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FINAL REPORT

VOLUME I
EXECUTIVE SUMMARY

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY • EAST

MCDONNELL DOUGLAS
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Saint Louis, Missouri 63166 (314) 232-0232

MCDONNELL DOUGLAS 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. ABSTRACT

This program, conducted under Contract NAS 8-28656, consisted of the construction of two test modules for a feasibility demonstration of a concept for reusable Space Shuttle wing leading edge surfaces. In this leading edge concept high temperature heat pipes were incorporated into the structure to cool the stagnation region, allowing the use of super-alloys in place of refractory metal, ablator protected, or carbon-carbon structures. The program was initiated 20 June 1972 and completed 20 April 1973.

The program included the analysis and design of the heat pipes, their integration into the test module structure, heat pipe development testing, construction of the test modules and a facility adapter, and formulation of recommended testing conditions. The heat pipe analysis and testing was 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 analyses indicate the test modules will meet their design goal; reducing the leading edge temperature at the stagnation line from 1315°C (2400°F) to less than 1010°C (1850°F). The development tests demonstrated that the module 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.

A test plan was formulated to be used in subsequent performance testing which will be conducted by the NASA, MSFC.

2. 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 approximately 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 on the wing and vertical fin. Obtaining an acceptable reusable surface in these regions presents a variety of problems.

A prior study, performed under contract NAS 8-27708, 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. The design, analysis, testing and construction accomplished under this contract are discussed briefly in the following sections of this summary volume and in greater detail in the technical report given in Volume II.

3. TEST MODEL DESCRIPTION

The configuration of the test part was dictated by the wing shape that the test facility could accept and the necessity to minimize the cost of the test part. The test facility was designed for operation with the test segment serving as the center body of a supersonic diffuser. The test arrangement is shown in Figure 1. Since modification of the wing cross-section would be expensive, the same cross-section was retained but the width of the test segment was reduced to the minimum thought to give representative results. The shaded area in Figure 1 shows the portion of the center body span the heat pipe occupies. The remainder of the span is occupied by a carbon/carbon segment which serves as the facility adapter.

A heat pipe segment width of 15.2 cm (6 in.) was selected because it would provide a segment large enough to demonstrate manufacturing feasibility and system performance at minimal program cost. This is the case since adapter segment was available at no cost to the program.

The heat pipe test module design is illustrated in Figures 2 and 3. It consists of conventional screen-wick heat pipes formed to the airfoil cross-section, with a thin skin covering the heat pipes. The heat pipes and skin are brazed to form an integral structure. The design allowed assembly of the unit for brazing with operational heat pipes, serviced with sodium, and fully checked out.

LEADING EDGE ENTRY TEST FACILITY

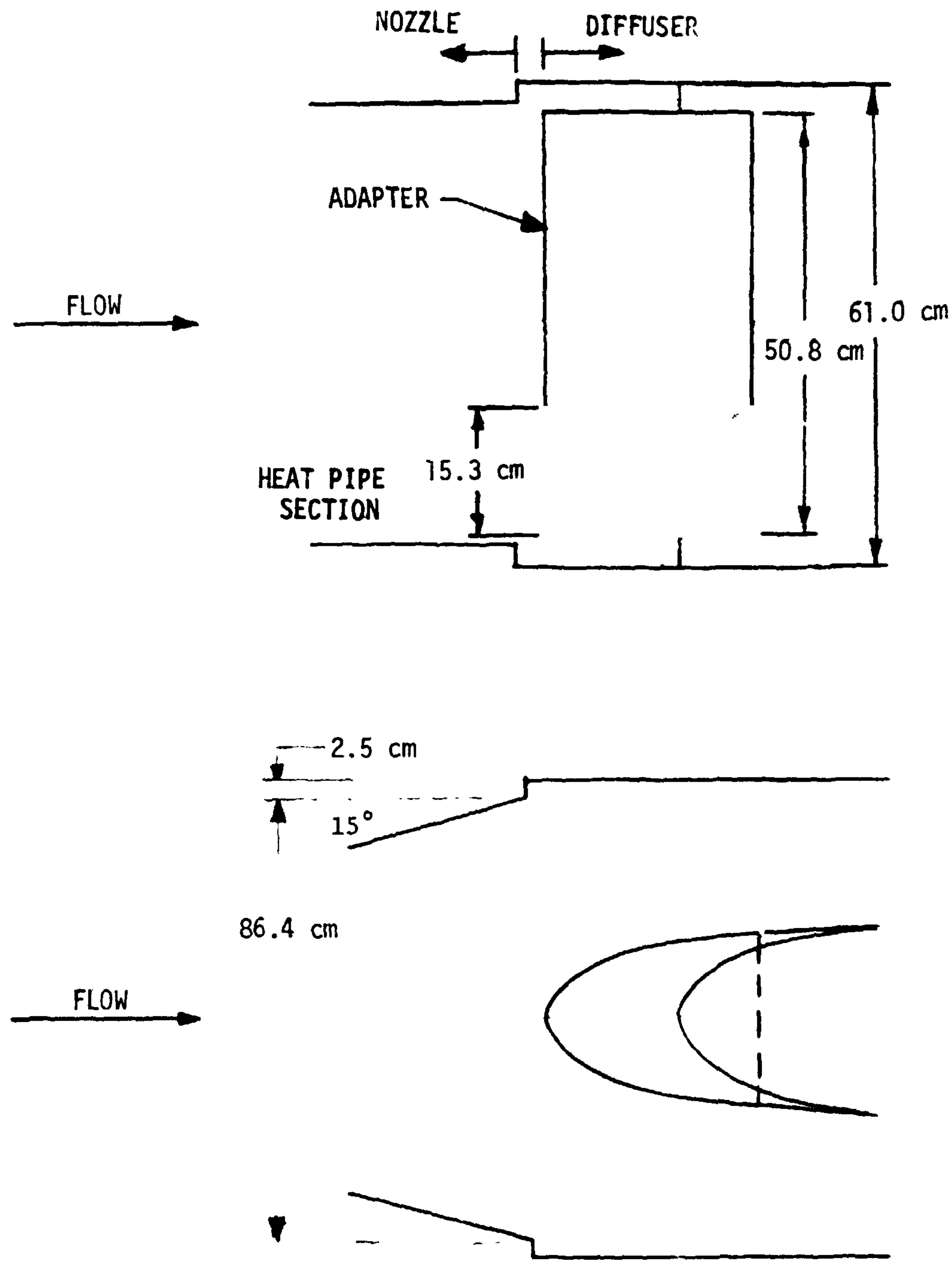


Figure 1

HEAT PIPE TEST ASSEMBLY

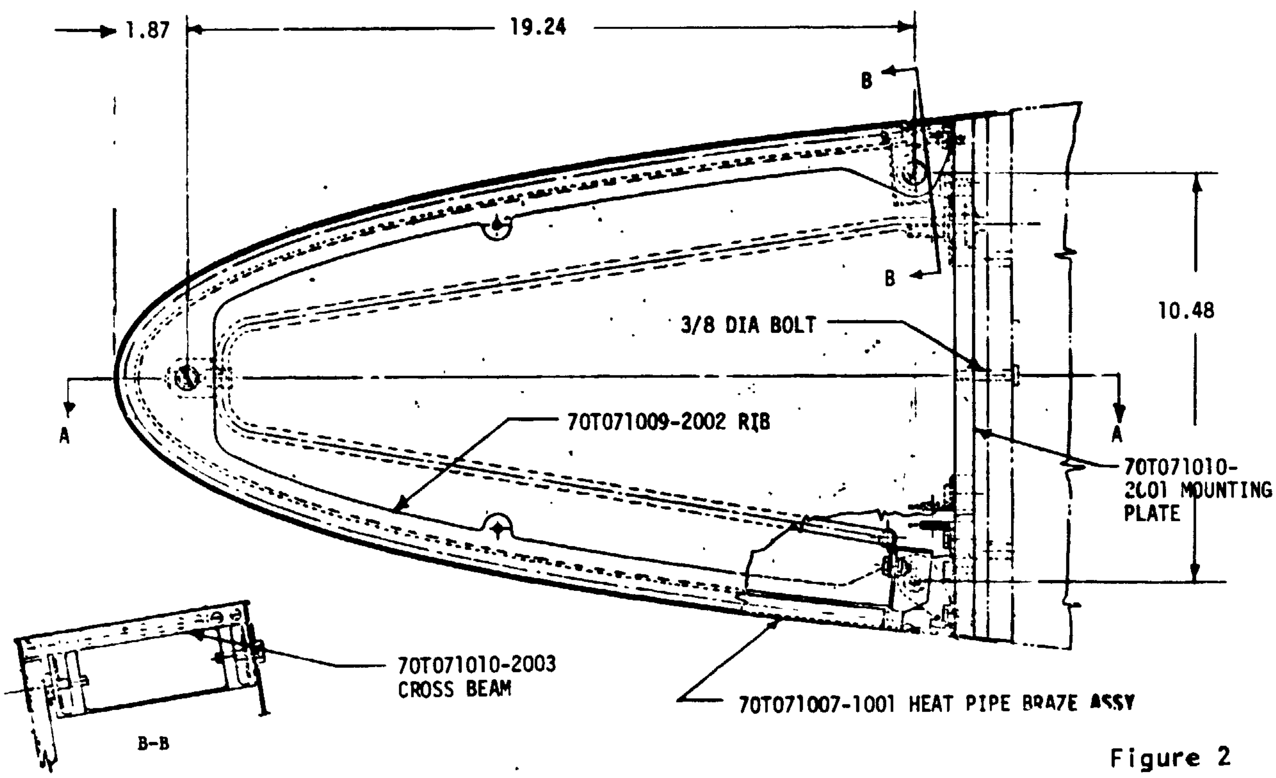
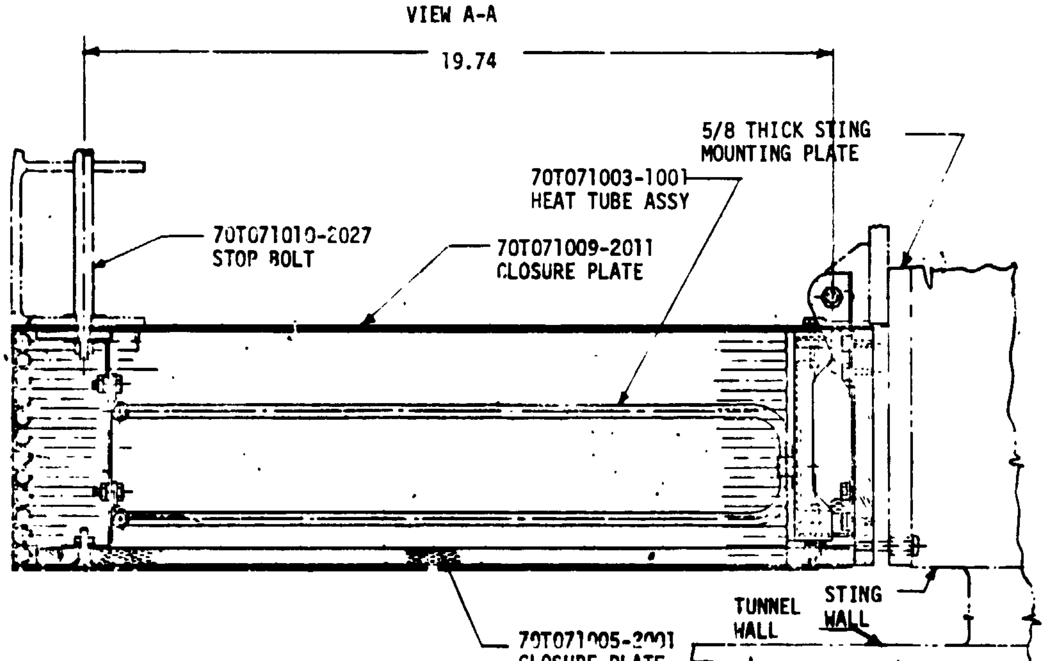


Figure 2

HEAT PIPE TEST ASSEMBLY

VIEW A-A



NOTE: DIMENSIONS IN INCHES

Figure 3

4. TEST MODEL ANALYSIS

Test Model Analysis - Thermal and structural, and producibility analyses were conducted with the basis of the preliminary design work done under NAS 8-27708. A test module configuration was established during that contract so that detailed analysis could be undertaken promptly with the award of the follow-on contract. Detailed thermal and strength analyses were conducted in parallel using the preliminary design as the starting point. Hardware details were firmed up as the results of structural and thermal analysis were obtained. The detailed analysis indicated substantial margins of safety with the available Hastelloy-X tubing.

4.1 Thermal Analysis - The purpose of the thermal analysis was to determine the transient response of the test model and to explore the effects of various heating rates. Evaluation of the transient response was necessary for the determination of thermal stresses due to temperature gradients.

The leading edge was designed to reduce the stagnation line temperature from 1315°C (2400°F) to 1010°C (1850°F). The corresponding heating environment was a cold wall heat flux of 409 kw/m^2 (36 BTU/ft^2-sec). Data from MSFC, however, indicated much higher heat fluxes could be produced in the facility planned for testing. Consequently, the designs ability to withstand higher heating rates was determined.

Results of the transient analysis are indicated in Figure 4 which shows the rapid development of thermal gradients in the expected test environment. The maximum gradients are developed very quickly and thus thermal stresses reach a maximum while the module is at a relatively low temperature.

The unit has a substantial overheat capability. Analysis of steady operation with several heat fluxes yielded the curve shown in Figure 5. The unit should, with all heat pipes operating, reduce the peak temperature from 1315°C (2400°F) to a temperature below 1010°C (1850°F). In fact, the heat pipe leading edge should withstand the contract statement of work (SOW) heat flux of 409 kw/m (36 BTU/ft^2 sec), which without exceeding 1010°C (1850°F). The ability to withstand even higher heating rates is such that an inadvertent brief exposure to the maximum rates attainable in the facility would not cause a catastropic failure.

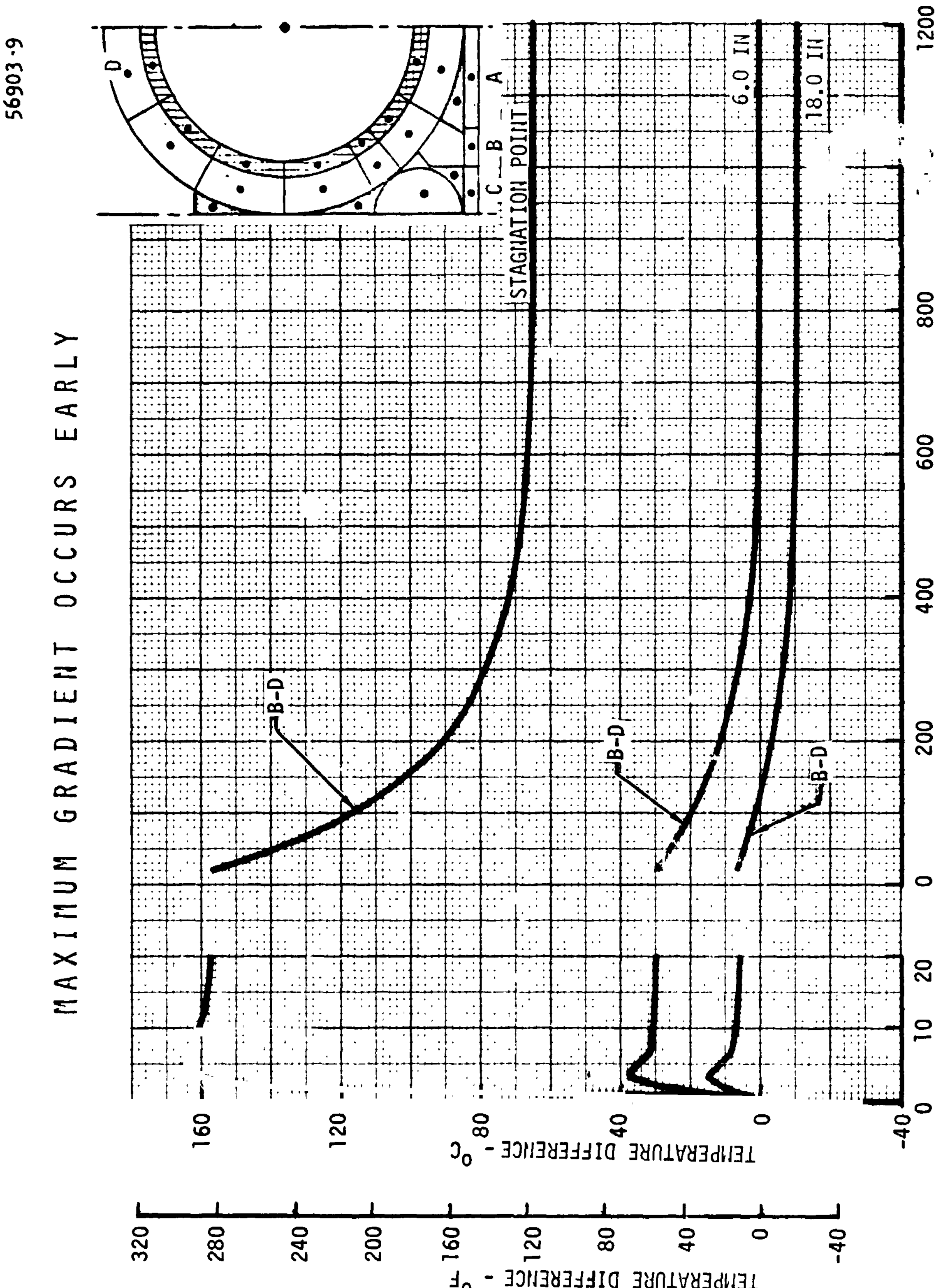

56903-9
MAXIMUM GRADIENT OCCURS EARLY
D
A
B
C
STAGNATION POINT
6.0 IN
18.0 IN
B-D
B-D
B-D
TIME - SECONDS
0
10
20
0
200
400
600
800
1200
TEMPERATURE DIFFERENCE - °C
160
120
80
40
0
-40
TEMPERATURE DIFFERENCE - °F
320
280
240
200
160
120
80
40
0
-40

Figure 4

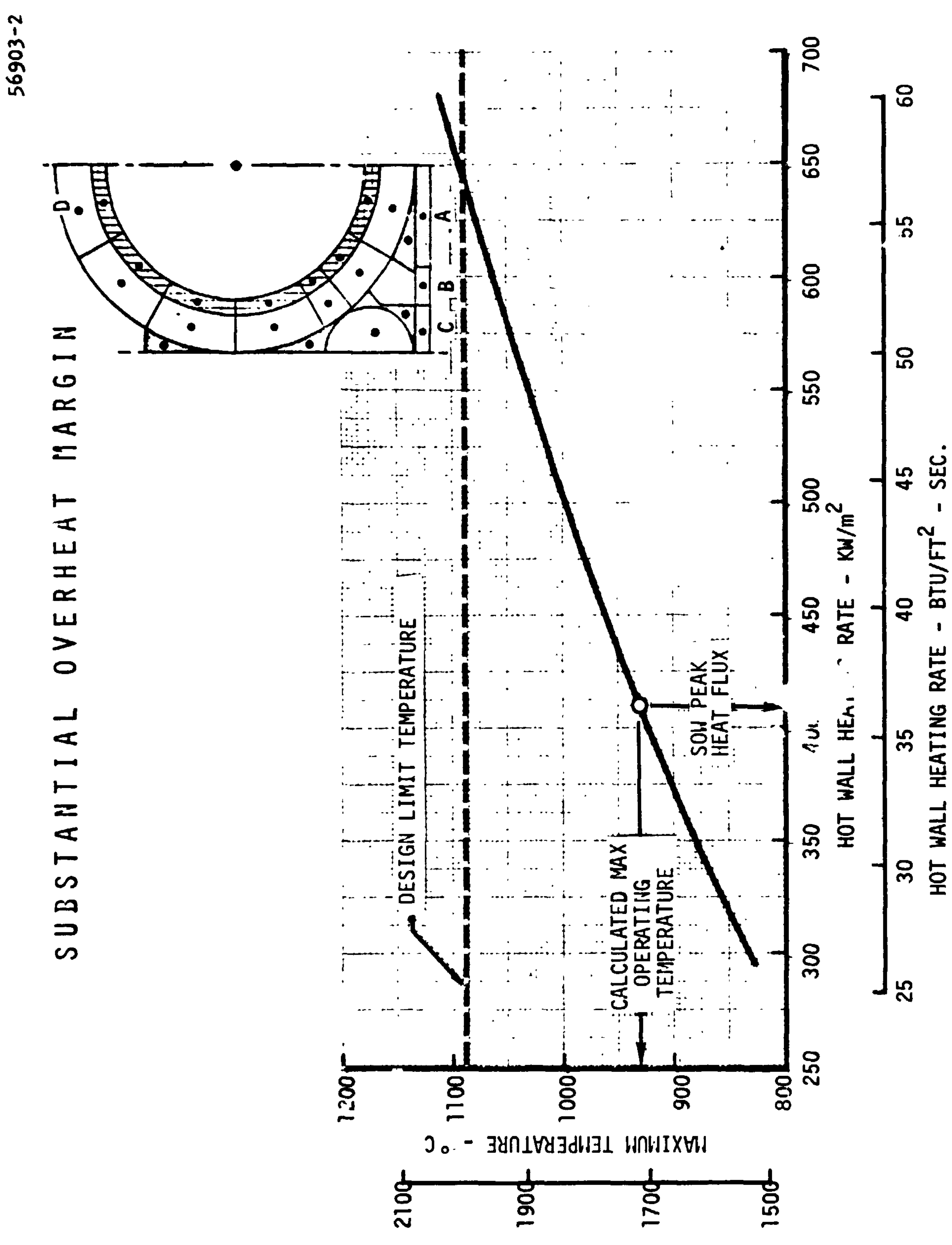

56903-2
SUBSTANTIAL OVERHEAT MARGIN
D
A
B
C
DESIGN LIMIT TEMPERATURE
CALCULATED MAX OPERATING TEMPERATURE
SOW PEAK HEAT FLUX
250
300
350
400
450
500
550
600
650
700
HOT WALL HEA... RATE - KW/m2
25
30
35
40
45
50
55
60
HOT WALL HEATING RATE - BTU/FT2 - SEC.
1200
1100
1000
900
800
MAXIMUM TEMPERATURE - °C
2100
1900
1700
1500
MAXIMUM TEMPERATURE - °F

Figure 5

4.2 Structural Analysis - The particular combination of pressure and heating rate imposed by the MSFC hot gas test facility results in large combined stresses. The strength analysis concentrated on the startup transient and the steady operating conditions. The startup transient imposes the highest loads but at relatively low temperatures. In steady operation the loads are lower but the temperatures are much higher and consequently the strength of the Hastelloy-X alloy is substantially reduced.

Pressure loads were developed from the chordwise distribution shown in Figure 6, with a worst case angle of attack of 0.1745 rad. (10 deg). During the startup transient, thermal stresses based on the maximum temperature gradients (indicated in Figure 4) occurred about 4 seconds after startup. The resulting bending moments are shown in Figure 7 which indicates the moments are well below the allowable values. With steady operation the moments are much lower than the allowable values because the temperature gradients are small. The analysis showed the design of the test model critically affected by the startup characteristic of the hot gas facility.

It may be noted that the steady state loads are far less than the allowable values and that the design exhibits a substantial margin of safety even in the transient load case. The large margin of safety results principally from consideration of material availability. The minimum delivery time for Hastelloy-X tubing was 13 weeks. Hastelloy-X tubing with a wall thickness of 1.27mm (0.050 in.) was available at MDAC however, and although oversized was used to prevent a program slip.

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 NAS 8-27708. A simple technique was used; that of accounting for the volume-density products of the component parts. The estimated weight breakdown was 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.)

56903-17

EXTERNAL PRESSURE IS MAXIMUM NEAR NOSE

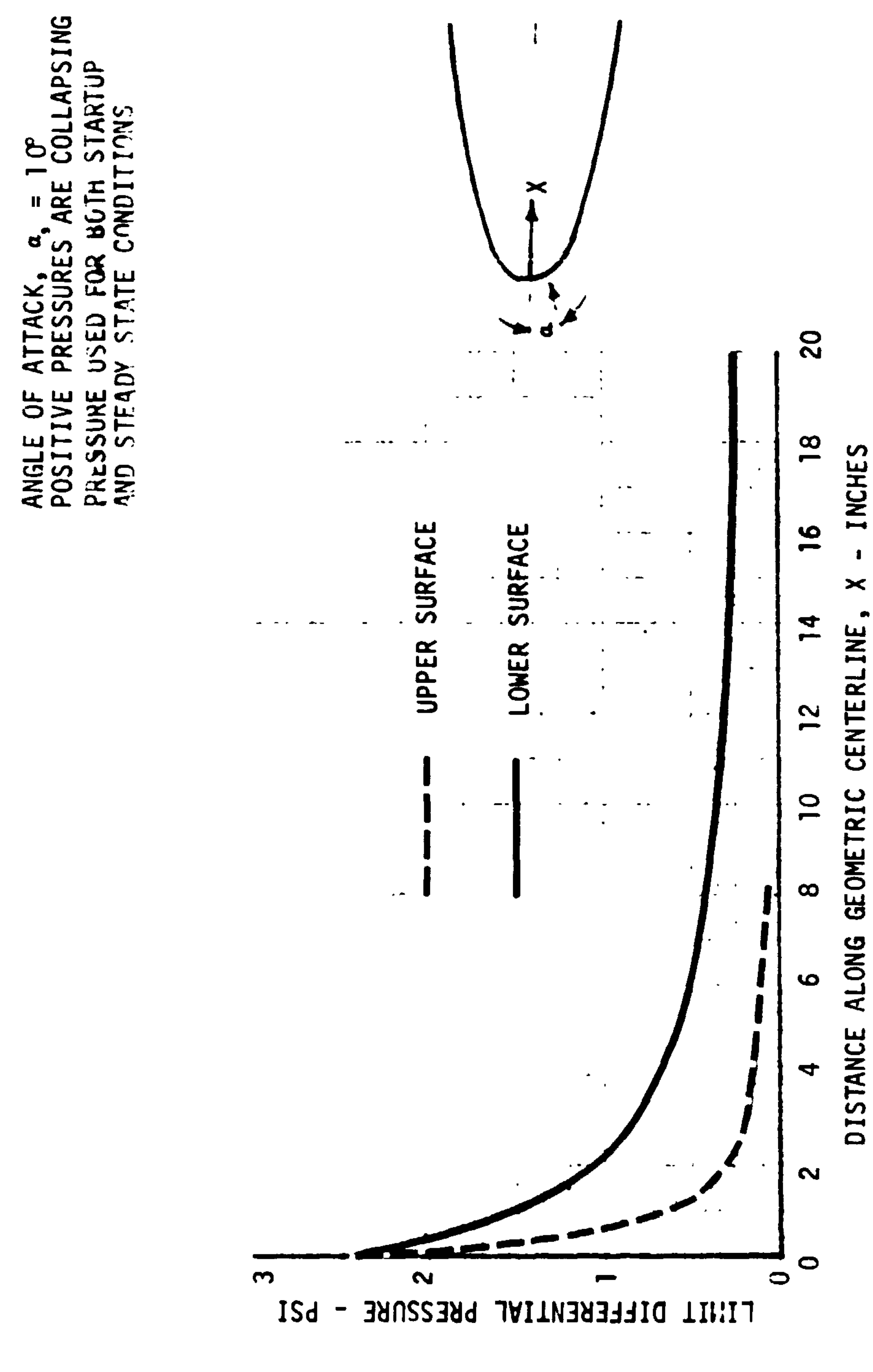


Figure 6

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HEAT PIPE BENDING MOMENTS
ARE MAXIMUM AT STARTUP

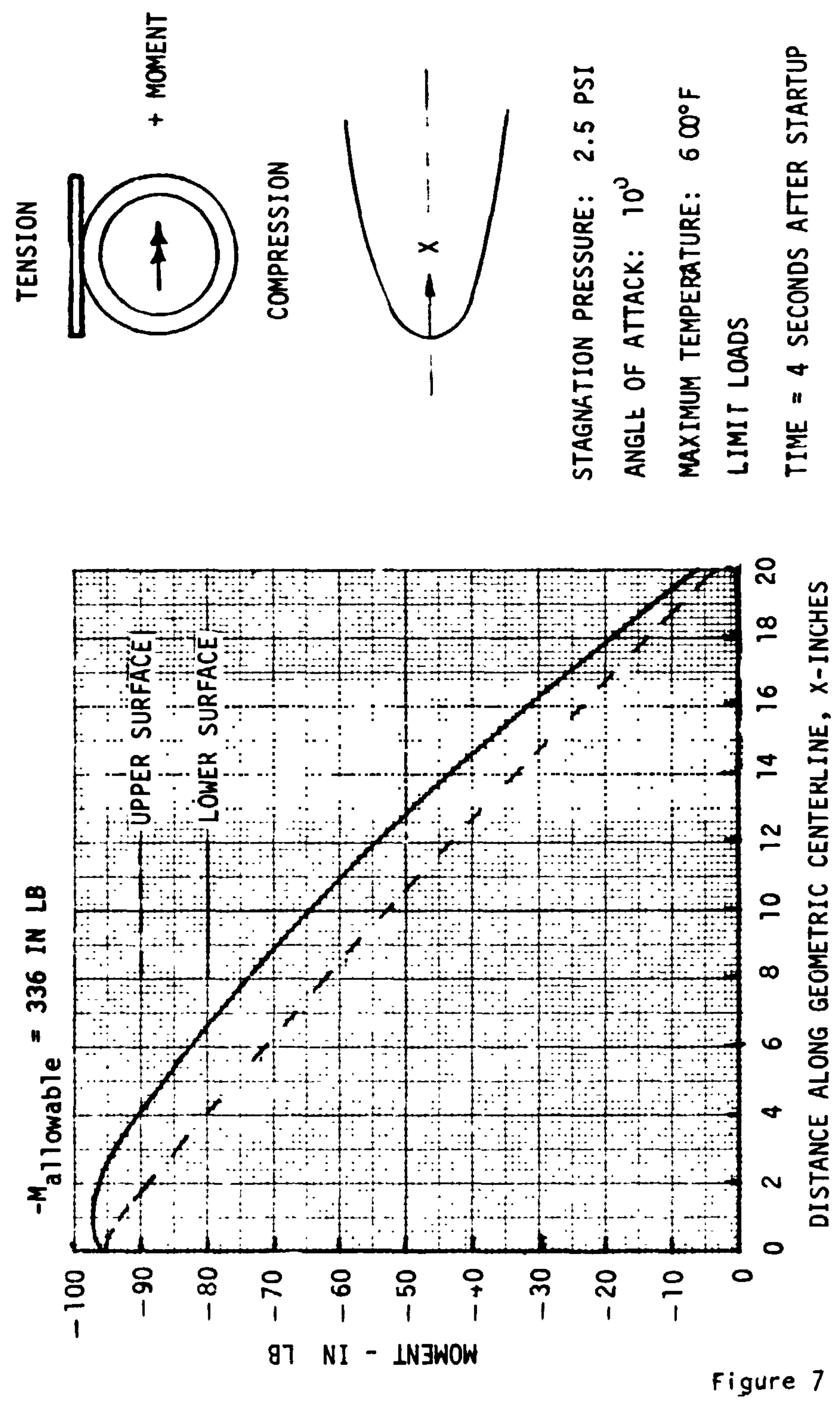

Figure 7

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 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 estimates for a flight-weight design.

4.3 Heat Pipe Leading Edge Modules Construction - The construction of the leading edge modules required both heat pipe processing and metal forming and assembly. The heat pipe processing was done at DWDL in Richland, Washington, and the forming and assembly was done at MDAC-E in St. Louis, Missouri.

After the Hastelloy-X tubing was procured it was shipped to DWDL for cleaning and installation of the wick. In addition, the tubes were filled with glass beads to support the tube wall during forming and to maintain the screen wick in intimate contact with the tube wall. The tubes were returned to MDAC-E and formed to the airfoil shape as shown in Figure 8. They were then trimmed to the correct length, vacuum annealed, and returned with the end fittings to DWDL for installation of the end fittings and servicing with sodium, the working fluid.

End fittings were TIG welded in place and each tube was pressure and leak checked prior to servicing with sodium. To minimize contamination the welding was done in a high purity inert gas glove box. After welding, the end closures were helium leak tested and x-rayed. The heat pipes were then attached to the sodium loading facility and charged with a nominal 22 gram load. After loading, the heat pipes were placed in radio frequency (RF) induction heating station and run in a reflux mode until each pipe was isothermal and all noncondensible gas was expelled from the wick assembly. The refluxing also served to thermally condition and wet the heat pipe interior. After completing the refluxing and degassing treatments, the fill tubes were flattened and an electron beam cutoff closure was made to seal the heat pipe. After sealing and x-ray examination of the closure, the heat pipes were reflux tested again to insure proper per-

FORMING TOOL AND TUBE

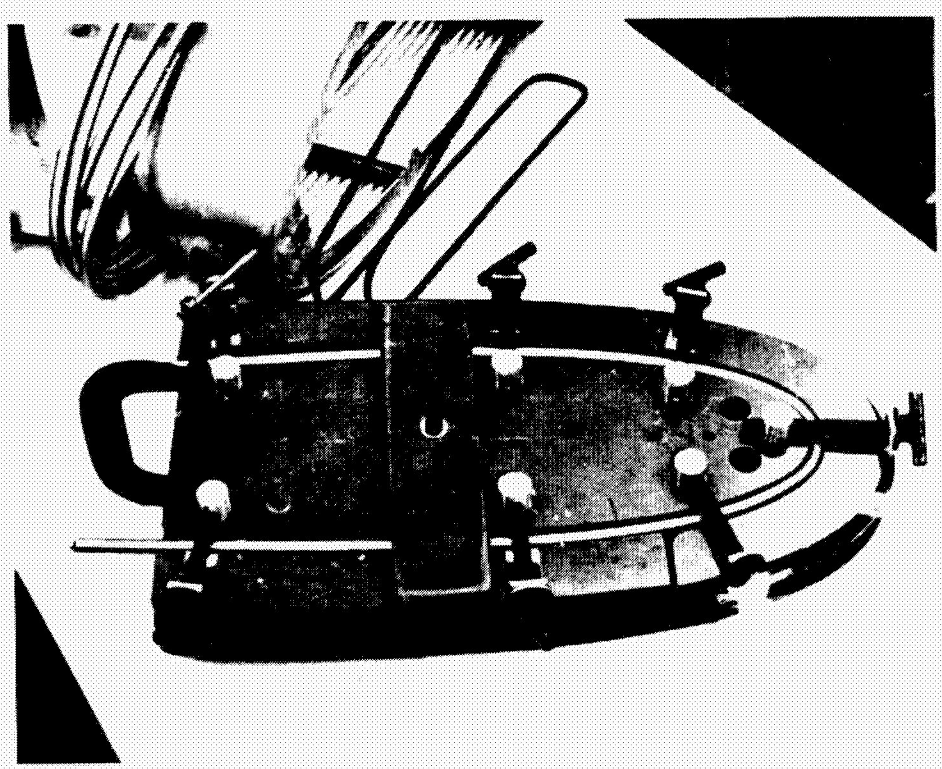

Figure 8

formance after sealing. Figure 9 shows one of the deliverable heat pipes undergoing testing to verify its performance.

The completed heat pipes were then cleaned and returned to MDAC-E for assembly into the braze unit. This unit consisted of the heat pipes, end fittings, skin, and stiffening ribs. The ribs were cold formed of 1.6-mm (0.063-in) sheet stock, and served a dual purpose; as stiffeners and as an integral part of the braze tooling. The heat pipe ends were first fitted into the cross beams and TIG welded so that the heat pipe array formed a leading edge surface. The ribs were installed with the flanges out to permit welding of the skin to the flange as part of the self-contained braze tooling. Filler wires were added to the nose section along with two sheathed chromel-alumel thermo-couples. A slurry of AMI 914 brazing alloy was then applied on both sides of the tubes along their full length. Figure 10 illustrates this major braze subassembly.

This subassembly was then placed in another subassembly consisting of the skin and a pressure plate as shown in Figure 11. A 0.13-mm (0.005-in) thick tape of braze alloy was attached to the inside surface of the Hastelloy-x cover skin to insure a braze alloy supply to the critical tube to skin interface. The skin was pulled taut with four jackscrews (two visible in Figure 11) and then spot welded to the rib flange (Figure 12) to complete the braze unit assembly.

The assembled test segment was then placed in a vacuum brazing furnace with the tubes in a horizontal plane. The nose section was lowered approximalely 2.5-mm (1-in) in order to insure the filling of the nose section joints with braze alloy. The first test segment was brazed at 1920°F for 30 minutes followed by a 3 hour 1875°F diffusion treatment to raise the remelt temperature. Similar diffusion treatments have been used for continuous applications at 2300°F. The first panel 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 1900°F for 30 minutes and followed by a 3 hour 1875°F diffusion treatment. Alloy drainage was eliminated on the second segment and the brazed fillets were significantly heavier. During the heat up phase of brazing, both test

HIGH TEMPERATURE CHECKOUT

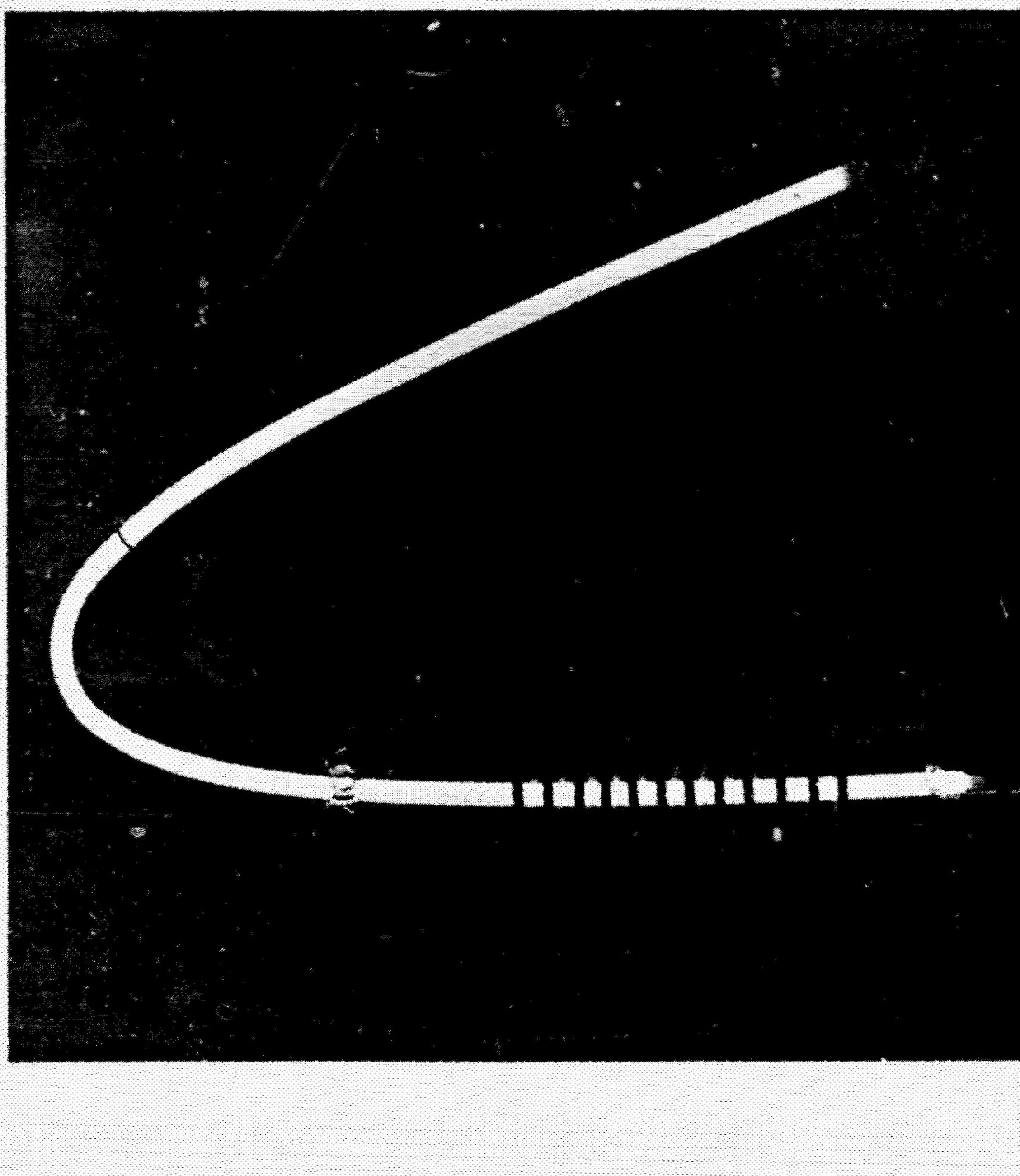

Figure 9

FINAL BRAZE ASSEMBLY

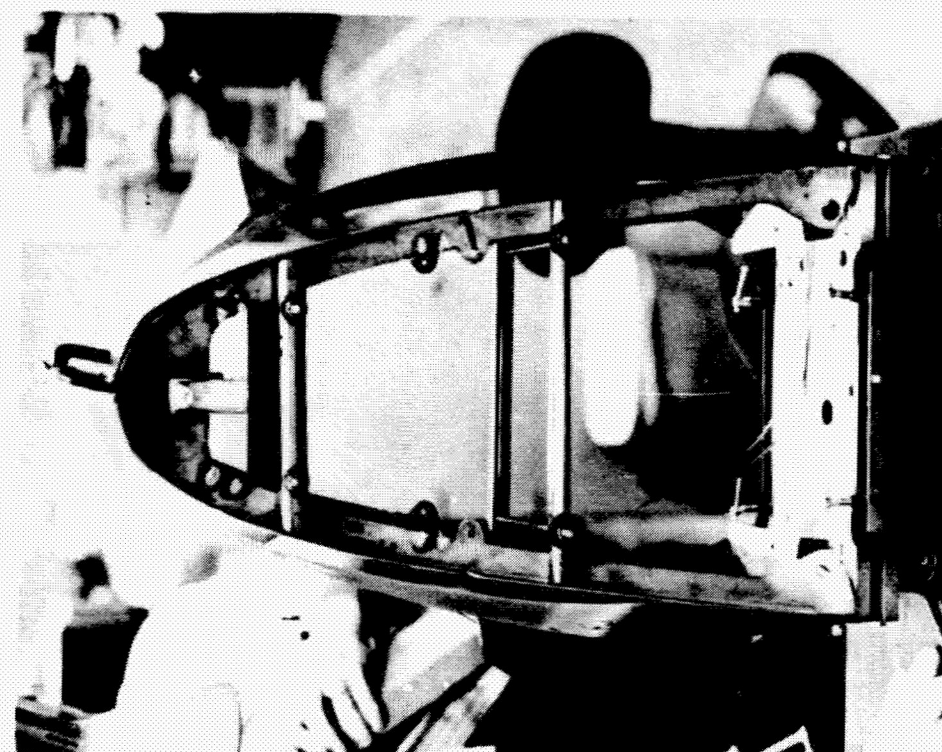

Figure 11

BRAZE SUBASSEMBLY

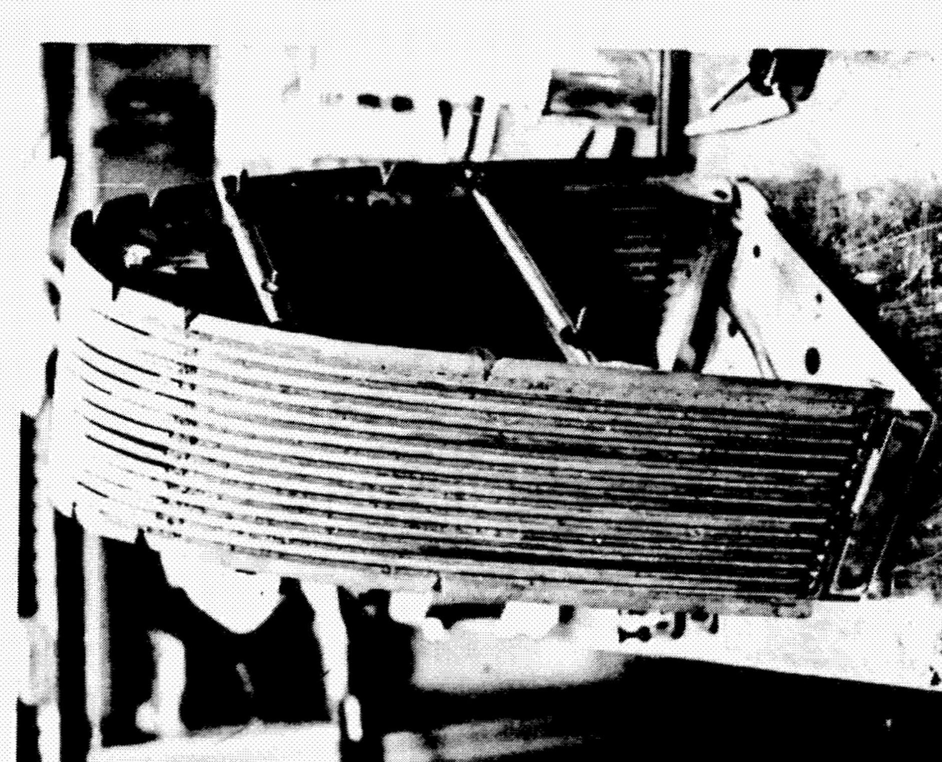

Figure 10

SPOT WELDED LEADING EDGE
BRAZE ASSEMBLY

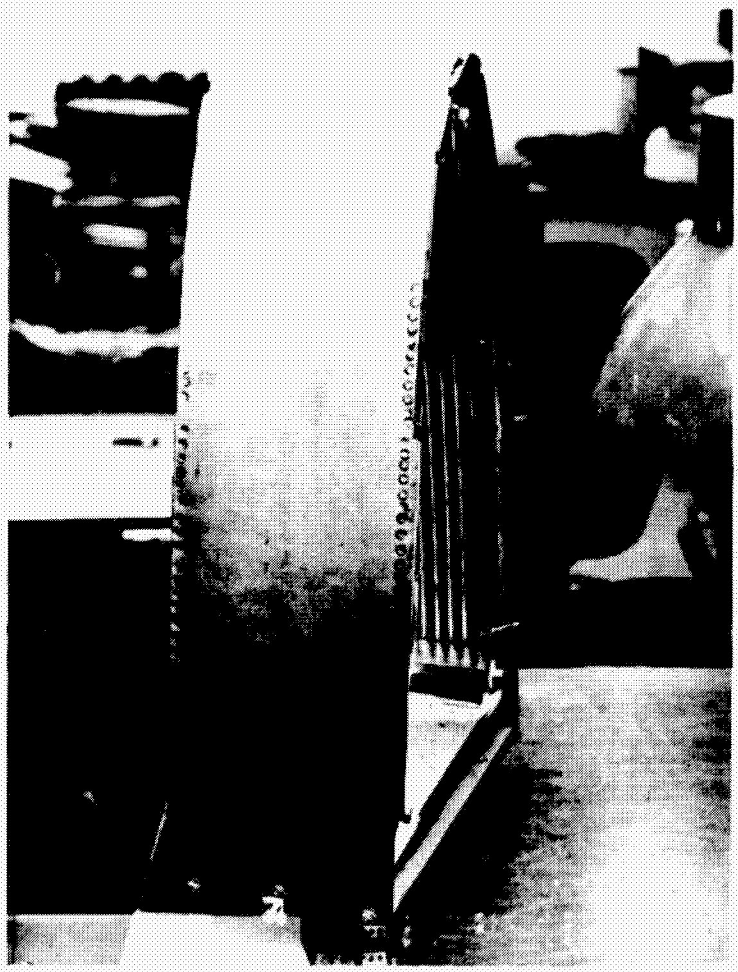

Figure 12

segments were checked visually and the heat pipes were operational. Subsequent to brazing the rib flange was removed. The completed heat pipe leading edge braze assembly is shown in Figure 13.

ASSEMBLY OF TEST MODEL

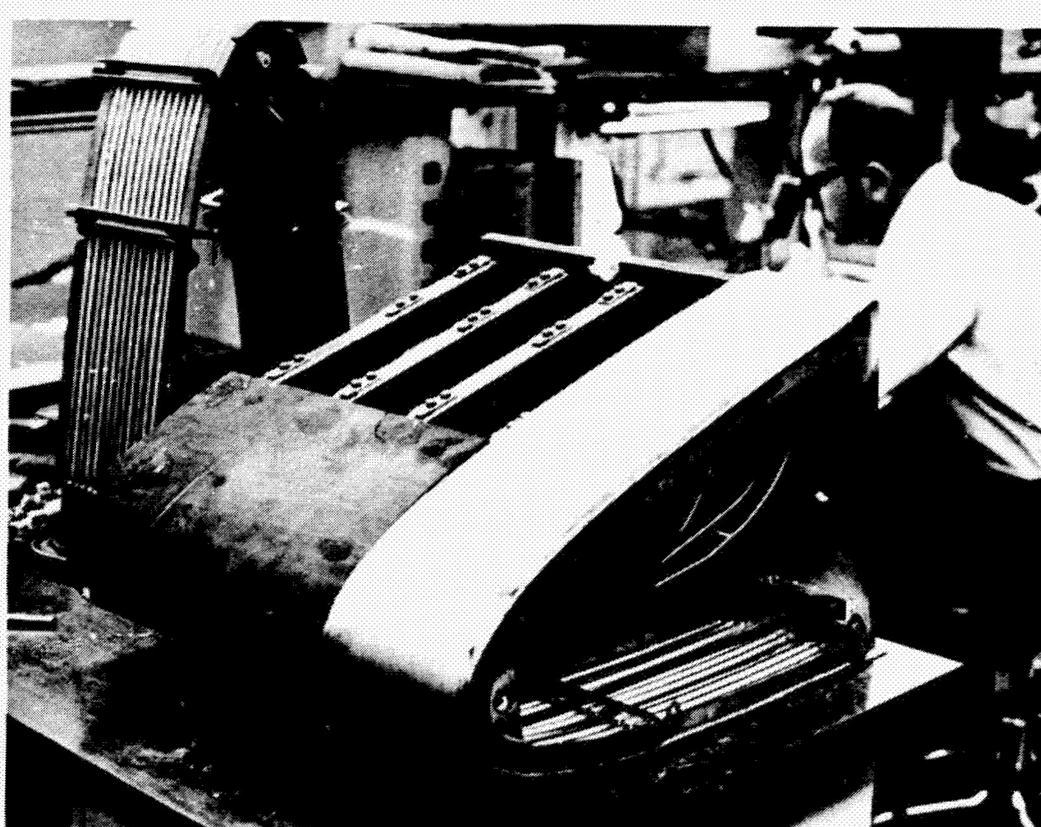

Figure 13

5. TEST PLAN SUMMARY

Two phases of testing were recommended for the MSFC O_2-H_2 hot gas flow facility. Phase I consists of a series of tests intended to verify the performance of the system and to map the ability of the leading edge to isothermalize the leading edge cap. These tests will accurately simulate entry heating environment. The design heating distribution will be simulated very closely, allowing accurate performance mapping. The success criterion for this test series is that the heat pipes maintain the maximum leading edge temperature at or below 1010°C (1850°F) in an environment producing an equilibrium temperature of 1315°C (2400°F), at an angle of attack of 0.1745 rad (10 deg.).

Phase II tests are for demonstration of 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 (supposedly 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 pipe operating temperature not exceed 1093°C (2000°F).

Additional tests are recommended to provide supplementary information that would be difficult to obtain in the MSFC hot gas facility. Basically these would be tests to establish the sensitivity of the design to varying "g" levels and also the ultimate performance of the heat pipe system.

6. CONCLUSIONS/RECOMMENDATIONS

The experience in the construction of the two leading edge test modules indicates that the concept presents minimal development risk. Further, the manufacturing processes are relatively straightforward and conventional metal fabrication techniques, e.g., cold forming, welding, and brazing. Heat pipe servicing and processing demands the requisite facilities and experience. Once completed, however, the heat pipes may be assembled by unsophisticated methods. The heat pipe cooled leading edge concept is unique in that it embodies advanced technology without requiring advanced fabrication techniques.

The program results indicated that conventional heat pipes may be easily used in two dimensional shapes. Thus, the cooling concept is applicable to wing and tail leading edge surfaces, air inlet leading edges, and other similar shapes, such as the chines on certain types of hypersonic flight vehicles.

The application of heat pipe cooling to the Space Shuttle is within the state of the art. The applicability of heat pipes is, however, dependent on both the environment and configuration. The configuration establishes the performance limit by the amount of leading edge surface for cooling. Thus the heat pipe design may not simply be substituted for another design subsequent to a design freeze. Early analysis sufficient to establish the design characteristics specific for the shuttle mission and configuration is necessary for the heat pipe leading edge to remain a workable alternate to the carbon-carbon leading edge.