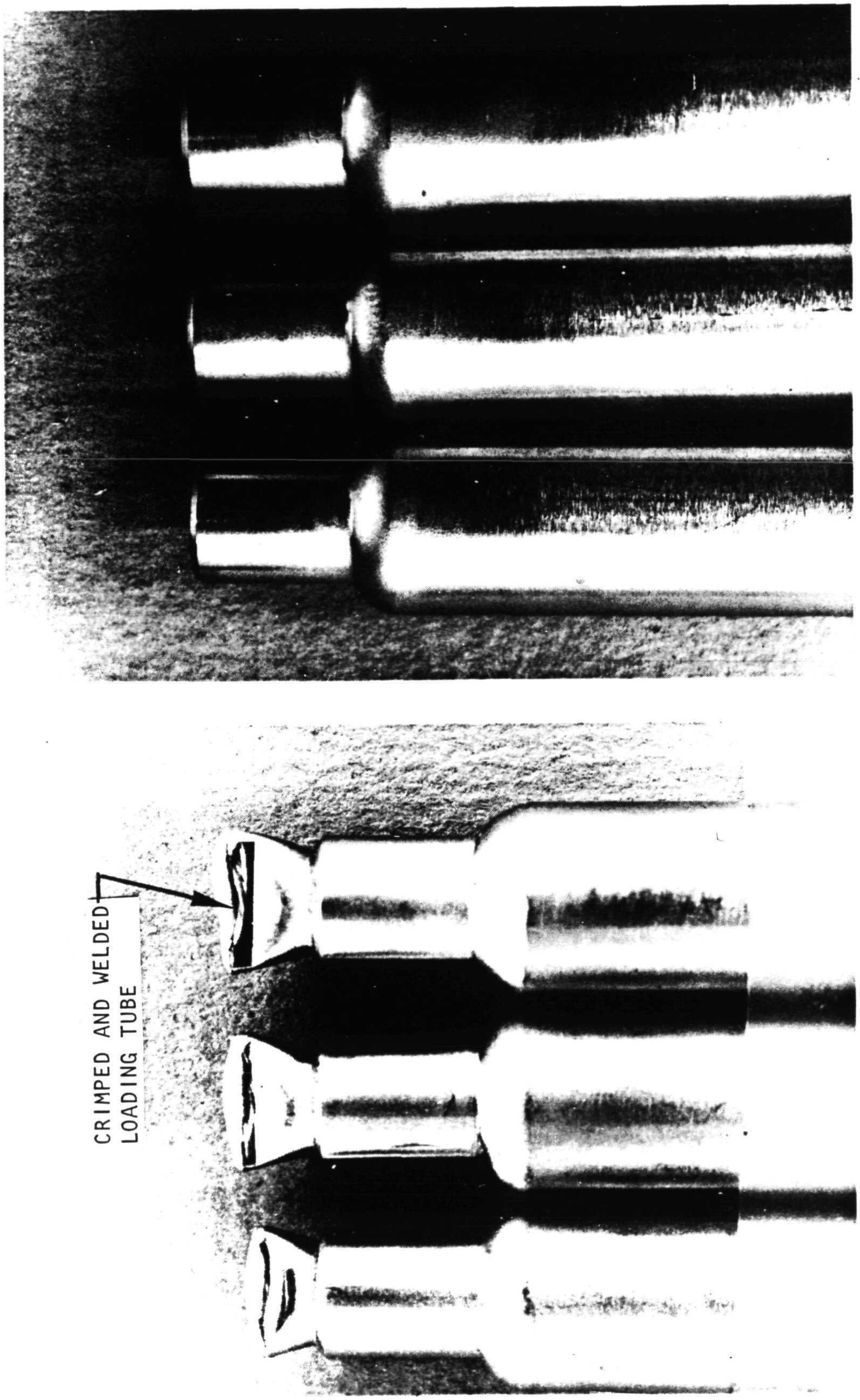

Figure 8

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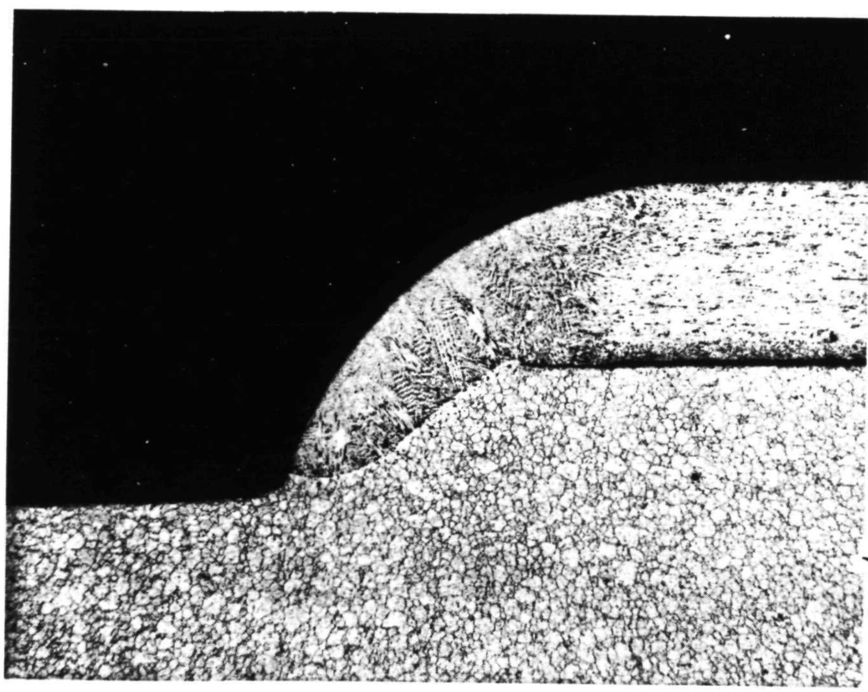
END PLUG WELDS

2a



2b

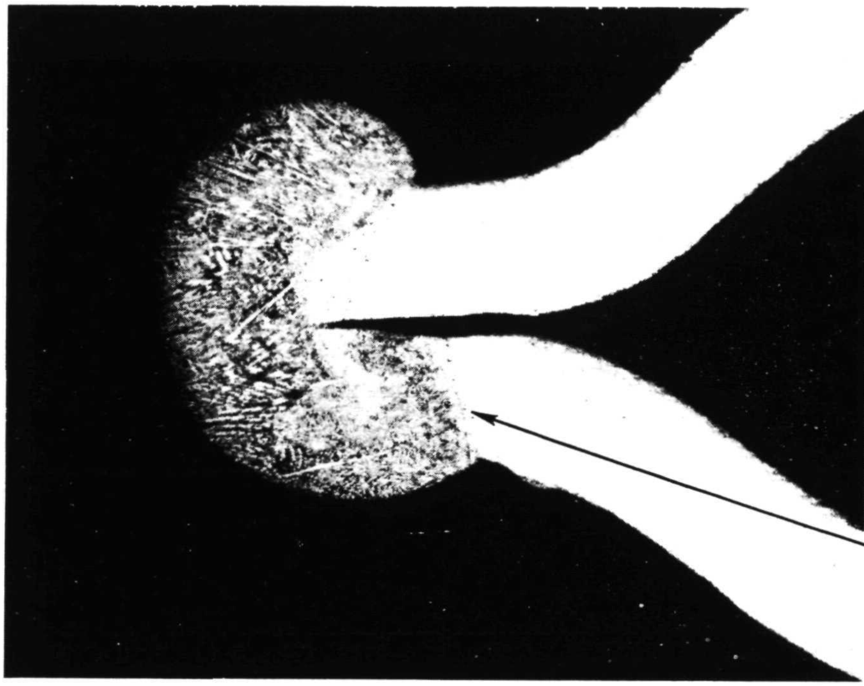


Figure 9

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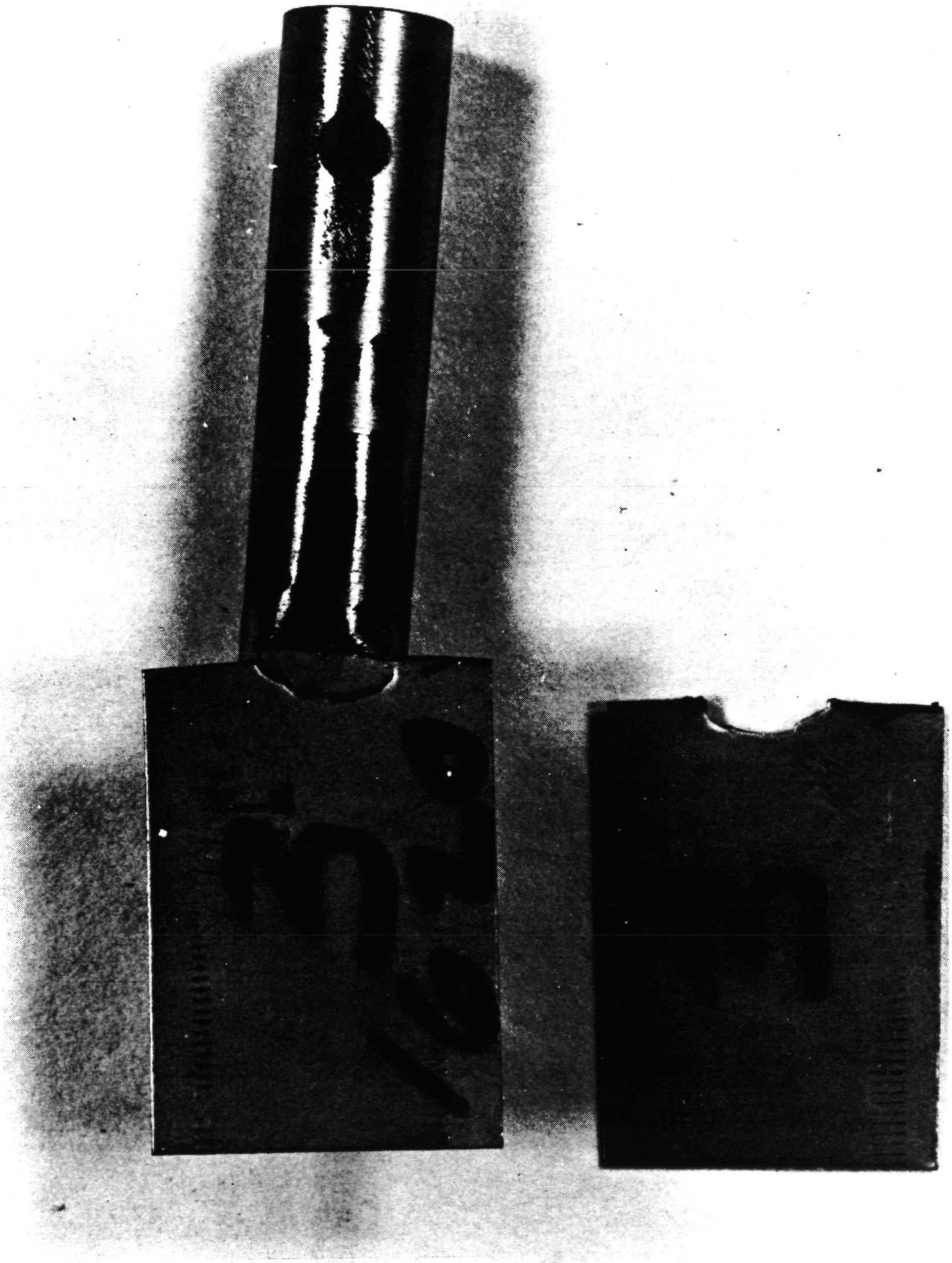


SHEAR STRENGTH SPECIMEN

Figure 10

3. LEADING EDGE MODULE DESIGN

3.1 Configuration - The configuration of the test module was established by the airfoil shape the test facility could accept and the necessity to minimize the cost of the test module. The facility planned for the testing was a hydrogen fueled hot gas tunnel at NASA-MSFC. This test facility had been designed for operation with a leading edge segment serving as the center body of a supersonic diffuser. The hot gas source was a rocket motor that used hydrogen and oxygen or air as the reactants.

The existing diffuser geometry, shown in Figure 11, had been established for a carbon-carbon leading edge. Consequently the calibration of the facility for that shape had been performed and both heating and pressure distributions were available. For this reason the heat pipe leading edge was designed with the same cross-section as the previously constructed carbon-carbon leading edge. To minimize program costs the width of the heat pipe cooled segment was reduced to 15.2-cm (6-in). This was the minimum width thought sufficient to demonstrate feasibility and could readily be accommodated with an adapter constructed with an available carbon-carbon segment.

The test facility imposed a severe transient environment because of its essentially instantaneous startup and, again to minimize costs, a very simple design was desired. The design which evolved within these constraints is illustrated in Figures 12 and 13. One test module consists of 12 conventional screen-wick heat pipes formed to the airfoil cross-section, with a thin skin covering the heat pipes. Each heat pipe was constructed of welded and drawn 1.27-cm (0.5-in) O.D. tubing having a wall thickness of 1.27 mm (0.050-in). The heat pipes utilized a composite screen wick with alternate layers of 100 and 200 mesh stainless steel. Stainless steel was found to be chemically compatible and so was selected because it was less expensive than Hastelloy-X screen. Sodium was selected as the working fluid based on performance and chemical compatibility studies. The heat pipes and skin were brazed to form an integral structure, with integral stiffening ribs at each end of the test module abbreviated span.

An interesting feature of the design was that it allowed assembly of the unit for brazing with operational heat pipes. Thus each heat pipe could be individually tested to verify acceptable performance prior to final assembly.

LEADING EDGE ENTRY TEST FACILITY

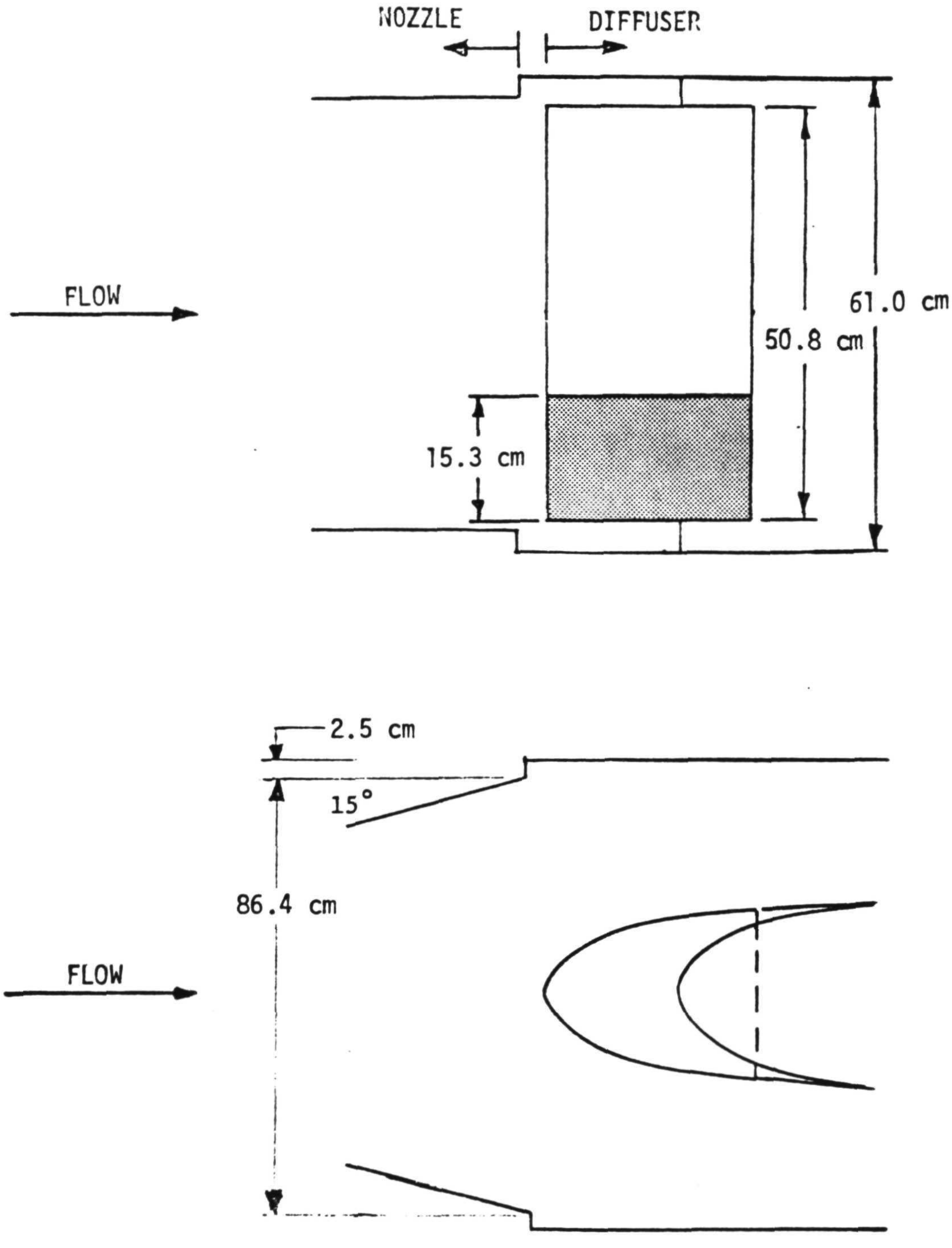
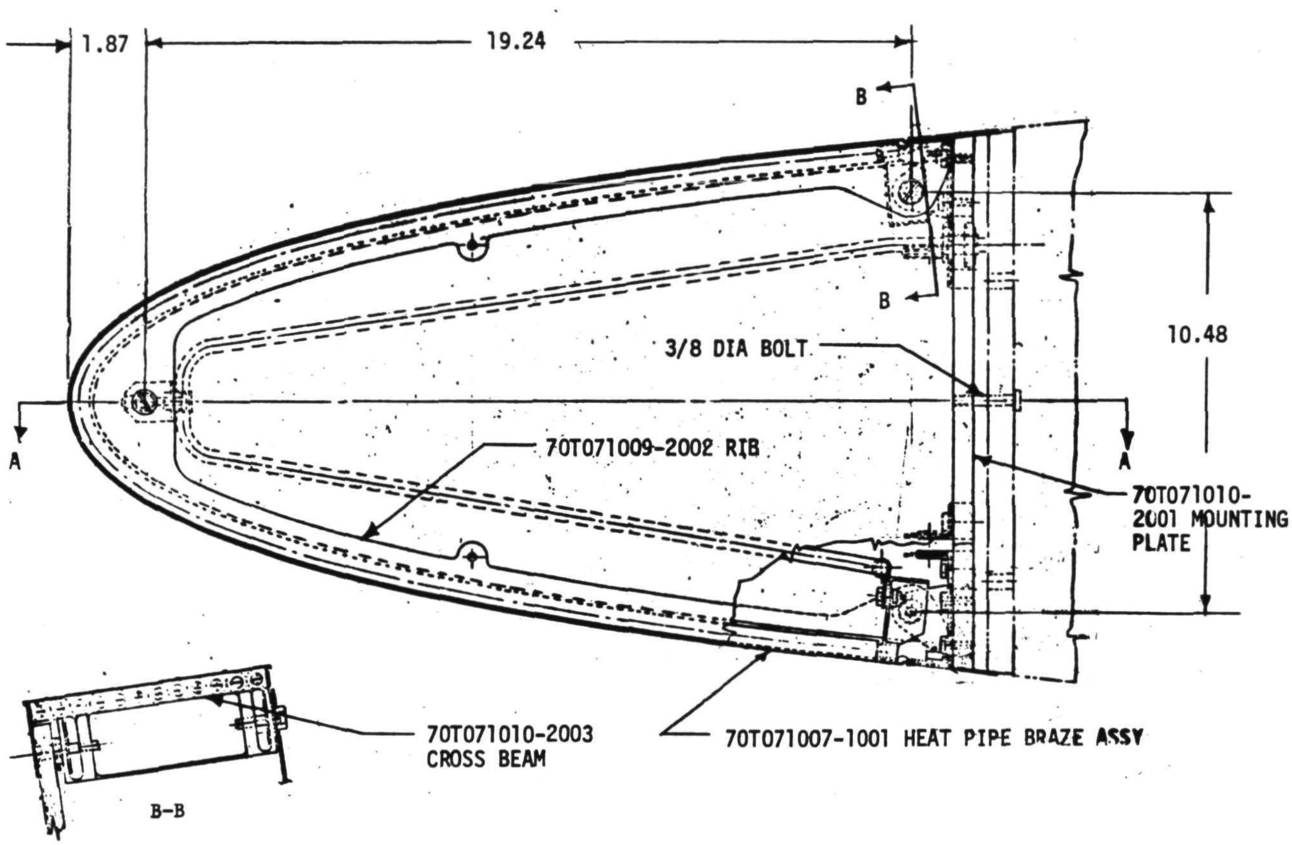


Figure 11

HEAT PIPE TEST ASSEMBLY



NOTE: DIMENSIONS IN INCHES

Figure 12

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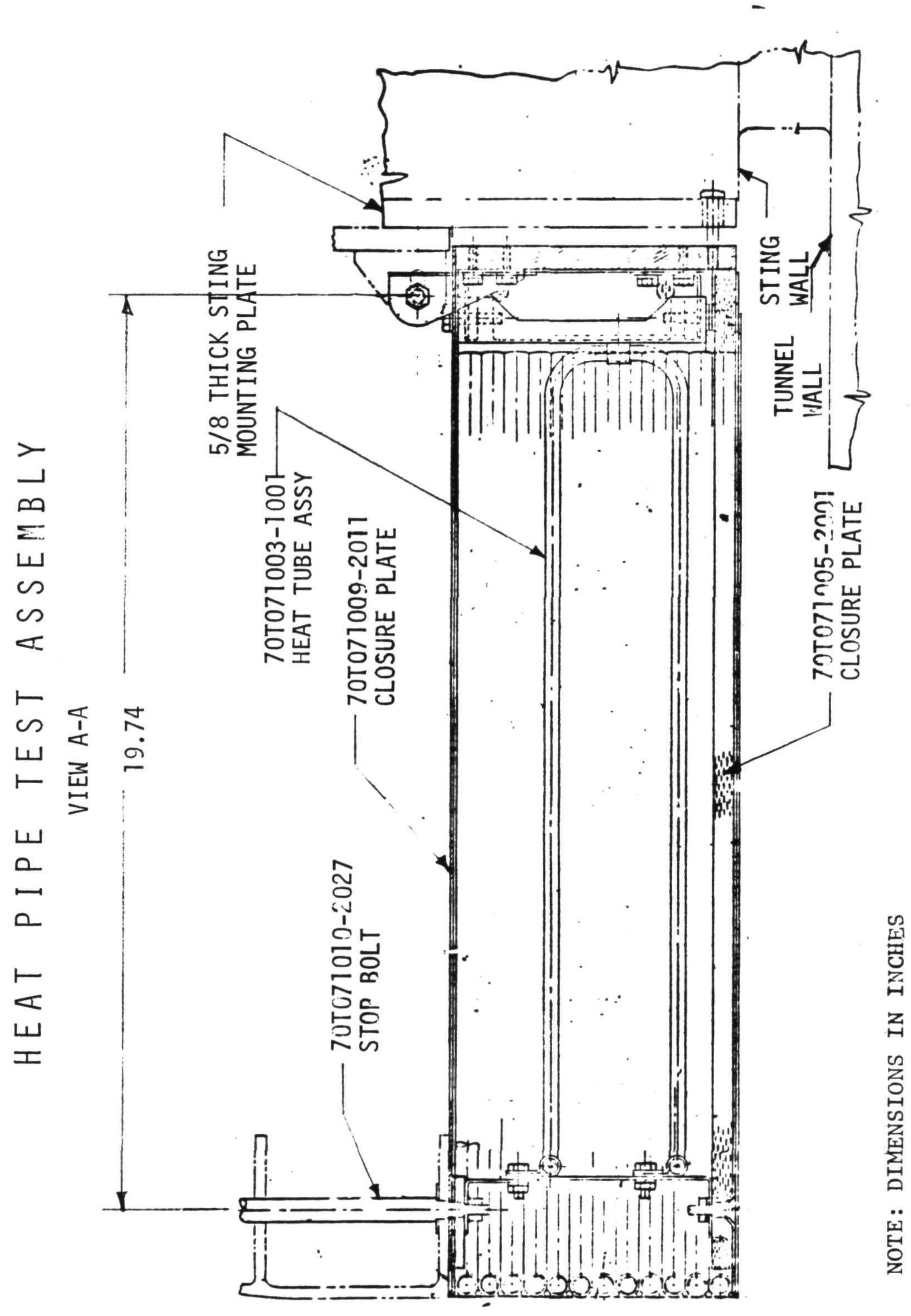


Figure 13

3.2 Thermal Analysis - An extensive analysis of the leading edge was performed to determine the transient response of the test segment to facility start-up and to explore the effects of higher than nominal heating rates. The transient response determined the thermal gradients for stress analysis and higher than nominal heating rates were analyzed to check a modification of the design deemed necessary for the heating rates anticipated in the MSFC facility.

The analytically computed temperature response is shown in Figure 14 and indicates that the system will reach steady state in about 10 minutes. The temperature gradient which induces stresses, peaks much earlier though, at about 4 seconds after heating is initiated. This is indicated by the temperature differences shown in Figure 15. The first 20 seconds are shown in expanded scale and as noted the peak occurs very early. Consequently the thermal stresses occur while the heat pipes are still relatively cool and are near maximum strength. At equilibrium, with the heat pipes operating, the temperature is higher but the gradient is much reduced. Note that during steady operation the heat pipe produces a reversal in the gradient about 15 cm (6 in.) back (measured along the surface) from the stagnation line. This is a necessary condition for the operation of the heat pipes since the heat removed from the stagnation region must be rejected in the aft portion of the heat pipes. In that region the heat pipes are hotter than the environment, thus the gradient is reversed. The effect is shown in Figure 16. The reversal is not apparent at the time of the peak gradient, however, because the entire leading edge has a net heat flux into it. The distribution of the maximum gradient is indicated by the temperature differences shown in Figure 17.

These gradients are based on the nominal peak heat flux given in the contract statement-of-work (SOW) heating profile. Discussion with MSFC personnel indicates that the facility may impose greater heating rates. This would exceed the design criteria for the heat pipe leading edge, but as shown in Figure 18 the test segment has a substantial overshoot capability. An over-temperature excursion does cause larger thermal gradients, however, as indicated in Figure 19, and consequently causes higher thermal stresses. Although the test module should withstand the maximum facility heat flux for a brief period the effect of combined stresses due to off-nominal heating was not determined. Therefore operation at heating rates substantially above the design values should be avoided.

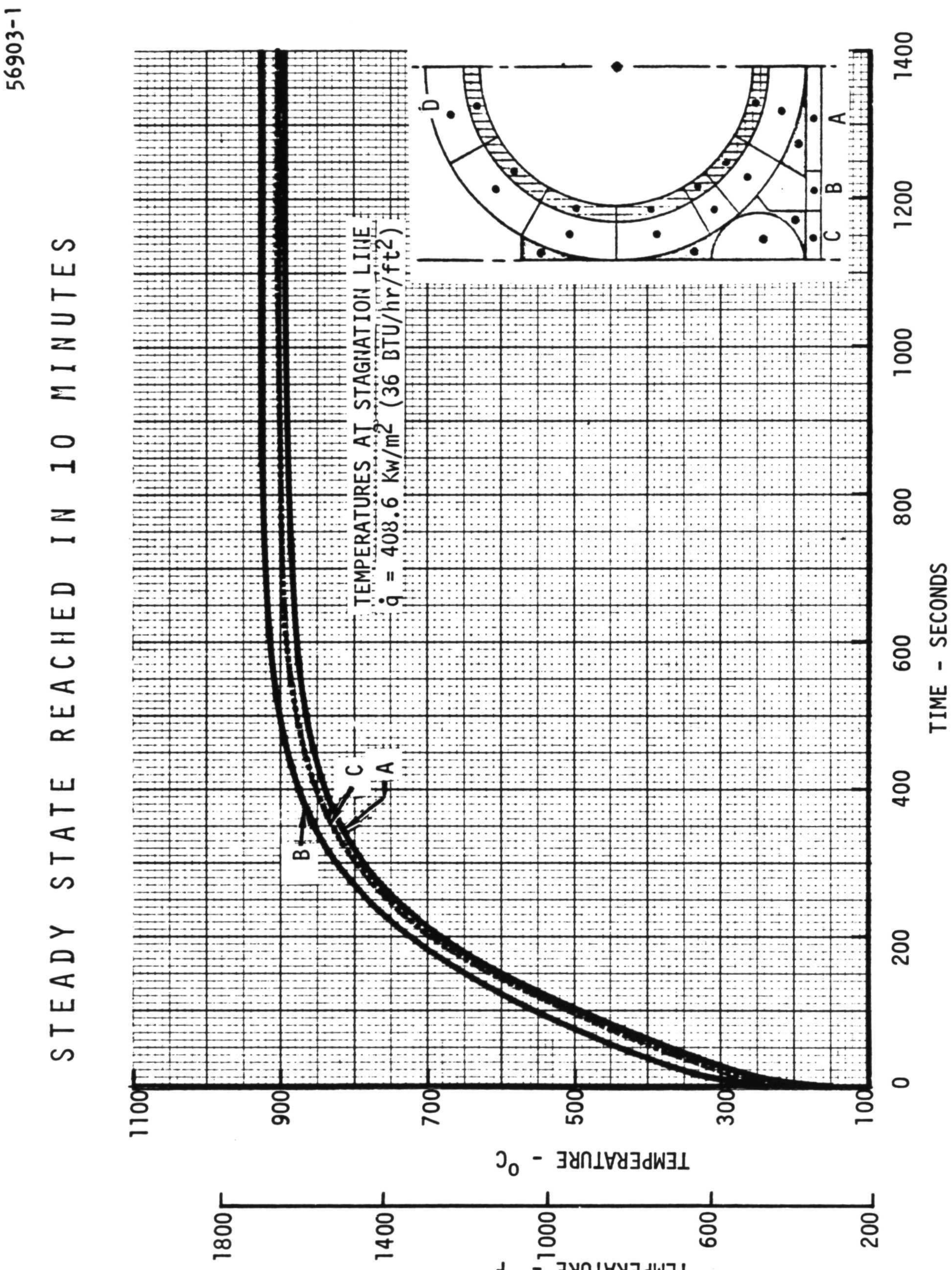

56903-1
STEADY STATE REACHED IN 10 MINUTES
TEMPERATURES AT STAGNATION LINE
$\dot{q}$ = 408.6 Kw/m² (36 BTU/hr/ft²)
A
B
C
D
TIME - SECONDS
0
200
400
600
800
1000
1200
1400
TEMPERATURE - °C
100
300
500
700
900
1100
TEMPERATURE - °F
200
600
1000
1400
1800

Figure 14

MAXIMUM GRADIENT OCCURS EARLY

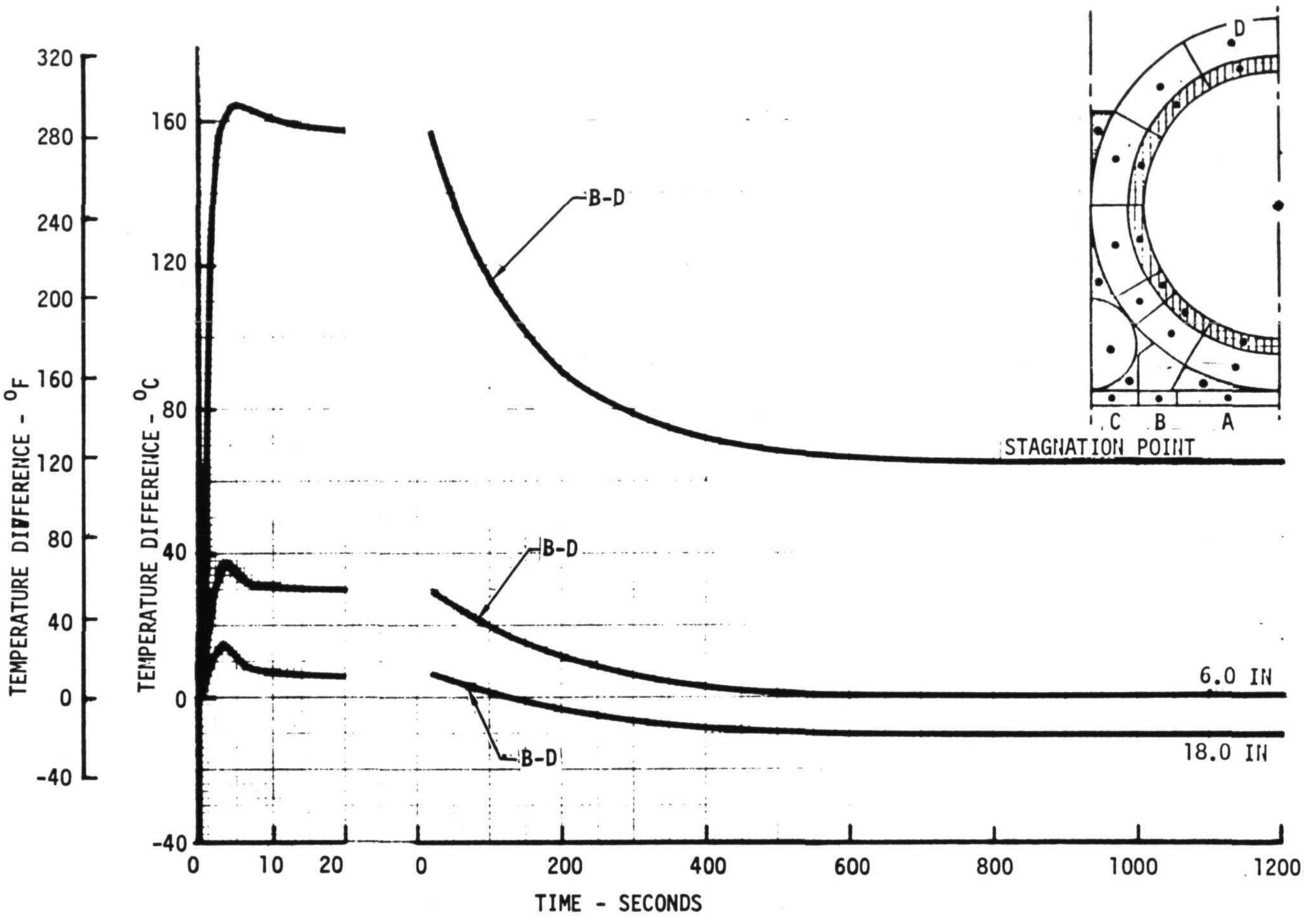


Figure 15

56903-5

HEAT PIPE REVERSES GRADIENT

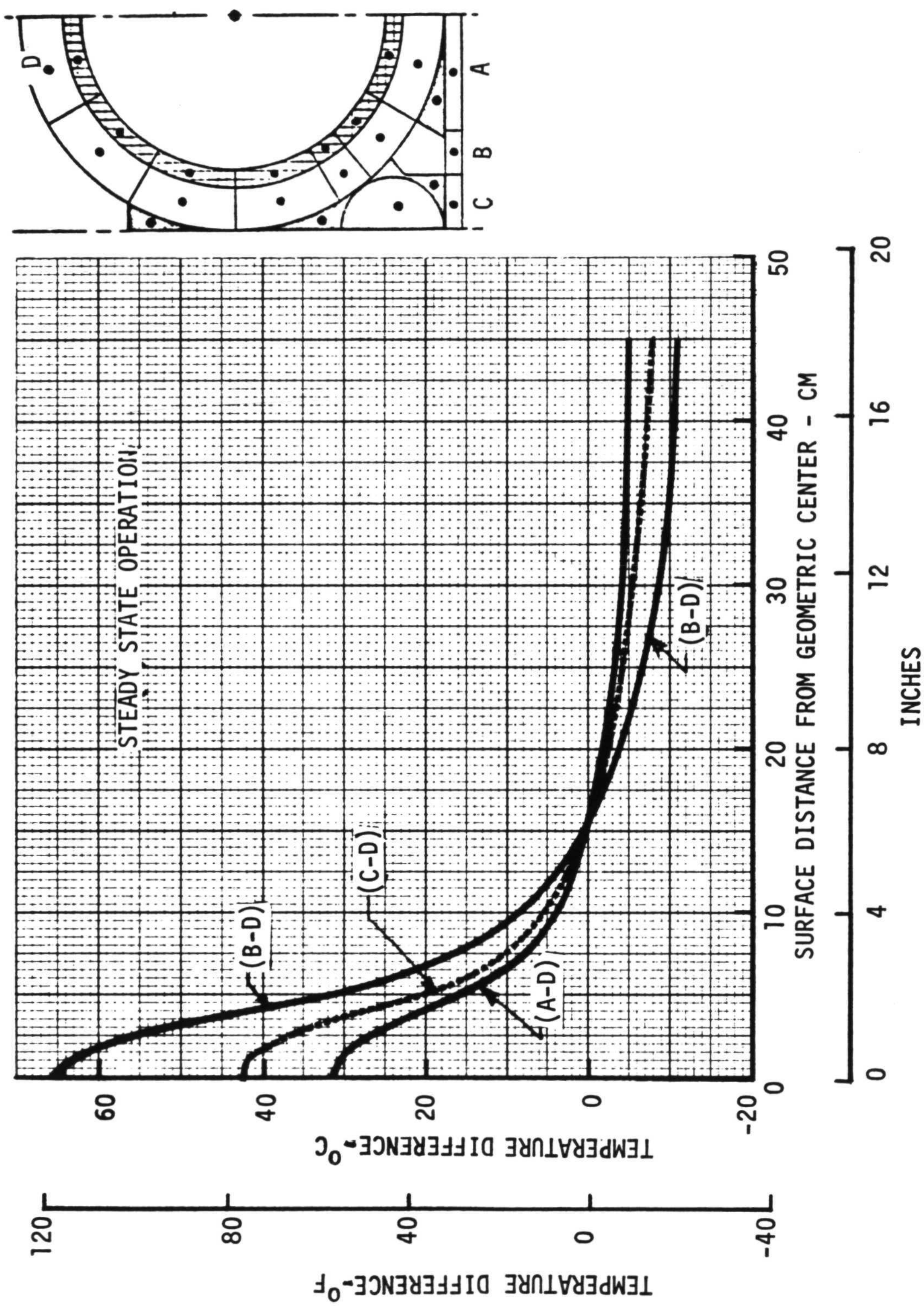


Figure 16

56903-7

MAXIMUM GRADIENT SIZES STRUCTURE

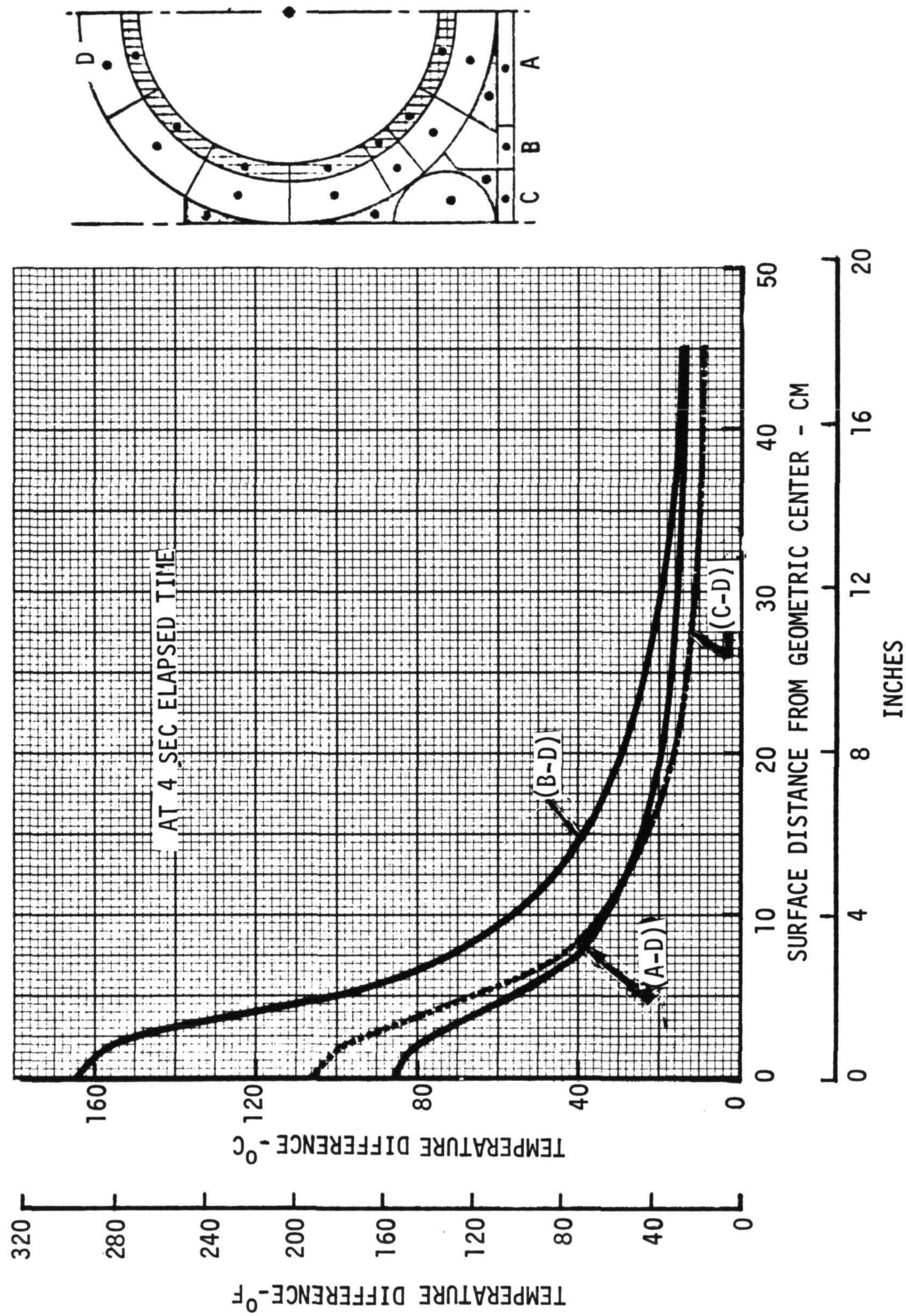


Figure 17

SUBSTANTIAL OVERHEAT MARGIN

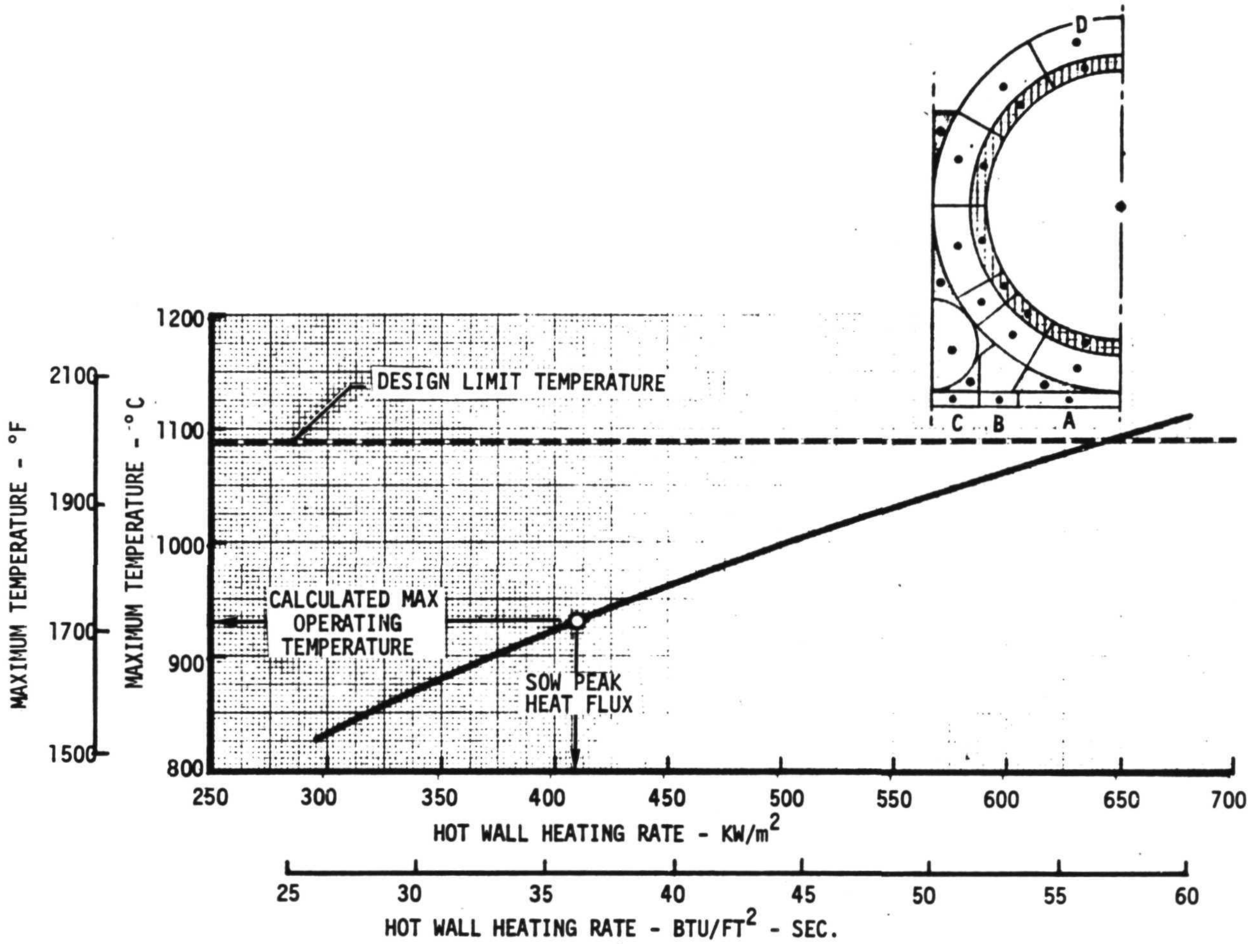


Figure 18

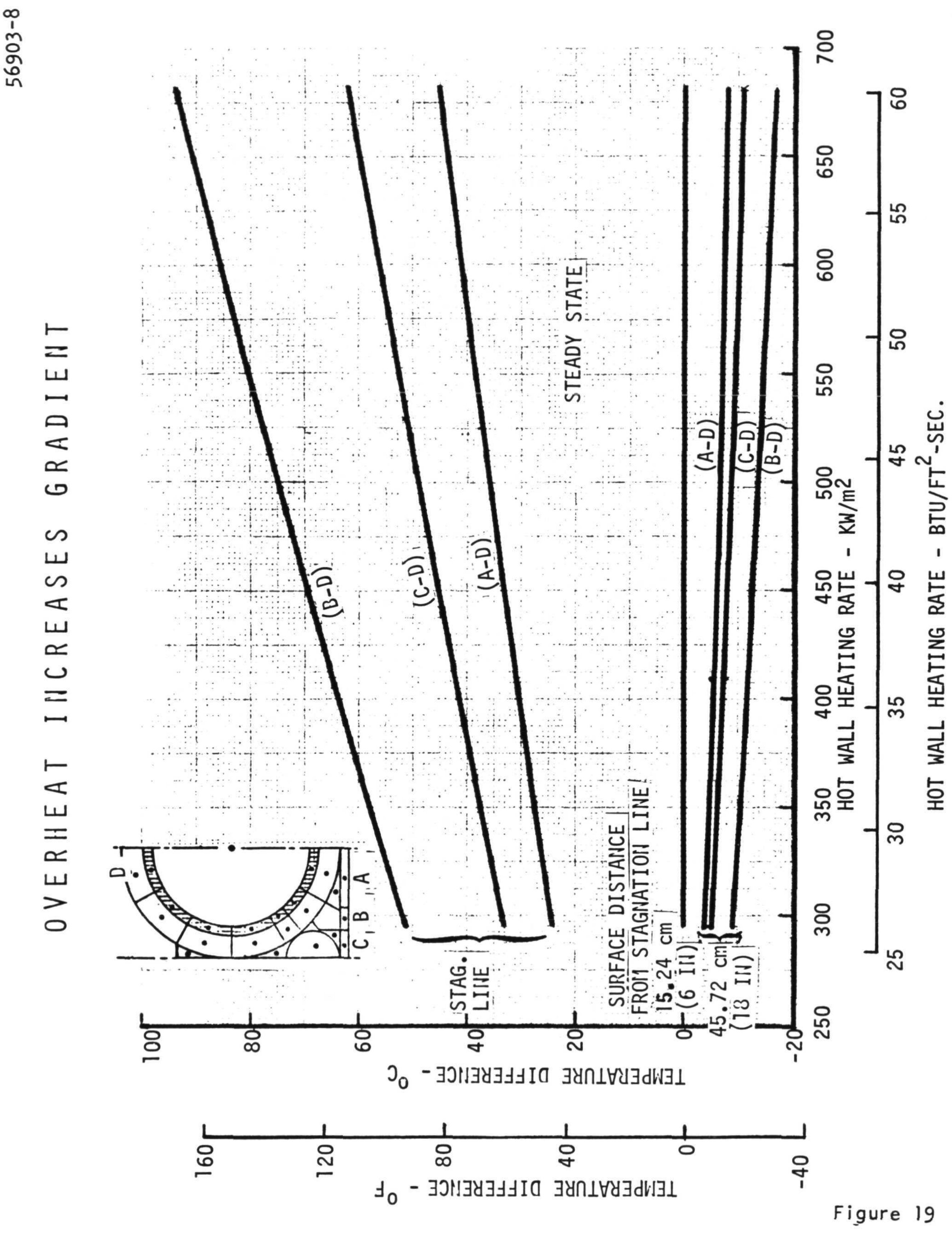

56903-8
OVERHEAT INCREASES GRADIENT
STEADY STATE
(B-D)
(C-D)
(A-D)
(A-D)
(C-D)
(B-D)
STAG. LINE
SURFACE DISTANCE FROM STAGNATION LINE
15.24 cm (6 IN)
45.72 cm (18 IN)
D
C
B
A
HOT WALL HEATING RATE - KW/m2
250
300
350
400
450
500
550
600
650
700
HOT WALL HEATING RATE - BTU/FT2-SEC.
25
30
35
40
45
50
55
60
TEMPERATURE DIFFERENCE - °C
100
80
60
40
20
0
-20
TEMPERATURE DIFFERENCE - °F
160
120
80
40
0
-40

Figure 19

During startup, the operation of the heat pipe must be assured because of the nearly instantaneous onset of heating in the MSFC facility. Unlike an atmospheric entry, in which the heating increases over a period of several hundred seconds, the facility reaches the peak heating rate in less than a second. This could cause a localized dryout of the wick unless the working fluid is liquid prior to startup. An electrical heater is provided to preheat the test segment and melt the working fluid. This heater was sized to provide a minimum initial temperature of 149°C (300°F) and will require input power capacity of approximately 2600 watts.

3.3 Structural Analysis - The heat pipe leading edge assembly is attached to the carbon/carbon facility adapter assembly with a 14.66-inch long step bolt located at the nose and slotted angle brackets and 3/8-inch diameter bolt, both located aft. The forward attachment provided close alignment of the leading edge surface in the stagnation region. The slotted brackets and 3/8-inch diameter bolt allow differential thermal expansion of the carbon-carbon adapter and the heat pipe assembly to the rear and laterally when heated. The carbon/carbon facility adapter is bolted directly to the tunnel centerbody mounted plate.

Strength Criteria, Design Temperatures and Pressures - The heat pipe leading edge assembly was designed to withstand the temperatures shown in Figures 14 through 18 and the pressures shown in Figure 20. The ultimate load was established as 1.4 times the limit load. The structure will stand limit loads at operating temperature without detrimental deflections and withstand ultimate loads at operating temperature without failure. Further, the structure will withstand, without failure, a fail-safe condition consisting of ultimate loads combined with temperatures resulting from one pipe inoperative.

Structural Analysis - A finite element computer model of the heat pipe leading edge was constructed using the STRUDL-II computer program. The model is shown schematically in Figure 21. Internal loads, reactions, and displacements were obtained for pressure and temperature conditions expected in the test facility. Two temperature environments were used in the analysis; those occurring at 4 and 1200 seconds from the start of testing. Four seconds after the onset of heating a maximum temperature gradient of 128.6°C/cm (588°F/in) was imposed on the heat pipe assembly with a surface temperature of 315°C (600°F). After about 1200 seconds, steady state was reached with a surface temperature of 930°C (1700°F). The temperature environments were combined with a pressure profile having a stagnation pressure of (2.5 psi) for a 10° angle of attack. The 10° angle of attack, used to account for any misalignment in the test facility, was a worst case assumed condition.

Figure 22 shows tube and facesheet bending moment versus distance along geometric centerline for the 600°F environment. A maximum moment of 11.08 $N\text{-}m/_m$ (98.1 in-lb) is shown near the nose, substantially less than the allowable moment. Figure 23 shows tube and facesheet bending moment for the steady state condition. The maximum bending moment for this condition is 1.66 $N\text{-}m/_m$

EXTERNAL PRESSURE IS MAXIMUM NEAR NOSE

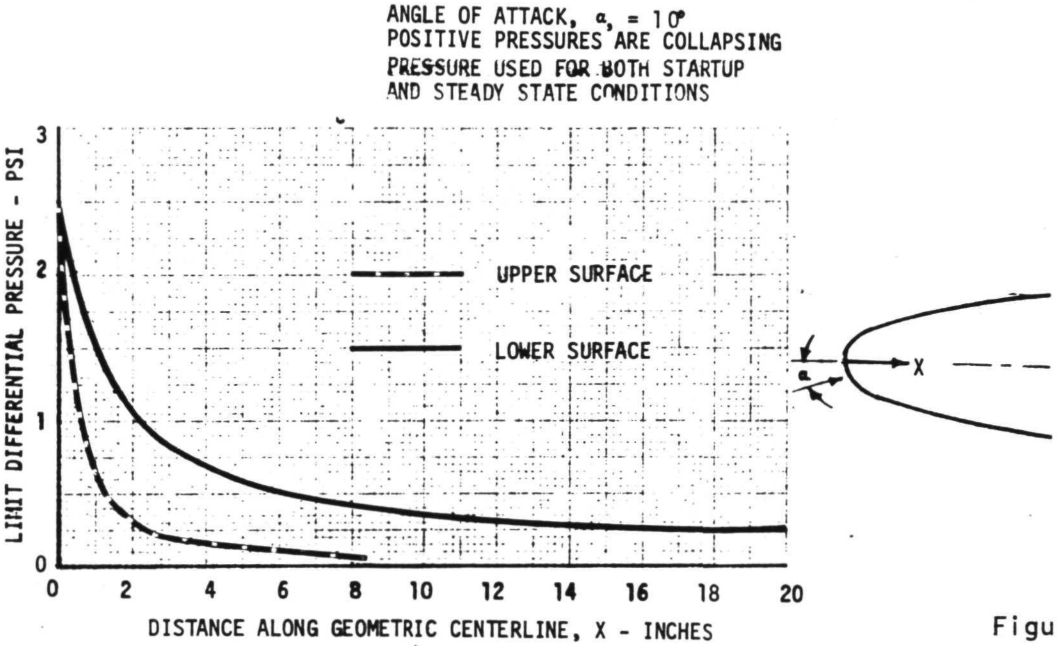


Figure 20

FINITE ELEMENT MODEL USES BAR ELEMENTS

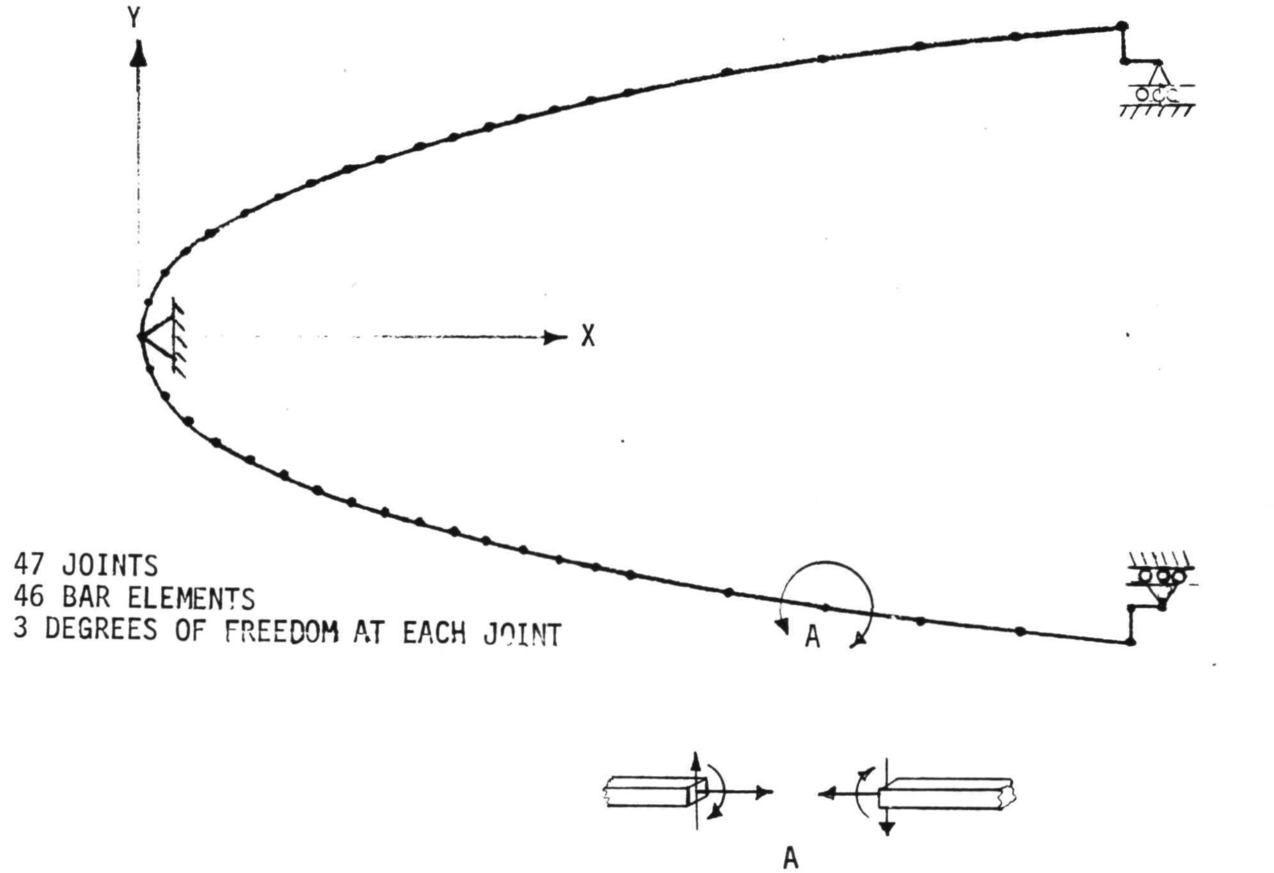
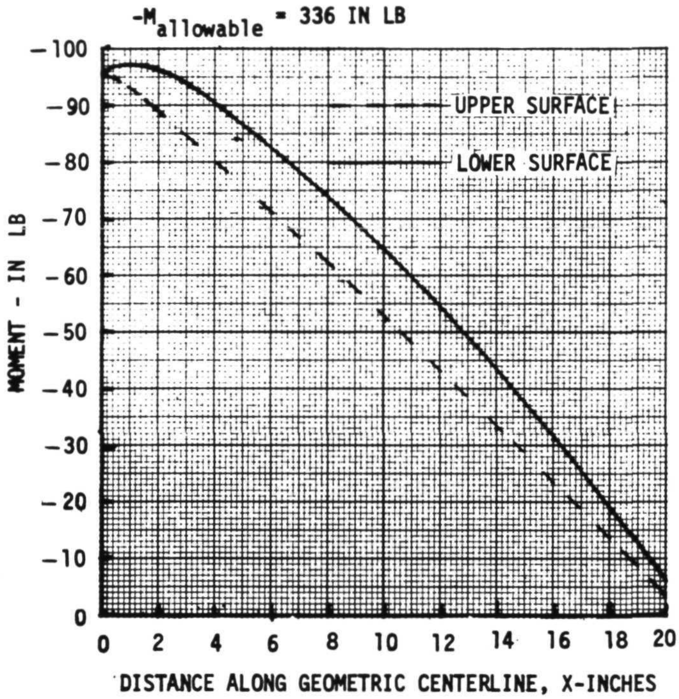
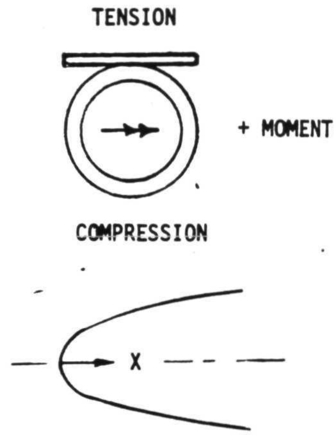


Figure 21

HEAT PIPE BENDING MOMENTS ARE MAXIMUM AT STARTUP





STAGNATION PRESSURE: 2.5 PSI

ANGLE OF ATTACK: 10^{o}

MAXIMUM TEMPERATURE: 6 00°F

LIMIT LOADS

TIME = 4 SECONDS AFTER STARTUP

Figure 22

56903-20

HEAT PIPE BENDING MOMENTS ARE LOW
FOR STEADY STATE CONDITION

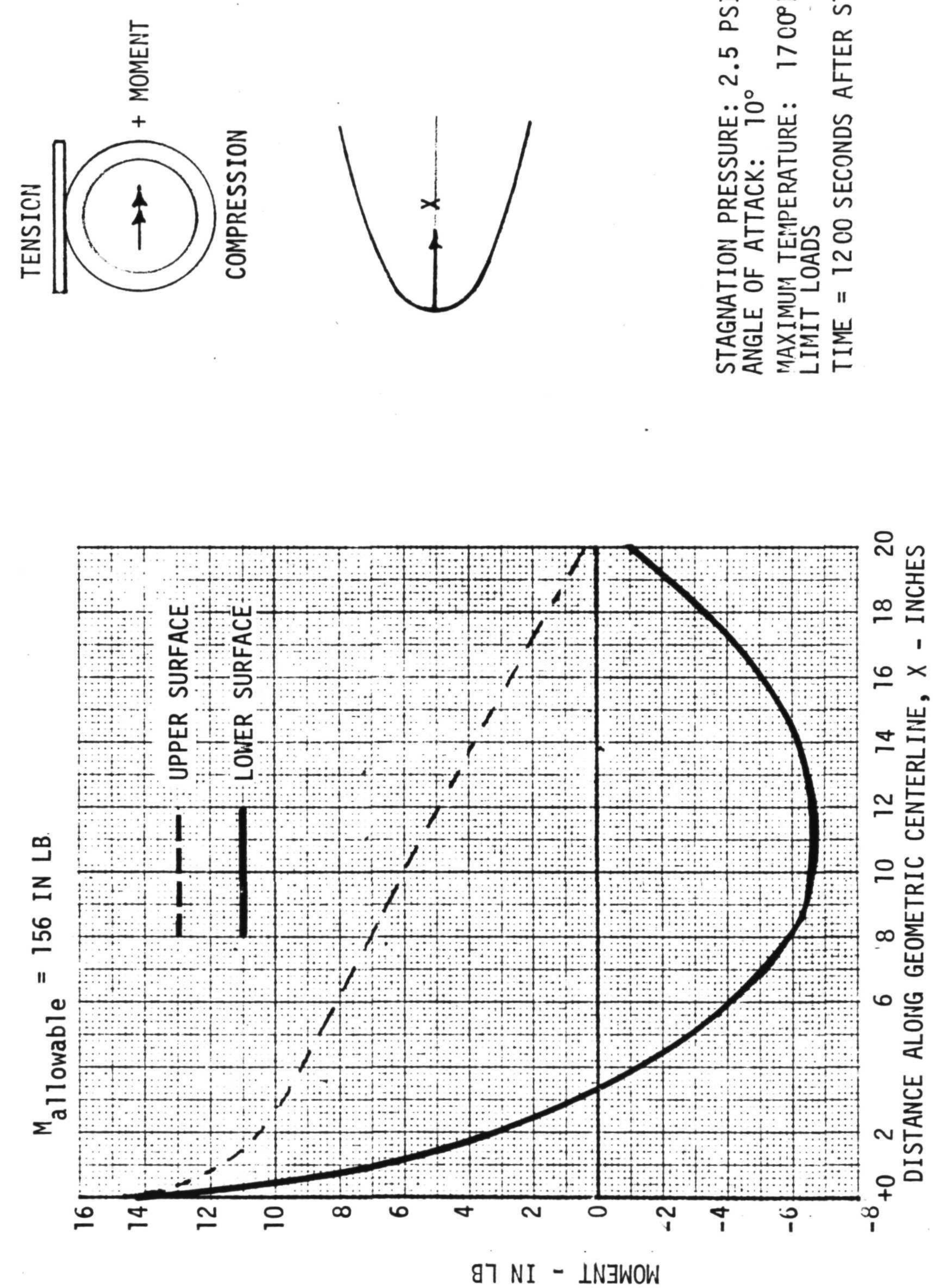


Figure 23

(14.7 in-lb/in) and occurs at the nose. These bending moments produce stresses in the tubes of 8.6×10^7 and 1.24×10^7 N/m^2 in steady operation. Allowable limit (yield) stresses for the corresponding temperatures are 2.96×10^8 and 13.8×10^8 N/m^2, respectively. (See Figure 24). Start up is the more critical design condition because the applied stresses are larger (relative to allowable stresses) than at the steady state condition with higher temperatures.

External load balances are shown in Figures 25 and 26. The figures show that loads are small for a structure of this size. Parts which makeup the heat pipe assembly were all analyzed using the internal loads and reactions obtained from the computer model. All parts have large positive margins of safety.

The large margins of safety result principally from consideration of material availability. The delivery time for Hastelloy-X tubing was at least 13 weeks. However, somewhat oversize tubing was available at MDAC-E and could be utilized for the program. This tubing, although of the correct diameter had a thicker wall than necessary. To avoid a long delay in receiving the material, the thicker wall tubing was utilized. These considerations led to a design with large margins of safety that was not a weight optimized design. The unit weight thus is greater than for a flight article because the environment is more severe (transient bending moment seven times steady state) but principally because program considerations dictated the use of available stock.

MECHANICAL PROPERTIES OF HASTELLOY-X

TEMP	F_{tu} KSI	F_{ty} KSI	α IN/IN/$^\circ$F X 10^{-6}	E KSI
600°F	103	43	7.75	26,000
1700°F	25	20	9.1	16,000

Figure 24

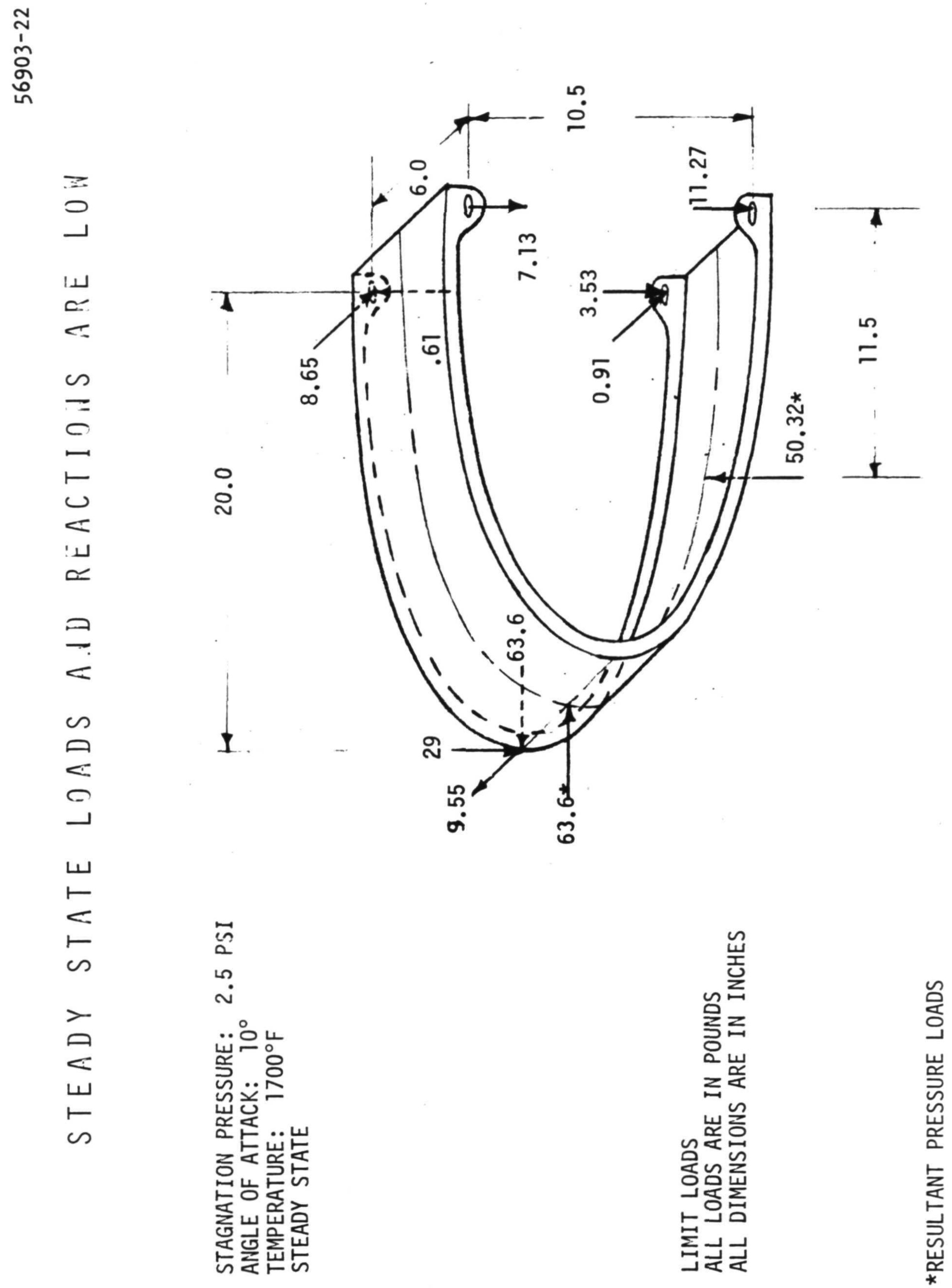
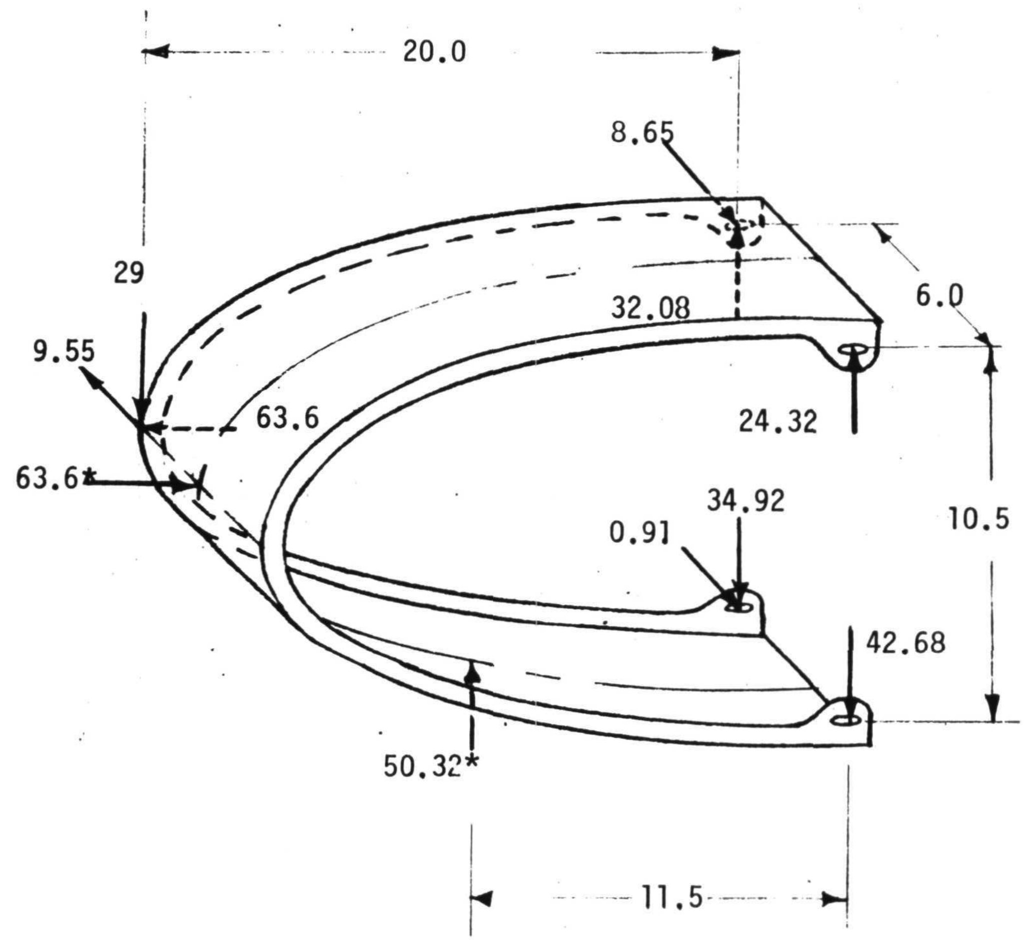

56903-22
STEADY STATE LOADS AND REACTIONS ARE LOW
STAGNATION PRESSURE: 2.5 PSI
ANGLE OF ATTACK: 10°
TEMPERATURE: 1700°F
STEADY STATE
10.5
6.0
11.27
7.13
3.53
8.65
.61
0.91
50.32*
11.5
20.0
63.6
29
9.55
63.6*
LIMIT LOADS
ALL LOADS ARE IN POUNDS
ALL DIMENSIONS ARE IN INCHES
*RESULTANT PRESSURE LOADS

Figure 25

56903-23

LOADS & REACTIONS AT STARTUP

STAGNATION PRESSURE: 2.5 PSI
ANGLE OF ATTACK: 10°
TEMPERATURE: 600°F



LIMIT LOADS
ALL LOADS ARE IN POUNDS
ALL DIMENSIONS ARE IN INCHES

*RESULTANT PRESSURE LOADS

Figure 26

Weight Analysis - An estimate of the test module weight was prepared prior to construction of the hardware. The methodology employed was identical with that used to predict the weight of flight version leading edges in contract NAS8-27708. A simple technique was used; that of accounting for the volume-density products of the component parts. The estimated weight breakdown is as follows:

Hastelloy-X Tubing	5.22 kg (11.5 lb)
Wick	0.56 kg (1.24 lb)
Sodium	0.27 kg (0.59 lb)
End Plugs	0.25 kg (0.54 lb)
Machined End Fittings	0.86 kg (1.89 lb)
Skin	0.73 kg (1.60 lb)
Edge Ribs	0.91 kg (2.00 lb)
Doublers	0.42 kg (0.93 lb)
Braze Alloy	1.22 kg (2.68 lb)
Nose Region Filler Wire	0.15 kg (0.32 lb)
Total Estimated Weight	10.57 kg (23.29 lb)

The actual total weight of about 10.16 kg (22.4 lb) was close to the analytically estimated weight. The close correspondence between estimated and actual weights for the test module lend credence to the previous for a flight-weight design.

4. LEADING EDGE MODULE CONSTRUCTION

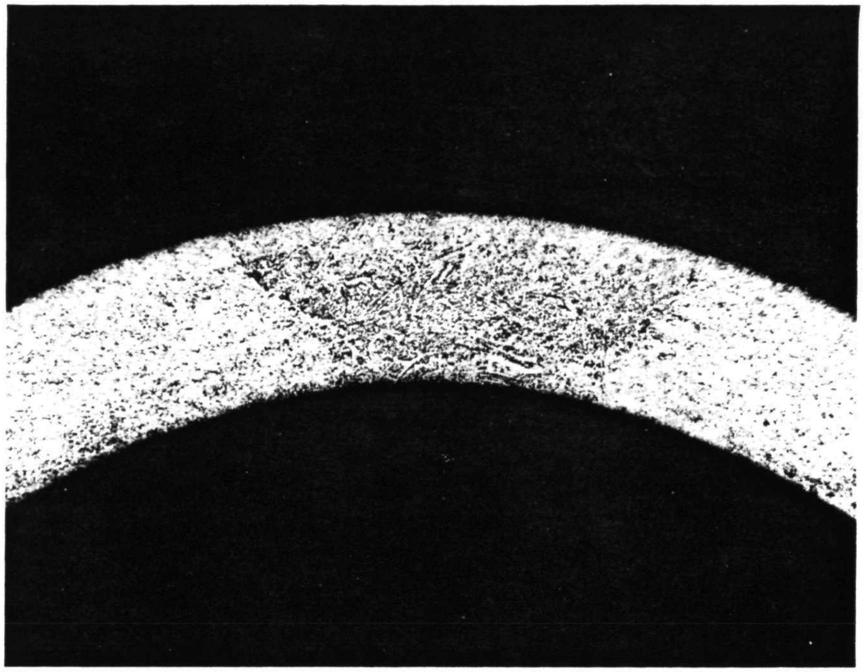
Hastelloy-X tubing with an outside diameter of 1.27-cm (0.500-in) and a wall thickness of 1.27-mm (0.050-in) conforming to AMS 5587 was purchased by MDAC-E, cut to 137-cm (54-in) lengths and shipped to DWDL. Upon receipt, representative sections were cut from four tubes, mounted, polished, etched, and metallographically examined for general quality. The welded area in the "weldrawn" tubing was checked closely because, in alkali metal service, these areas are sensitive to local attack if the welded micro-structure is not broken up during drawing and annealing operations. These examinations indicated that the welds were all of high quality and barely discernable in the tube structure. Examples are shown in Figure 27. The ASTM grain size of 7 indicates a fine grained structure suitable for liquid metal service. Micro-hardness traverses of the welded region showed no sigificant changes in hardness, indicating that the area has the same strength and ductility as the base metal.

The Hastelloy-X tubing was then swab cleaned with isopropyl alcohol followed by etching with a 20% HNO_3, 5% HF solution to remove any oxide film or scale on the interior of the tubing. After etching, the tubes were rinsed with distilled water and then isopropyl alcohol, followed by drying with bottled nitrogen. The tubes were immediately fitted with clean plastic "cap-lugs" to maintain internal cleanliness. Stainless steel screens were cut to proper length and width, ultrasonically cleaned in Freon and dried. The screens were vacuum annealed for 15 minutes at 1100°C to facilitate subsequent wick loading and forming operations. The vacuum annealing cycle also served to remove any entrapped particles and back reduce any oxide films on the screens.

The screens were then rolled on a mandrel on the screen rolling tool and inserted into the Hastelloy-X tubes, after which they were trimmed slightly shorter than the tube length and expanded against the tube wall. Spherical glass beads were added and tamped into place to support the wick and tube walls during subsequent forming. The tubes were then shipped to MDAC-E for forming to the airfoil shape.

Forming was done at the MDAC-E facility and checked for dimensional compliance The forming was done in a two-step process. First the small nose radius was bent in an automatic tube bender. The pre-bent tube then was

FINE GRAINED TUBE WELD MICROSTRUCTURE



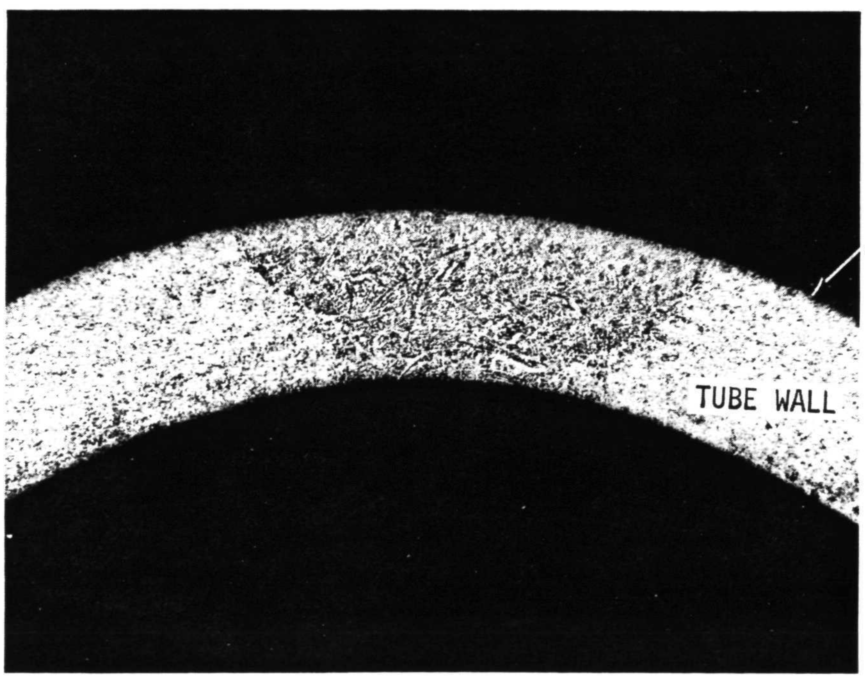


Figure 27

formed to the final shape over a Formica tool as shown in Figure 28. The tubes, in the pre-bent and finished form are shown in Figure 29.

The presence of glass beads during forming prevented crushing of the tube and held the wick in contact with the tube wall along the outer moldline. As expected the wick buckled locally on the inside of the bend in the small radius region as shown in the Figure 30 X-ray photograph. This was observed in development testing and is not critical to pipe operation since intimate contact of the wick with the tube is necessary only on the outside of the bend. The necessity for the glass beads, even in the regions with an effective large bend radius is shown in Figure 31. In this X-ray photograph of a tube finish formed with the glass beads removed after the nose radius had been formed it can be seen that the wick separated from the outer periphery of the tube, a condition which is unacceptable.

After forming, the glass bead filler was removed and the tubes were trimmed to length. The tubes were then shipped to Paulo Products Co. and vacuum annealed at 1080 $\pm$ 14°C for 15 minutes in a vacuum of 1×10^{-4} torr. The purpose of the vacuum annealing cycle was to thermally condition the heat pipe internal surface and to minimize distortion from residual stresses during the brazing cycles. The vacuum annealed tubes were then packaged and shipped with the end plugs to DWDL for welding and charging.

Concurrent with the forming operation the various machined and sheet metal parts were fabricated. These included the heat pipe end plugs, the support brackets, stiffening ribs, doublers and numerous other small sheet metal parts.

The end plugs were ultrasonically cleaned in Freon and then vacuum annealed at 1975°F $\pm$ 25°F for 15 minutes to thermally condition their internal surfaces and to anneal the fill tube. The fill tube is crushed closed prior to sealing by electron beam welding so it is imperative that the alloy be in the annealed state to prevent cracking during this critical operation.

The wick assembly was trimmed back at each end approximately 1-cm and the end plugs were fitted in place. The heat pipes were then loaded into a high purity (less than 10 ppm O_2 + H_2O) glove box and manually tungsten inert gas (TIG) welded. Internal contamination during welding was eliminated by the use of the glove box and the welds were of a high quality. After welding each heat pipe was tested to insure that it was helium leak tight to a sensitivity of 1×10^{-9} std cc/sec. The welds were subjected to -ray

FORMING TOOL AND TUBE

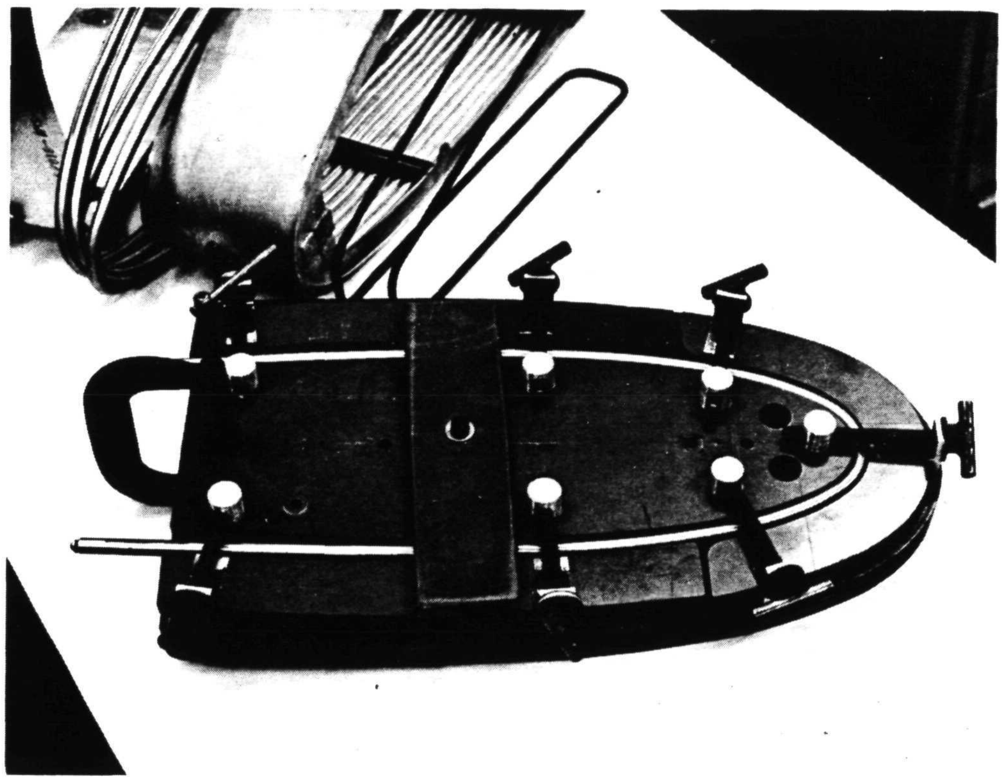
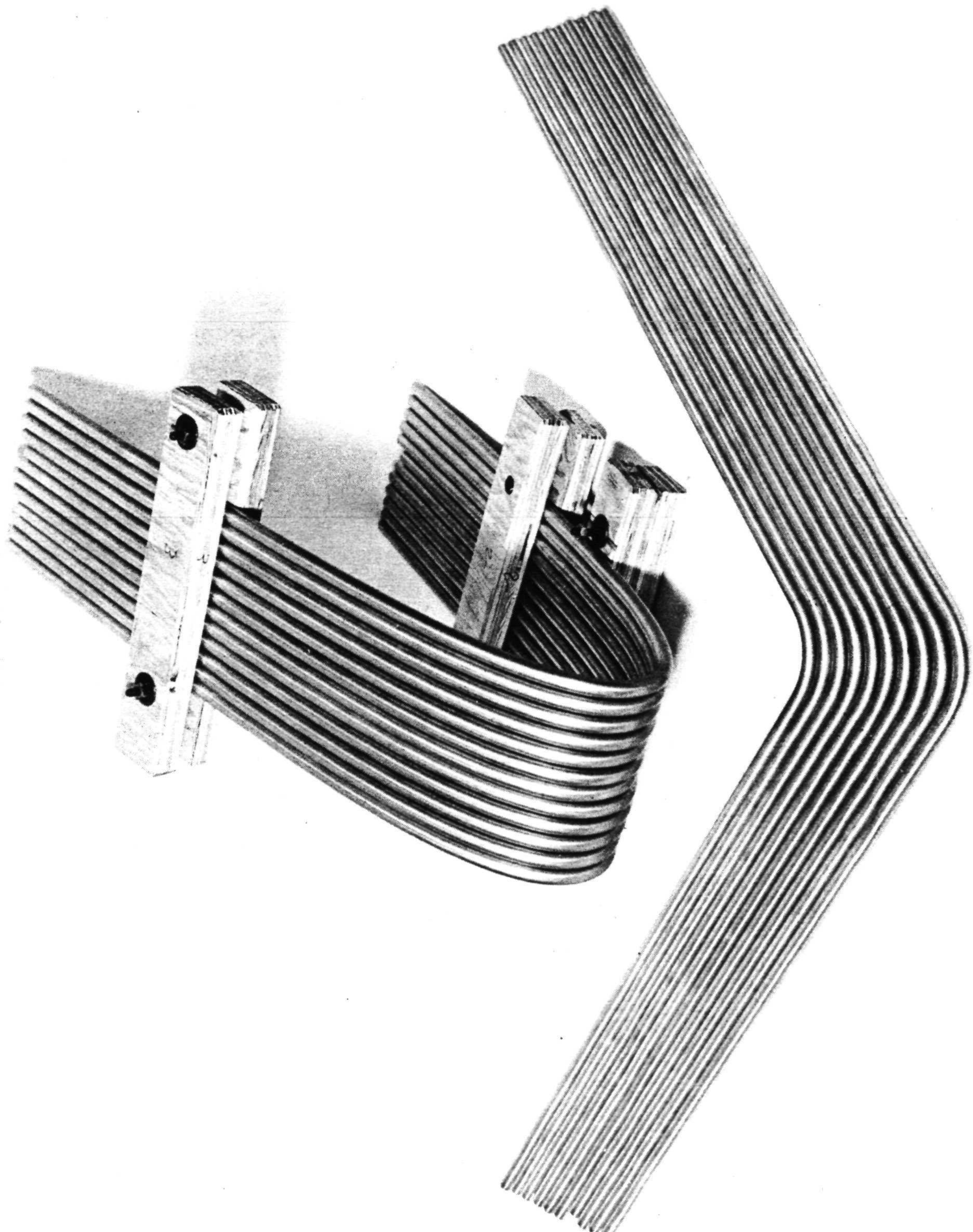


Figure 28

56903-31



TUBE FORMING SEQUENCE

Figure 29

WICK FORMING REQUIRES INTERNAL SUPPORT

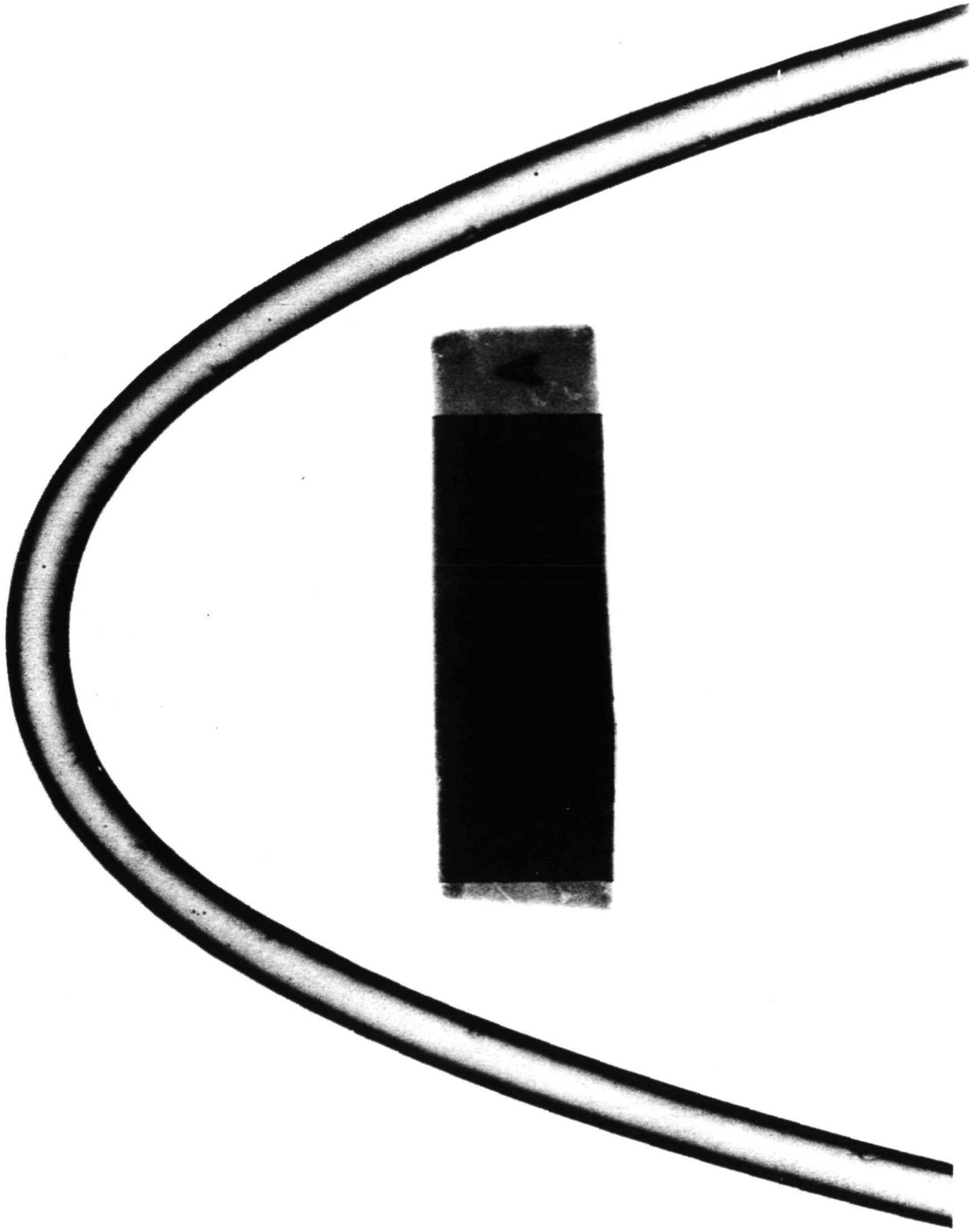


Figure 30

LACK OF INTERNAL SUPPORT ALLOWS
WICK/TUBE SEPARATION

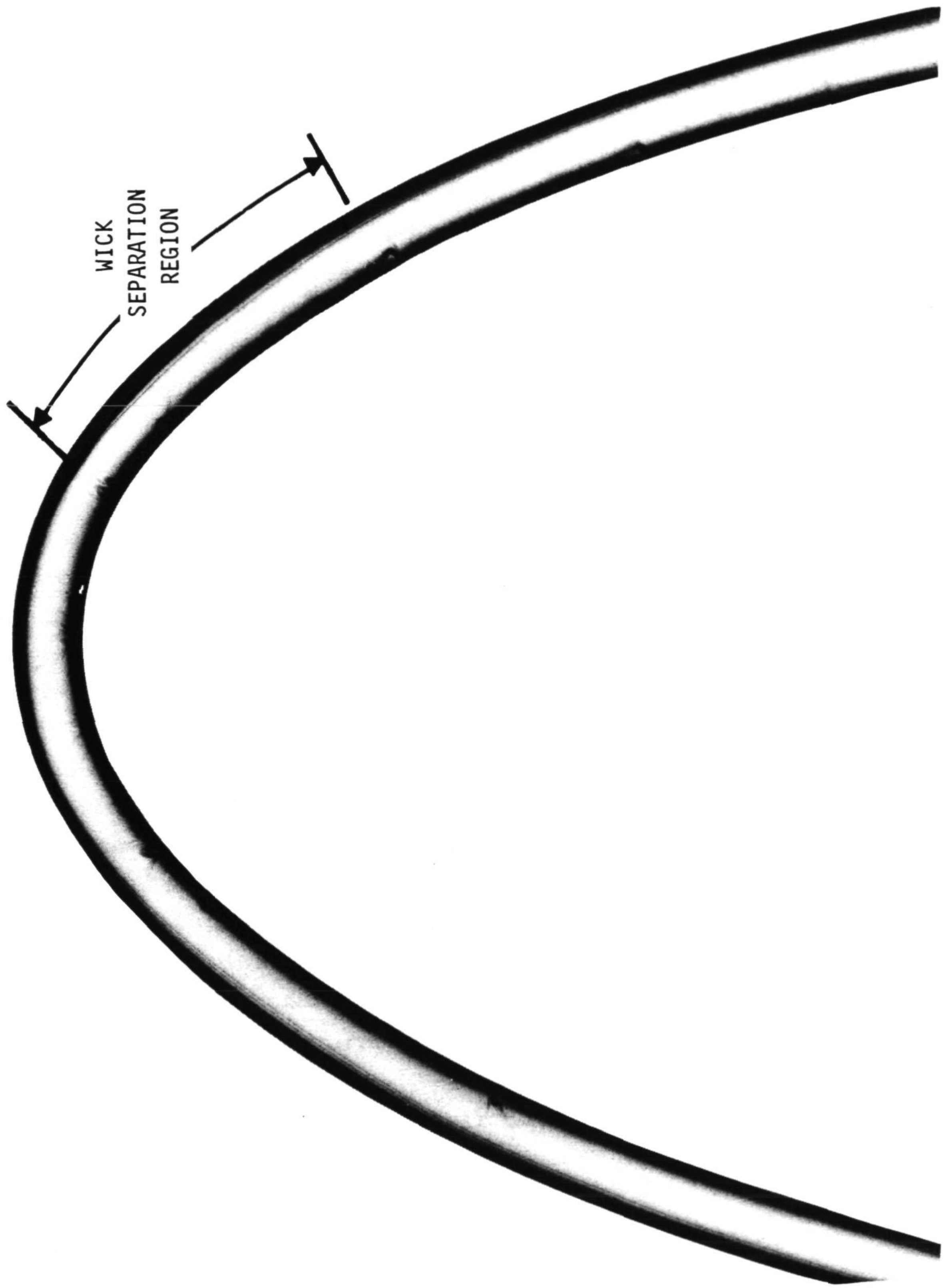


Figure 31

examination to insure that no subsurface defect greater than 0.5-mm diameter was present. This was followed by full length X-ray examination of the heat pipe to document the wick configuration after bending and to check the screen to I.D. gap in the critical nose section of the heat pipes. The gaps observed were 0.5-mm or less which is considered to be an excellent fit for heat pipe performance.

The heat pipes were then fitted with all metal connectors and attached to the sodium loading facility. The heat pipes were evacuated and the system was helium leak checked to insure that no air leakage was present during charging. The heat pipes were heated to approximately 260°C and maintained there during the charging sequence. The heating accomplished two purposes, adsorbed gasses were driven off during the evacuation cycle and the elevated temperature kept the sodium in the molten state during the injection cycle. Unless the heat pipe is kept above the melting point of sodium the liquid metal freezes in the valve seat or end plug, resulting in a deficient charge. The heat pipes and isolation valves were weighed before and after charging to document the charge weight. Figure 32 lists the charges of each heat pipe used in each of the two test segments. After loading and checking, the heat pipes were placed in an R.F. heating station and run in reflux mode to wet all of the inside surfaces. All inside surfaces must be completely wetted or "hot spots" can form which would cause premature "burn out" of the heat pipe during reentry simulation tests. The refluxing also serves to expell all non-condensible gas such as argon or helium adsorbed in the wick assembly during the welding operations. Once the heat pipe was isothermal and any gasses had been expelled, the heat pipe was cooled and removed from the charging station with the isolation valve in place. The fill tube was then flattened in a pair of hydraulically actuated dies followed by an electron beam cutoff/closure to seal the heat pipe. All end fitting weld closures were X-rayed to document weld quality and to check for subsurface defects such as bubbles caused by sodium vapor. The heat pipes were again reflux tested to insure that no gas leakage occurred during sealing operations. The completed and operationally tested heat pipes were then cleaned to remove outside surface oxide films, packaged and shipped to MDAC-E for integration and brazing.

The finished heat pipes were inserted in supporting cross beams and traced to determine the necessary edge rib shape. The rib forming tool was shaped to have the same profile as the heat pipes. The ribs were then formed in a 7000 ton press by punching the part into a polyurethane block.

SODIUM CHARGING SUMMARY

TEST SEGMENT NO. 1		TEST SEGMENT NO. 2	
HEAT PIPE S/N	SODIUM CHARGE IN GMS	HEAT PIPE S/N	SODIUM CHARGE IN GMS
1	23.9	3	24.7
2	24.1	4	24.7
5	22.5	6	22.6
8	21.1	7	20.9
9	22.6	10	20.9
11	22.0	15	21.8
12	22.0	17	17.3
13	20.8	18	22.5
14	23.1	19	21.2
16	19.0	20	24.8
21	19.8	23	23.6
22	24.5	24	21.1

Figure 32

The cross beams were in turn mounted on a Hastelloy-X plate to establish the leading edge rear dimensions. The tubes were then carefully aligned so that the 12 adjacent heat pipes formed a flat planar array in the shape of the leading edge. Tungsten inert gas tack welds were then made between the end plugs and cross beams to fix the heat pipe positions. The stiffening edge ribs were then added. Tie bars were welded to the edge ribs to hold the heat pipes together over their entire length. Gaps between adjacent heat pipes were checked with feeler gages to insure that the joint clearance did not exceed 0.1-mm. In the first assembly, all joints between heat pipes were 0.01-mm in. or less. In the second assembly, a few areas in the nose section exceeded the tolerance and stainless steel shim stock was added to these areas to provide the correct joint clearance. Nickel 200 filler wires 3.2-mm in diameter were then shaped to the nose contour of the leading edge section. Two sheathed chromel-alumel thermocouples were fitted in place to monitor the nose centerline temperature and the stagnation area temperature. A slurry of AMI 914 brazing alloy was then applied to both sides of the heat pipes along their full length (Figure 33) and to specified areas of the edge ribs and cross beams. A 0.1-mm thick tape of AMI 914 alloy was attached to the inside surface of the Hastelloy-X cover skin to insure an adequate supply of braze alloy to the critical tube-to-skin interface. The cover skin was then stretched over the heat pipes with the brazing fixture as shown in Figure 34 to insure full length intimate contact between the heat pipes and cover skin. After the skin was pulled taut, it was spot welded to the rib flange (Figure 35) to complete the braze assembly.

The assembled test segment was shipped to Paulo Products, Inc. of St. Louis and placed in a vacuum brazing furnace. The test assembly was positioned so that the heat pipes were roughly horizontal with the nose area lowered approximately 2.5-cm (1-in). This position assured an adequate supply of braze alloy and insured wetting and refluxing of the heat pipes in the critical nose area. The first test segment was brazed at 1048°C for 30 minutes followed by a 3 hour diffusion treatment at 1079°C to raise the braze alloy remelt temperature. Similar diffusion treatments have been used with AMI 914 for continuous service at 1260°C in jet engine applications.

BRAZE SUBASSEMBLY

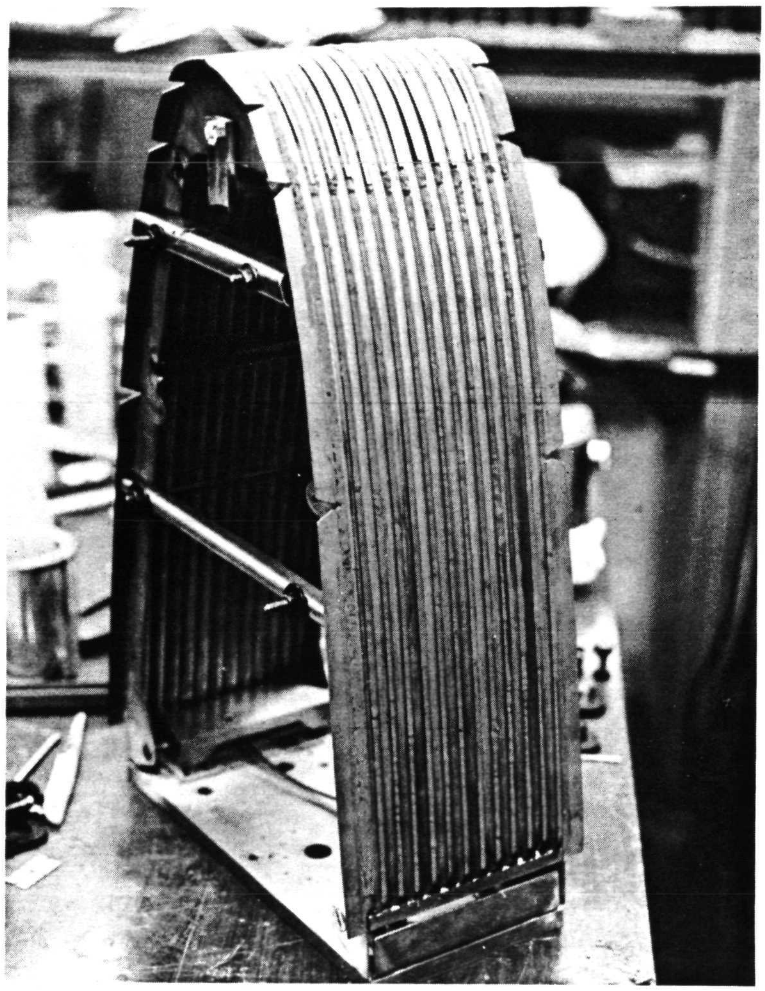


Figure 33

FINAL BRAZE ASSEMBLY

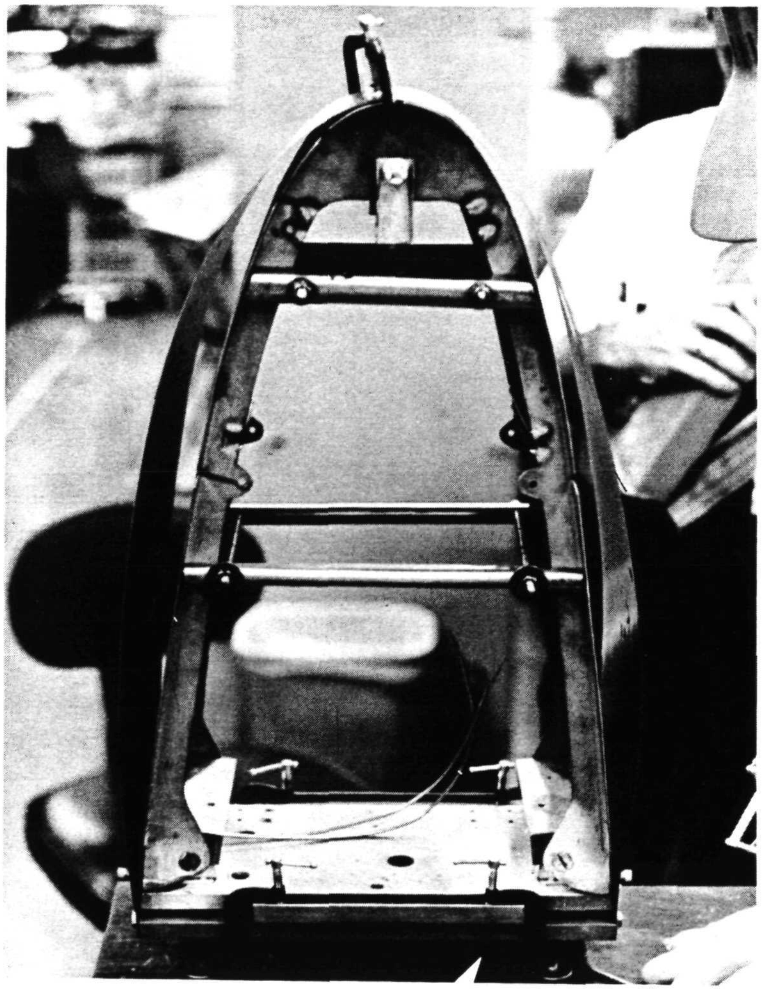


Figure 34

SPOT-WELDED LEADING EDGE BRAZE ASSEMBLY

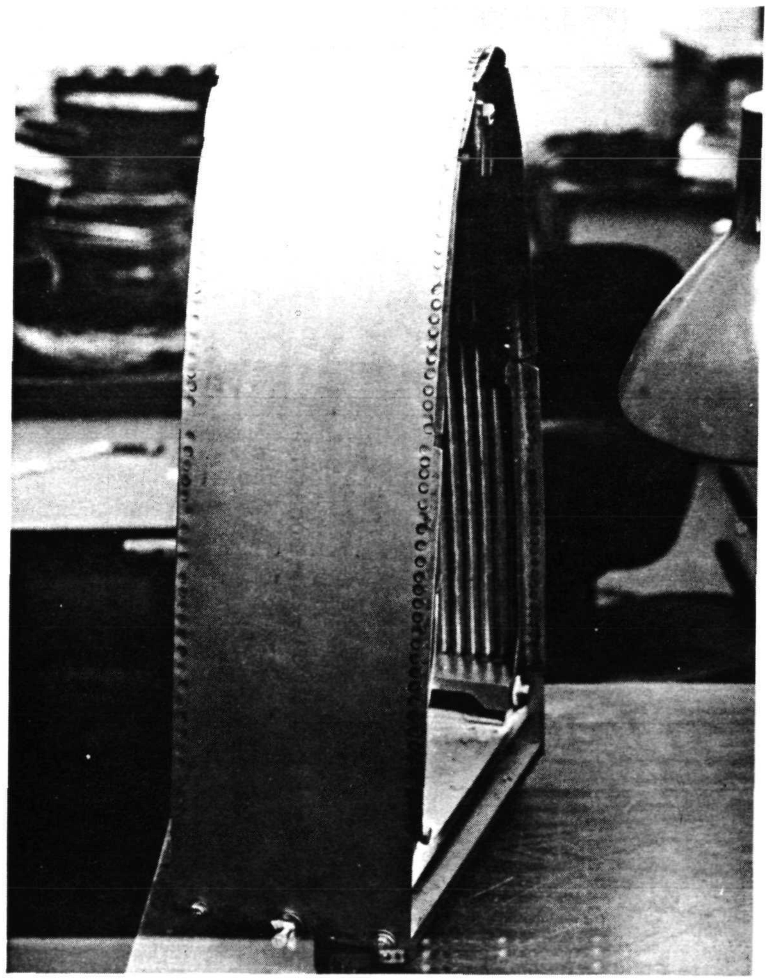


Figure 35

The first module was very well brazed but some of the braze alloy drained out of the nose section leaving a few isolated voids as evidenced by x-ray examination. To minimize alloy drainage and to thicken the fillets, the second test segment was brazed at 1037°C for 30 minutes and followed by a 3 hour 1024°C diffusion treatment. Alloy drainage was eliminated in the second sefment and the braze fillets were somewhat larger. During the heating cycle, both test segments were checked through a view port and the heat pipes appeared to be isothermal and operating properly.

The first unit brazed is shown in Figure 36 mounted to the carbon-carbon facility adapter. The second unit,which was being assembled for brazing, appears in the background.

ASSEMBLY OF TEST MODEL

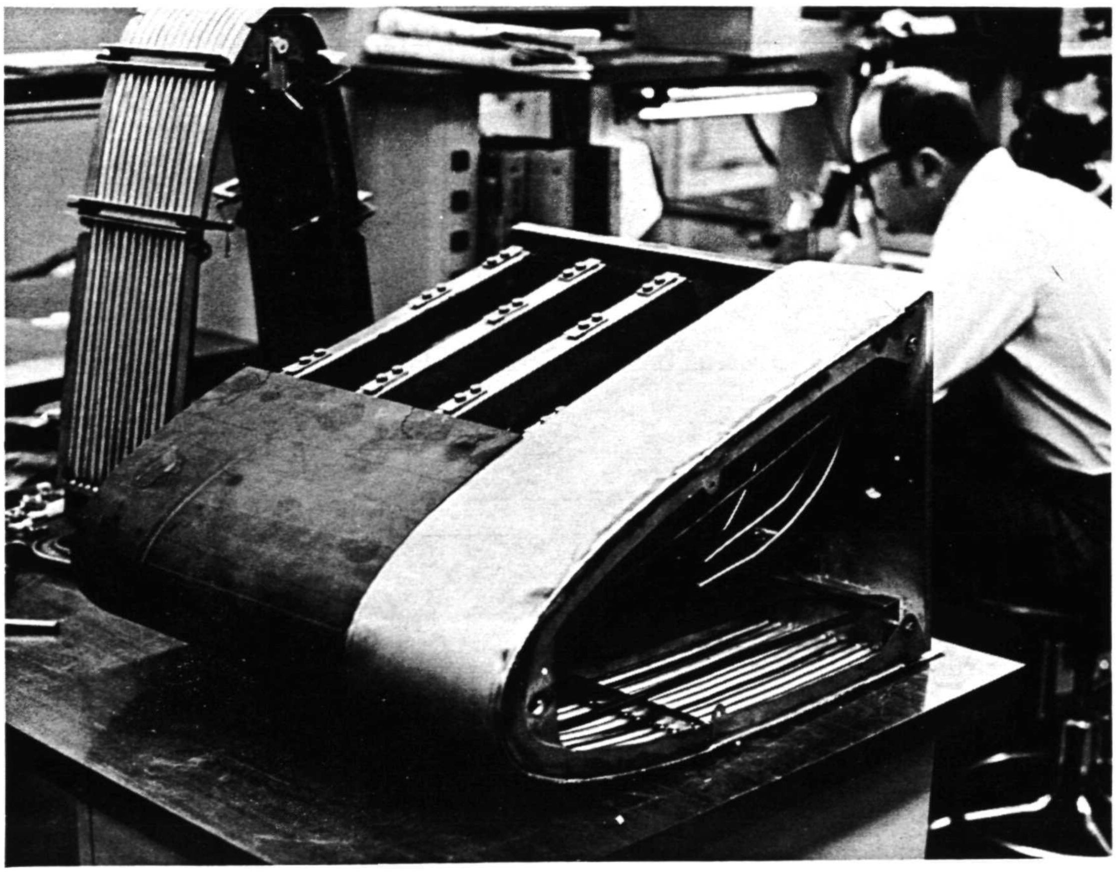


Figure 36

5. FACILITY ADAPTER

The adapter cross-section was dictated, as with the heat pipe test modules, by the shape for which calibration data were available. The carbon-carbon segment which was available had the necessary airfoil shape but required trimming to the proper size and construction of a leeward (upper) surface cover plate. The adapter design is illustrated in Figure 37.

The principal test module attachment is the bolted connection near the nose of the leading edge. A long Hastelloy-X bolt was used to make this connection and to attach the carbon-carbon side plate. Two slotted supports at the aft end carry the small reaction loads due to the heat pipe module weight and aerodynamic pressure. The slots accommodate the differential expansion of the carbon-carbon adapter and the Hastelloy-X heat pipe test module. Four Hastelloy-X webs attach the carbon-carbon segment to a steel base plate that may be bolted to the facility centerbody.

The aft potion of the leeward side, which will not reach temperatures requiring carbon-carbon is covered with a Hastelloy-X panel. A flat zee-stiffened panel design was selected to minimize the construction cost since this region has a small curvature and the mismatch would be negligible.

FOLDOUT FRAME

FOLDOUT FRAME

HEAT PIPE LEADING EDGE

THICK CARBON/CARBON LEADING EDGE ADAPTER

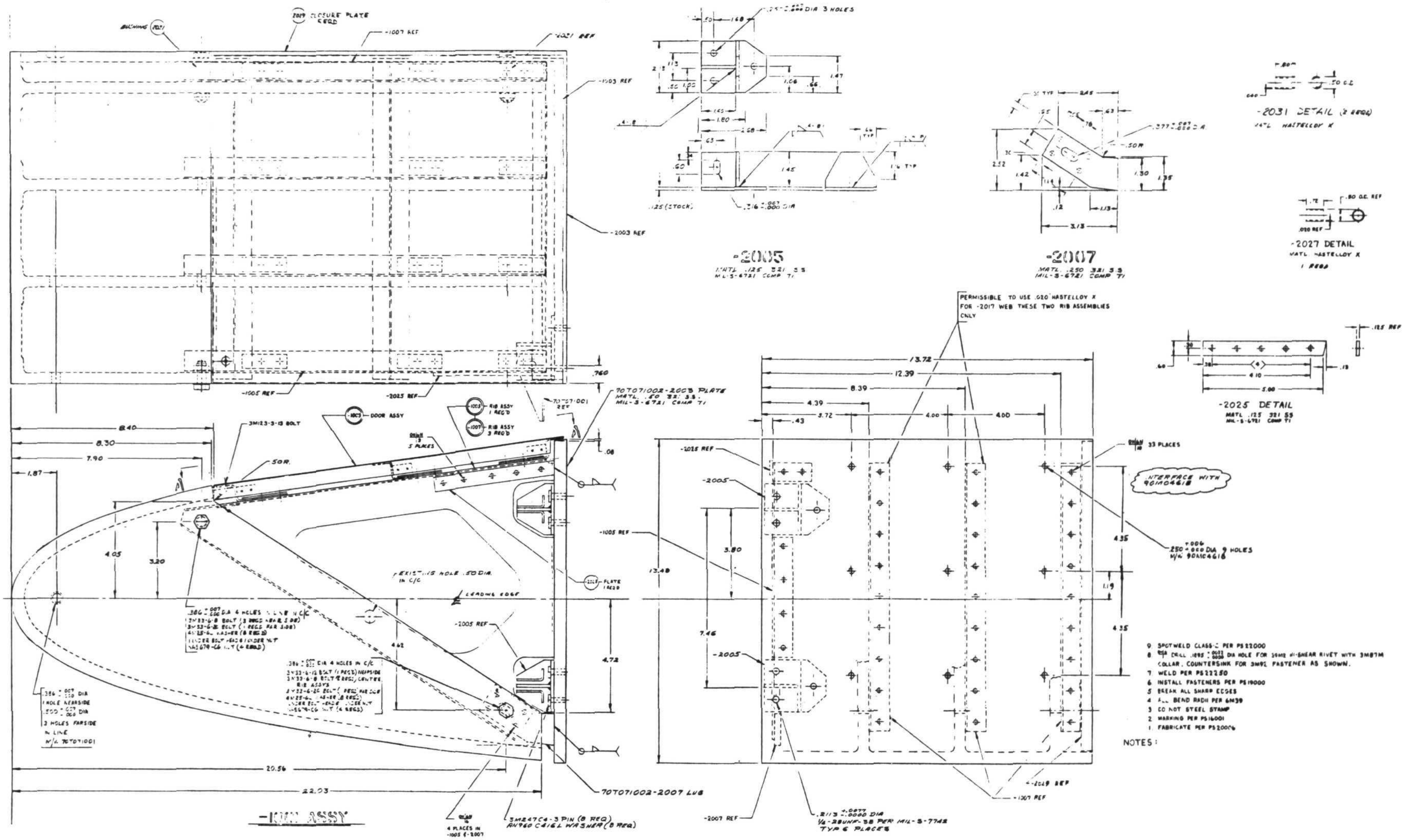


Figure 37

55 (a)

6. RECOMMENDED PERFORMANCE TESTING

Conditions for testing the heat pipe leading edge are outlined below and provide close correspondence with several anticipated flight conditions. In general these conditions are consistent with the capabilities of MSFC hot gas facility. The recommended test conditions, in the MSFC hot gas facility, are given in Figure 38. The tests are shown in the sequence in which they would be performed with initial (Phase I) tests intended to provide verification of system performance with external convective heating. Phase I and II tests would demonstrate and explore the capability (including fail-safe design) of the system when subjected to entry convective heating in the MSFC hot gas facility. In addition, two optional tests are recommended, both utilizing radiant heaters, so that the test model would not be subjected to aerodynamic loads as in hot gas flow testing.

The first series of optional tests recommended is a precursor to hot gas flow tests which may be performed without exact simulation of the heating distribution. This test would allow a slow heat-up cycle (to minimize thermal stresses) with steady operation at several heat flux levels and with various orientations to simulate differing acceleration or "g"-levels. Both the orientation and angle of attack are limited in the hot gas facility. Since two test modules are available, the preliminary tests could be performed with one unit while the other is being setup for testing in the hot gas facility. The purpose of the second series of optional tests would be to explore the capability of the design to withstand greater than nominal heating conditions and the heat transfer levels at which heat pipe inherent limitations are manifested, vis., at what heating rate sonic flow, nucleate boiling, wick capillary pumping capacity or other phenomena limit the heat pipe performance. Again, the flexibility of the lamp facility and its no-load characteristic would be useful.

Test Environment - The nominal test environment specified for the MSFC hot gas facility is as follows:

Total Temperature: 2898°C (5250°F) Stagnation Pressure: 17,237 n/m^2 abs. (2.5 psia)
Angle of Attack Range: 0 to 0.175 Rad. (0 to 10 deg.)

Cold Wall Heating Rate: Model Centerline, 2.2 in. radius

Angle of Attack	Cold Wall Heat Flux (37.7°C)
0 rad. (0 deg.)	1078 kw/M^2 (95 BTU/ft^2-(sec)
0.1745 rad. (10 deg.)	908 kw/M^2 (80 BTU/ft^2-(sec)

RECOMMENDED TEST CONDITIONS

PHASE I: PERFORMANCE VERIFICATION FLOW TESTS

FACILITY: NASA-MSFC H_2-O_2 FACILITY

RUN	HOT WALL HEAT FLUX (BTU/FT^2-SEC)	ANGLE OF ATTACK	REMARKS
1	20	ZERO DEGREES	PERFORMANCE MAP DATA
2	30	ZERO DEGREES	PERFORMANCE MAP DATA
3	36	ZERO DEGREES	PERFORMANCE MAP DATA
4	36	10 DEGREES	DESIGN POINT VERIFICATION

PHASE II: FAIL-SAFE/SAFETY DEMONSTRATION

FACILITY: NASA-MSFC H_2-O_2 FACILITY

RUN	HOT WALL HEAT FLUX (BTU/FT^2-SEC)	ANGLE OF ATTACK	REMARKS
1	20	ZERO DEGREES	TEST FAIL-SAFE PROVISION WITH SINGLE PIPE EMPTY
2	30	ZERO DEGREES	TEST FAIL-SAFE PROVISION WITH SINGLE PIPE EMPTY
3	36	ZERO DEGREES	TEST FAIL-SAFE PROVISION WITH SINGLE PIPE EMPTY

Figure 38

It should be noted that the nominal heating rates are more severe than the design value specified in the contract but a reduction in heating rate by changing the O_2-H_2 mixture ratio or by nitrogen injection could provide heating rates consistent with the design entry heating profile shown in Figure 39.

Heat Pipe Scaling - The test segment and test conditions defined in the program differ from the anticipated flight situation in three important areas: (a) the test segment is about 1/2 the orbiter wing thickness, (b) testing will take place in a 1-g environment, and (c) test angles of attack will be between 0 and 10 degrees, whereas the vehicle angle during reentry heating is expected to be approximately 0.524 rad. (30 deg.). To provide a meaningful verification of system performance, therefore, proper scaling between test conditions and anticipated flight environment must be provided.

Three parameters, the maximum structural temperature, the heat flux, and the acceleration vector must be properly combined for a reasonable simulation of the flight articles performance with the test hardware. The maximum temperature is dependent upon the heat flux and also the leading edge segment size and shape. Since the test model size and shape was determined so that an existing calibration model could be used only the heat flux may be varied. To achieve a maximum temperature of 982°C (1800°F), a stagnation line heat flux of about 409 kw/m^2 (36 BTU/ft^2-sec) will be required. The maximum temperature will occur at the stagnation line in the thin skin covering the heat pipes and will be affected somewhat by the size of the braze fillets. If larger than expected fillets occur, then the heat flux necessary to produce 982°C (1800°F) will be greater, perhaps as high as 500 kw/m^2 (44 BTU/ft^2-sec).

In the expected flight reentry trajectory, maximum heating occurs at an angle of attack of about 30° with a nominal 0.6 "g" load acting perpendicular to the plane of the wing. Testing of the segment will be in a 1-g environment at angle of attack between 0 and 10^o. The impact of these differences is primarily on the wick design and can be explained by considering the pumping limit equation.

ORBITER ENTRY HEATING RATE

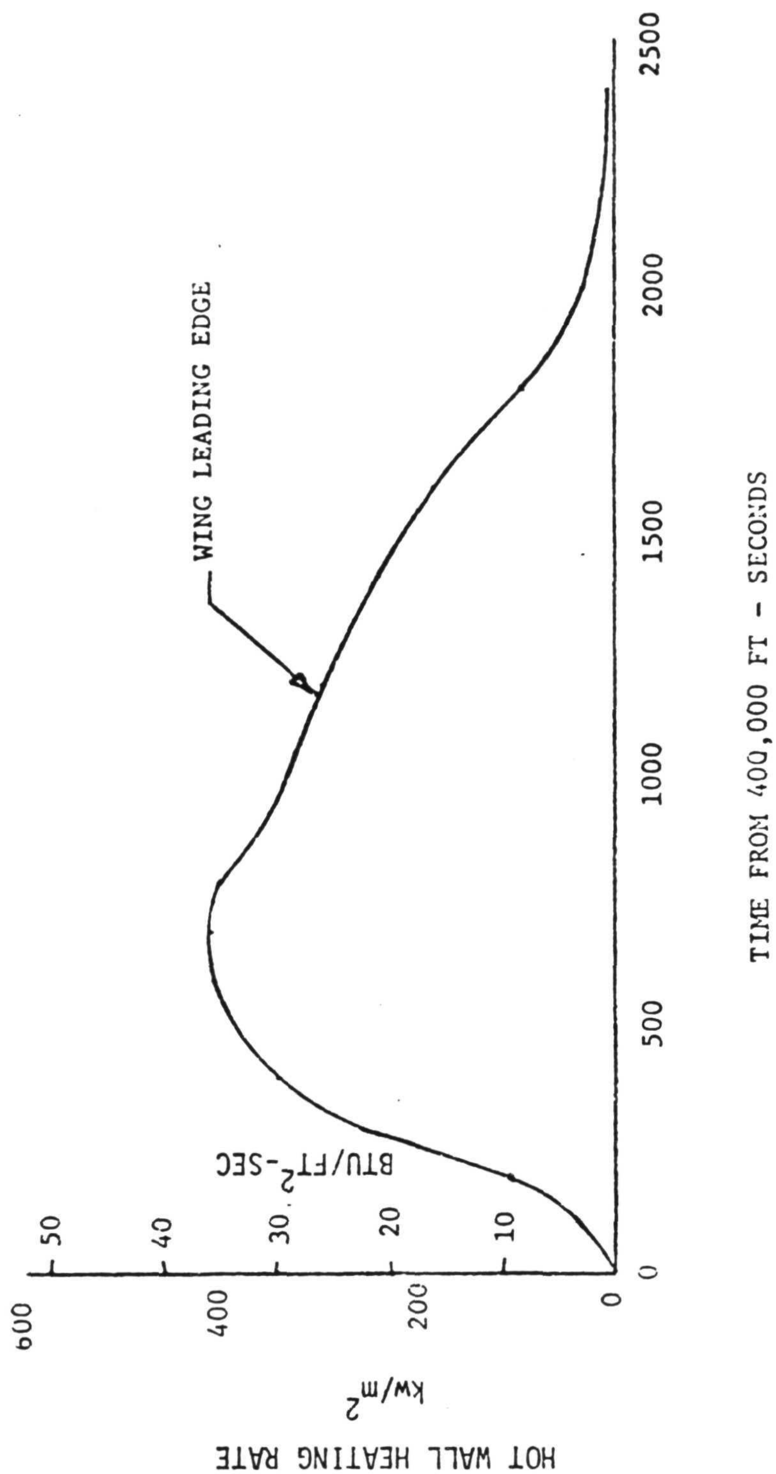


Figure 39

Neglecting vapor pressure drop, the following equation must be satisfied to ensure adequate liquid return flow to the evaporation region.

$$\frac{2\sigma}{r_c} \geq \frac{1}{K_P A_W} \frac{\mu_L}{\rho_L h_{f_g}} \frac{W_{qo}}{g_c} \iint \frac{q(x)}{q_o} \, dxdx + \rho_L \frac{g}{g_c} h \qquad (2)$$

The value of $\frac{2\sigma}{r_c}$ is a function of the wick pore size at the liquid vapor interface and the liquid properties. Since the temperature, working fluid, and wick material for the test and flight system are identical, the lefthand side of the equation will be the same for both cases. For the same reason, K_P and the term $\mu_L/\rho_L \, f_g$ are also the same for the test and flight units. Heat pipe diameter is the same in both cases and w, therefore, does not change. The terms which cause the value of the righthand side of Equation 2 to differ between the two cases are $q_o \iint \frac{q(x)}{q_o} \, dxdx$ and "gh". Both of these terms are functions of the angle of attack and can be calculated based on trajectory data for the flight case and tunnel conditions for the experiment. To balance the difference in these terms, the value A_W was increased for the test segment heat pipes over that required by the flight design. The corresponding value of A_W for the flight case would be obtained by calculating the value of A_W which equates the righthand side of the equation for both the test and flight parameters. Thus by this scaling procedure, adequate performance for the test pipes proves that the cross-sectional area calculated in this manner for the flight system will be adequate.

Criteria for Success - Phase I tests will simulate the entry heating environment in a hot gas facility. The design heating distribution will be simulated nearly exactly, allowing performance mapping of the leading edge. The test will also provide for demonstration of the capability to withstand the design heat flux in the flow test environment. The success criterion for these tests is that the heat pipes successfully reduce the maximum leading edge temperature from 1315°C (2400°F) to 1010°C (1850°F) or less with an angle of attack of 0.1745 rad (10 deg.) in the 1-g environment.

The Phase II tests are to demonstrate the fail-safe feature of the heat pipe design. A three test sequence of increasingly severe tests will determine the response of the heat pipe system to the loss (undetected) of working fluid from a heat pipe. The criteria for success in this test are: (1) the structural integrity of the segment be maintained and (2) the adjacent heat pipes operating temperature not exceed 1093°C (2000°F).

The optional precursor and ultimate performance tests are of a research nature. Consequently success criteria are inappropriate.

7. RECOMMENDED FOLLOW-ON EFFORT

This work accomplished under Contract NAS8-28656 and in a prior study under Contact NAS8-27708, indicates that the heat pipe cooled leading edge is feasible for Space Shuttle Application. Flight designs generated for the Phase B configuration and environment in the prior study indicated a generally thinner metal structure than was constructed in this contract. This prior study, however, did not yield a fully-iterated design. The design process considered working fluid compatibility, the combined stresses due to internal pressure, aerodynamic loads, and temperature gradients. Selection of the panel cross-section, support spacing, tube diameter and many other elements of the design was based on individual optimality criterion in serial fashion. The final design, based principally on creep criteria, therefore was probably not the minimum weight achievable. In addition, it was not specific for the current orbiter mission.

Thus, there are two recommended items of follow-on effort. The first is a design study task to define an iterated weight optimized design for the current orbiter configuration and environments. The configuration establishes a performance limit by defining the amount of leading edge surface available for cooling. Consequently, the heat pipe design cannot necessarily be substituted in a simple fashion for another design subsequent to a design freeze. To remain a viable alternate, early analysis to establish the design characteristics of the heat pipe leading edge specific to the shuttle mission and configuration is required. The second follow-on task relates to manufacturing development to assure that a thin structure can be fabricated with acceptable costs. This work should include construction of flight weight samples to investigate thin wall tube forming, the effect of forming on a single-layer wick, and the suitability of self-contained braze tooling in a thin-wall structure.

8. REFERENCES

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9. NOMENCLATURE

A_v	Cross sectional area of vapor passage
A_w	Cross sectional area of wick
BS	Body station
E	Youngs modulus
F_{tu}	Ultimate strength
F_{ty}	Yield strength
g	Acceleration
g_c	Gravitational constant
h	gravity head
h_{fg}	Heat of vaporization
k	Rate constant
K_p	Permeability coefficient
$K_p A_w/W$	Wick design parameter
L	Developed length measured from nose centerline
l_{eff}	Effective heat pipe length
q	Local heat flux
q/qo	Ratio of local to stagnation heat flux
q_o	Stagnation heat flux
ra	Artery radius
r_c	Capillary radius
r_v	Radius of vapor passage
T_{max}	Maximum temperature
t	Time
W	Width of wing cooled by single heat pipe
v_s	Sonic velocity
x	Distance
α	Coefficient of thermal expansion
ΔP	Pressure drop
ΔP_L	Liquid Pressure Drop
Θ	Tilt angle
ΔP_c	Available capillary pumping pressure rise
ΔP_v	Vapor pressure drop
μ_L	Liquid viscosity
ρ_v	Vapor density

ρ_L	Liquid density
σ	Surface tension
γ	Ratio of specific heats
μ	Vapor viscosity
ΔT	Temperature difference