RADIATIVE, ACTIVELY COOLED PANEL TESTS RESULTS

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INTRODUCTION

This paper describes a test program and some preliminary test results on a 0.61 m (2 ft.) by 1.22 m (4 ft.) radiative, actively cooled panel (RACP). The RACP (described in references 1 and 2) incorporates all of the essential features of a full scale 0.61 m (2 ft.) by 6.1 m (20 ft.) panel designed to withstand a uniform incident heat flux of 136 kW/m^2 (12 Btu/ft^2-sec) to a 422 K (300°F) surface temperature. The structure was designed to carry a uniform inplane limit load of $\pm$210 kN/m ($\pm$1200 lb/in) and a uniform normal pressure of $\pm$6.89 kPa (+1.0 psi). Additionally, the panel was designed to sustain, without failure or coolant leakage, 20 000 cycles of fully reversed load.

RADIATIVE AND ACTIVELY COOLED PANEL (RACP)

(Figure 1)

The RACP features corrugation-stiffened beaded-skin René 41 shields backed by a thin layer of high temperature insulation contained within a stainless steel foil package, and an adhesively bonded aluminum honeycomb sandwich structure with half round coolant tubes next to the outer skin. Frames representative of typical transport construction support the panel at 0.61 m (2 ft.) intervals. The aluminum panel duplicates the essential features of the full scale design except that the coolant inlet and outlet manifolds located at the panel ends are only 1.22 m (4 ft.) apart rather than 6.1 m (20 ft.). The heat shield has a longitudinal row of fasteners to simulate a splice and transverse joints which allow thermal growth. The longitudinal splice was not necessary for this panel but was included since the heat shield design does require a limited number of such splices. Performance evaluation of the RACP consisted of preliminary static thermal/mechanical loading and aerothermal flow tests in the facilities indicated on figure 2.

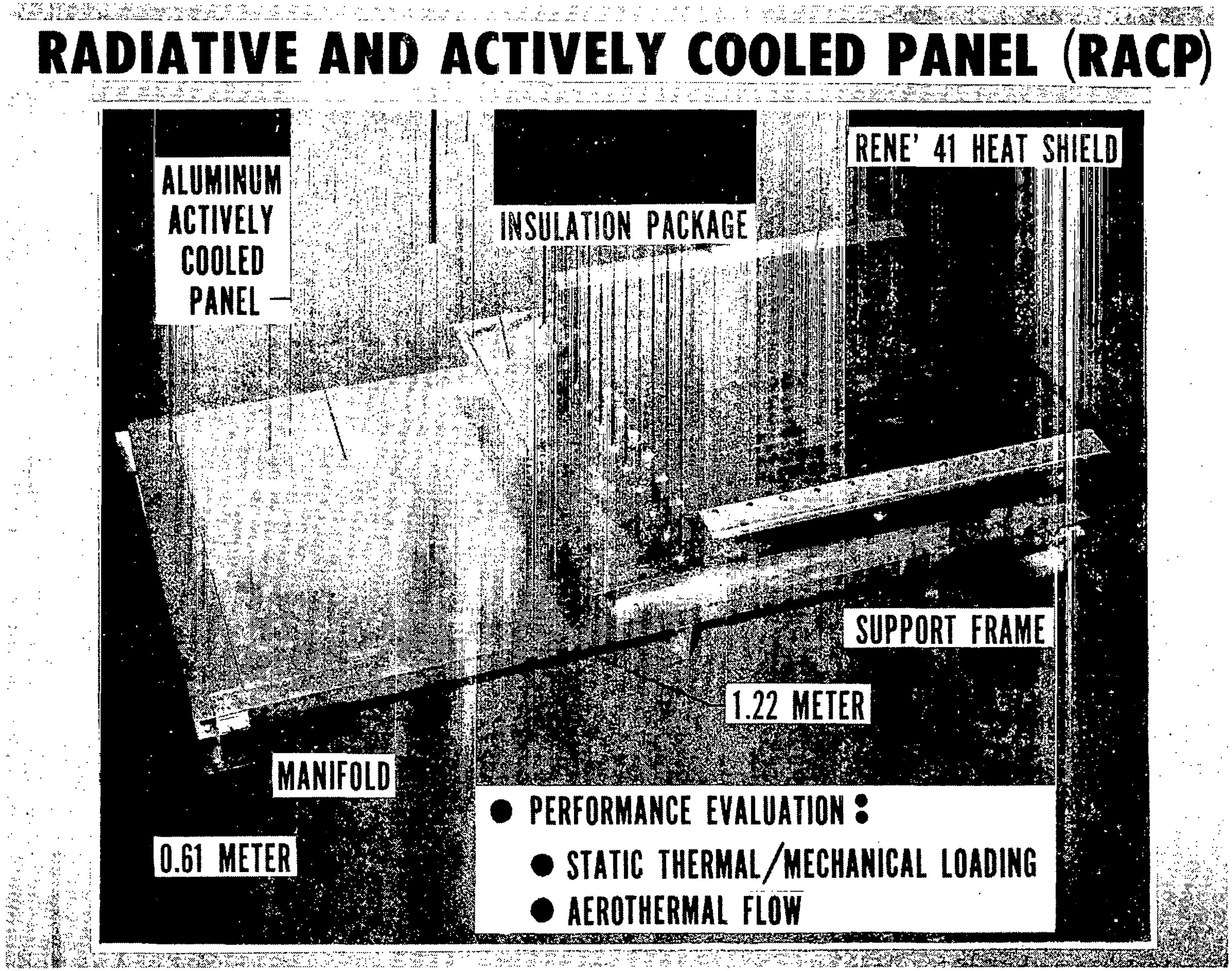

RADIATIVE AND ACTIVELY COOLED PANEL (RACP)
ALUMINUM ACTIVELY COOLED PANEL
INSULATION PACKAGE
RENE' 41 HEAT SHIELD
SUPPORT FRAME
1.22 METER
MANIFOLD
0.61 METER
● PERFORMANCE EVALUATION:
● STATIC THERMAL/MECHANICAL LOADING
● AEROTHERMAL FLOW

Figure 1

PANEL TESTS

(Figure 2)

Two Langley facilities were used to evaluate the RACP performance. The active cooling test stand (ACTS) employs a bank of air cooled radiant heaters to provide long term heating of test articles of up to 284 kW/m^2 (25 Btu/ft^2-sec). At the same time a uniaxial fatigue testing machine can be used to impose cyclic loading of up to $\pm$489 kN ($\pm$110 000 lb.). The Langley 8-foot high-temperature structures tunnel (8-foot HTST) is a M=7 blowdown facility which simulates aerodynamic heating conditions at altitudes ranging from 24 km (80 000 ft.) to 40 km (132 000 ft.) and imposes realistic pressure loading on test specimens. Details of the 8-foot HTST and appropriate test techniques for flight weight test articles are discussed in reference 3. Coolant flow to the RACP for tests in either facility was provided by the cooling system shown in figure 3.

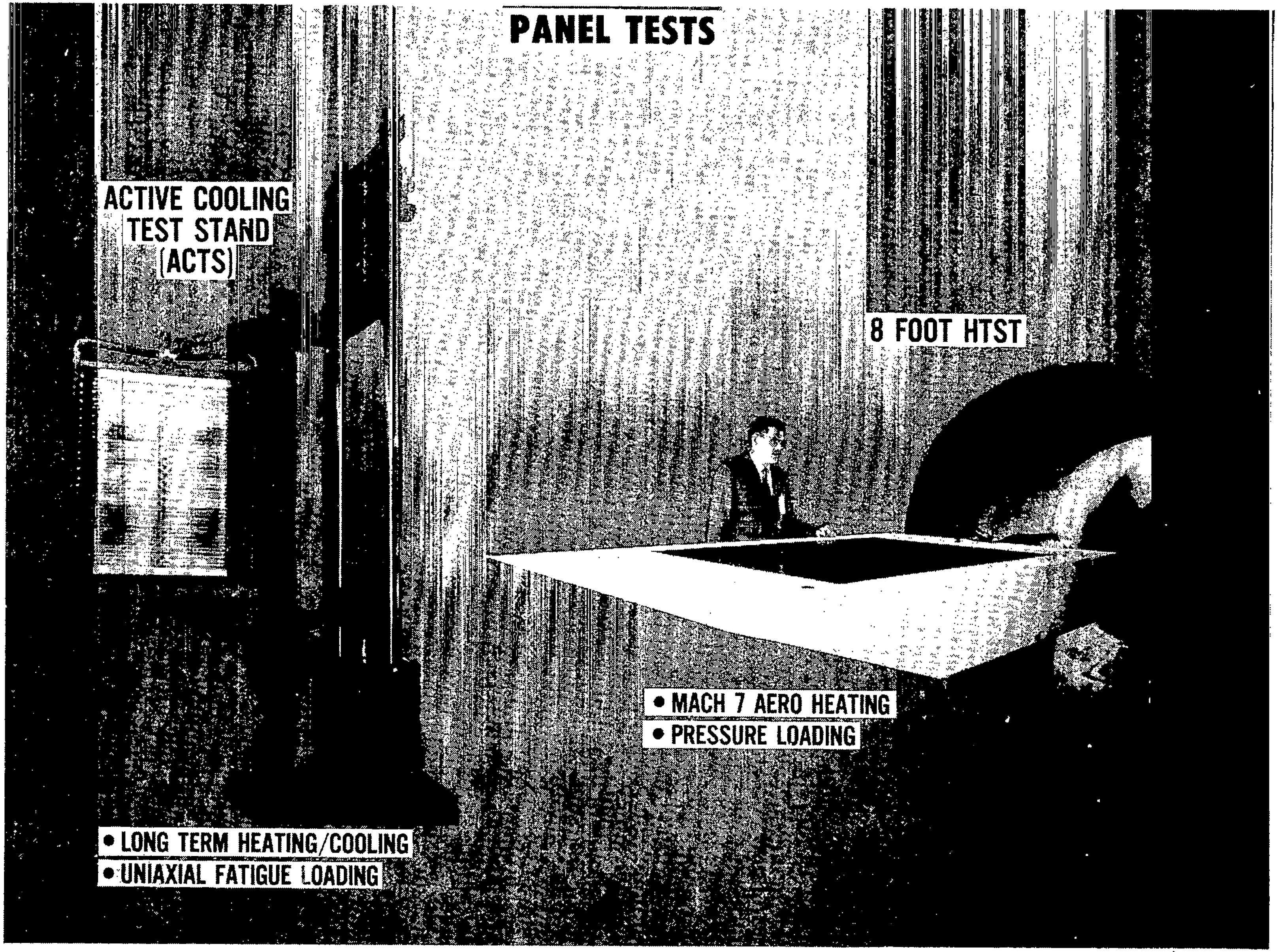

PANEL TESTS
ACTIVE COOLING
TEST STAND
(ACTS)
8 FOOT HTST
• MACH 7 AERO HEATING
• PRESSURE LOADING
• LONG TERM HEATING/COOLING
• UNIAXIAL FATIGUE LOADING

Figure 2

ACTS COOLING SYSTEM

(Figure 3)

A chilled (244 K (-20°F)) 60/40 mass solution of ethylene glycol/water was used to cool the RACP. The cooling system consists of a 19 kiloliters (5000 gal.) storage tank, circulating pumps, flow control valves and a 47 kW (13.5 ton) refrigeration unit. As shown on the figure inset, independent pumping systems circulate the coolant from the storage tank through the panel and the refrigeration unit. Coolant mass flow rate and the coolant pressure and temperature at the RACP inlet were controlled by the flow system and the coolant pressure and temperature at the RACP outlet were monitored during the tests. Heated coolant from the RACP was mixed with chilled coolant from the storage tank to maintain the desired inlet temperature.

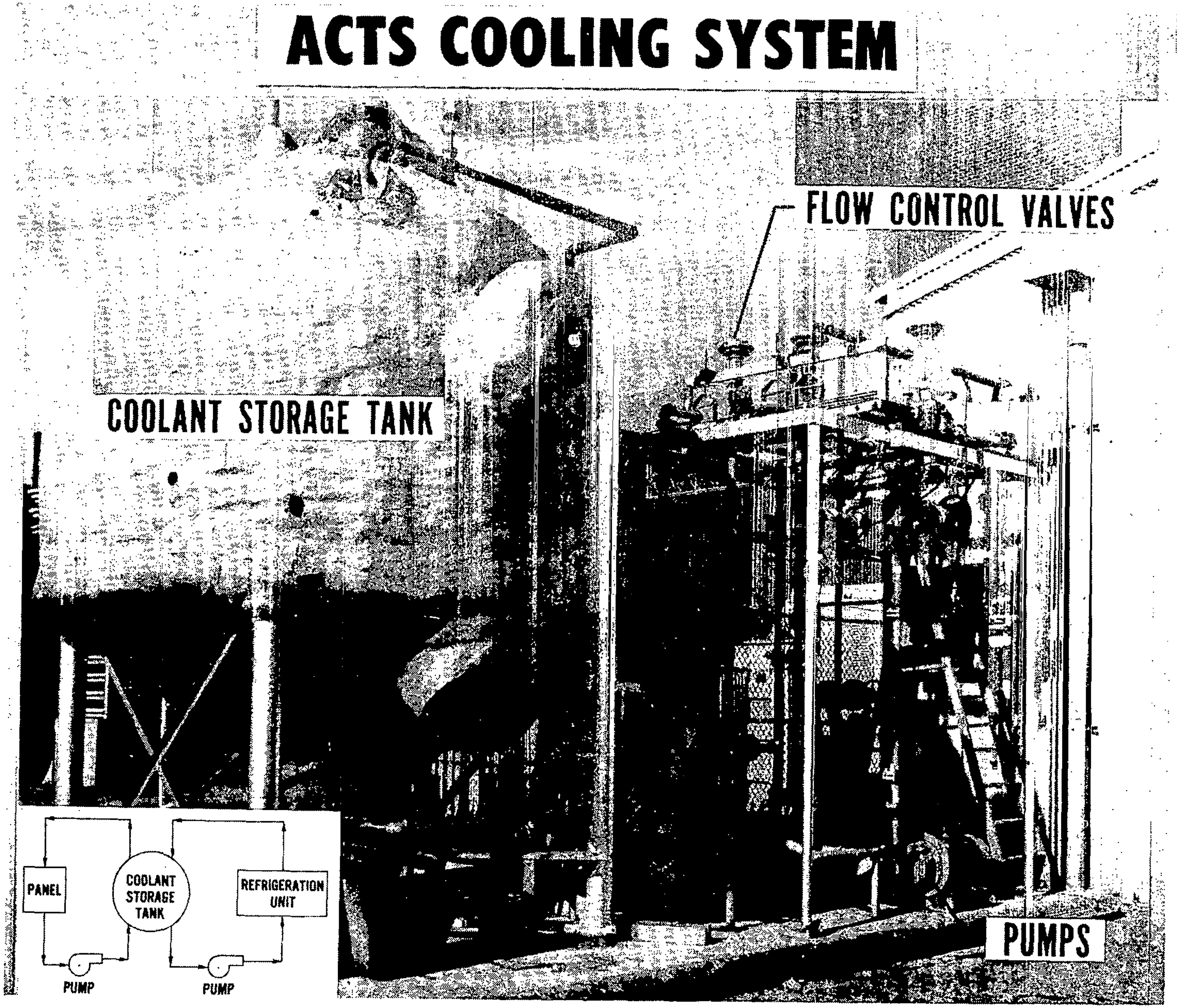

ACTS COOLING SYSTEM
FLOW CONTROL VALVES
COOLANT STORAGE TANK
PUMPS
PANEL
COOLANT STORAGE TANK
REFRIGERATION UNIT
PUMP
PUMP

Figure 3

TEST PROGRAM FOR RADIATIVE AND ACTIVELY COOLED PANEL

(Figure 4)

The test program for the RACP consists of four types of tests. (1) Preliminary static thermal/structural check-out tests were conducted in ACTS. In these tests the RACP was exposed to the design incident heat flux of 136 kW/m^2 (12 Btu/ft^2-sec), and design limit load of ±210 kN/m (±1200 lb/in.). The coolant flow rate was maintained at the design value of 13 liters/min (3.4 gal./min) and the coolant inlet temperature varied between 272 and 320 K (20 to 120°F). Variation of the coolant inlet temperature allows the 1.22 m (4 ft.) test panel to simulate various regions of the full scale 6.1 m (20 ft.) panel.

(2) Aerothermal performance tests were then conducted in the 8-foot HTST at a nominal Mach number of 7. In these tests the RACP was exposed to the design incident heat flux by aerodynamic heating for various coolant inlet temperatures. An important objective of these tests was to check for hot gas ingress to the cooled aluminum panel which could seriously degrade the performance of the RACP. Other objectives were to look for hot spots on the panel and fasteners and to evaluate heat shield joint motion.

(3) As a part of the ongoing RACP evaluation program the RACP will be reinstalled in the ACTS for some detailed thermal/structural tests including some cyclic loading tests to provide fatigue data for the cooled panel.

(4) Thermal fatigue tests will be conducted on a seperate heat shield specimen to provide life data on such structures which have previously been designed for hundreds of cycles rather than the thousands of cycles required for the RACP.

TEST PROGRAM FOR RADIATIVE AND ACTIVELY COOLED PANEL

- COMPLETED
  - PRELIMINARY STATIC THERMAL/STRUCTURAL CHECK-OUT IN ACTS
    - DESIGN INCIDENT COLD WALL HEAT FLUX: 136 kW/m^2
    - VARIOUS COOLANT INLET TEMPERATURES: 272 TO 320 K
    - DESIGN LIMIT LOAD: ± 210 kN/m
  - AEROTHERMAL PERFORMANCE IN MACH 7 8-ft HTST
    - DESIGN INCIDENT HEAT FLUX
    - VARIOUS COOLANT INLET TEMPERATURES
    - CHECK FOR HOT GAS INGRESS
- FUTURE
  - DETAILED THERMAL/STRUCTURAL TESTS IN ACTS
  - THERMAL FATIGUE TESTS ON SEPARATE HEAT SHIELD SPECIMEN

Figure 4

RENÉ 41 HEAT SHIELD

(Figure 5)

To monitor temperatures over the heat shields, 32 thermocouples were spot welded to the back side of the corrugation stiffening sheet in the locations shown on the figure. The photo also shows the condition of the surface after preliminary tests in ACTS.

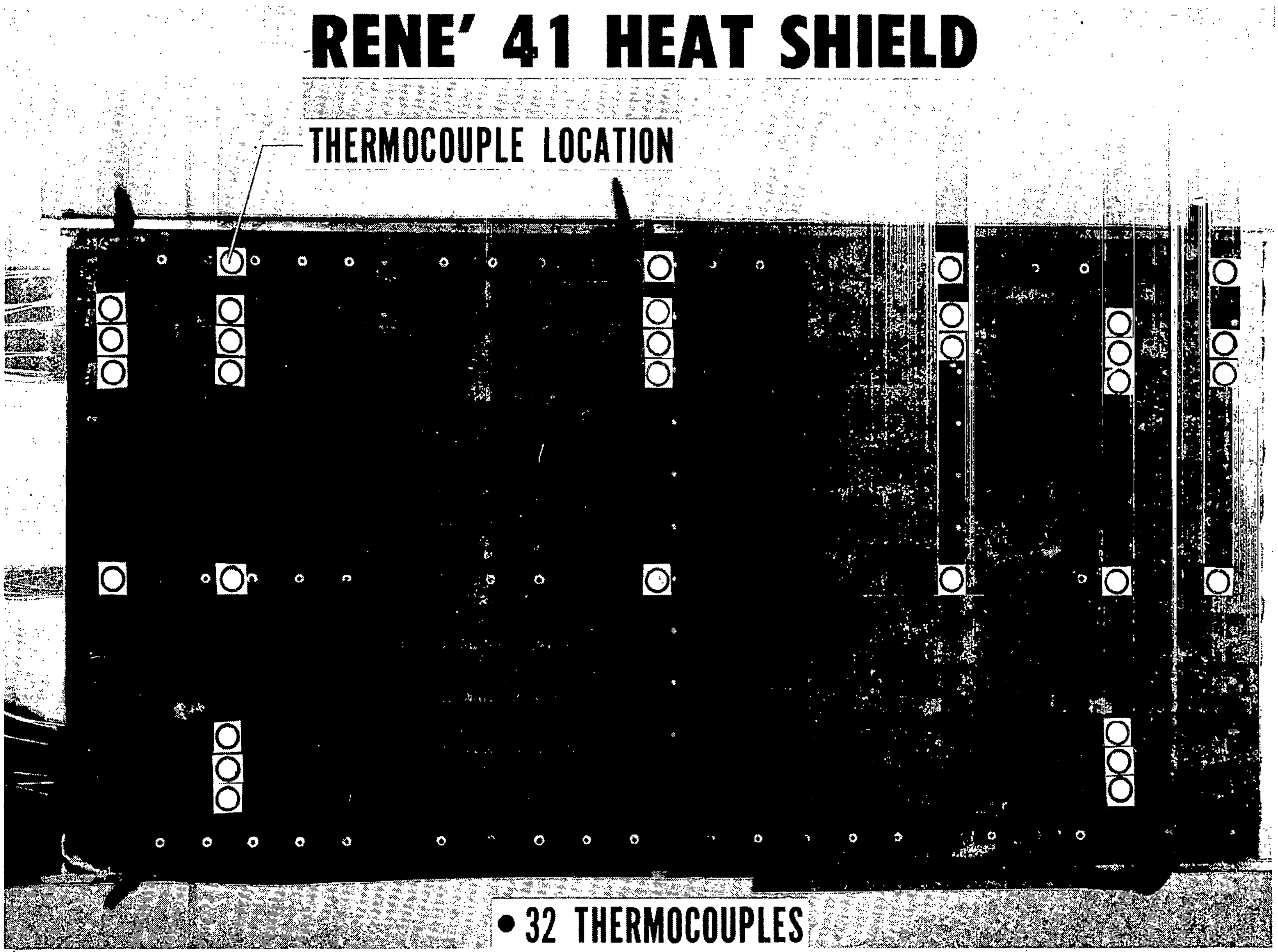

RENE' 41 HEAT SHIELD
THERMOCOUPLE LOCATION
• 32 THERMOCOUPLES

Figure 5

HIGH TEMPERATURE INSULATION BLANKET

(Figure 6)

A total of 19 thermocouples spot welded to small stainless steel tabs which were then spot welded to the insulation package were used to monitor the insulation package temperatures: seven on the hot side and 12 on the cool side. This photo, which was taken after the preliminary tests in ACTS, also shows the condition of the insulation package after several exposures to design operating conditions. The most noticeable effects of the heating are the darkening of the surface from oxidation and the large number of wrinkles induced by thermal expansion of the stainless steel foil package and interference with the heat shield.

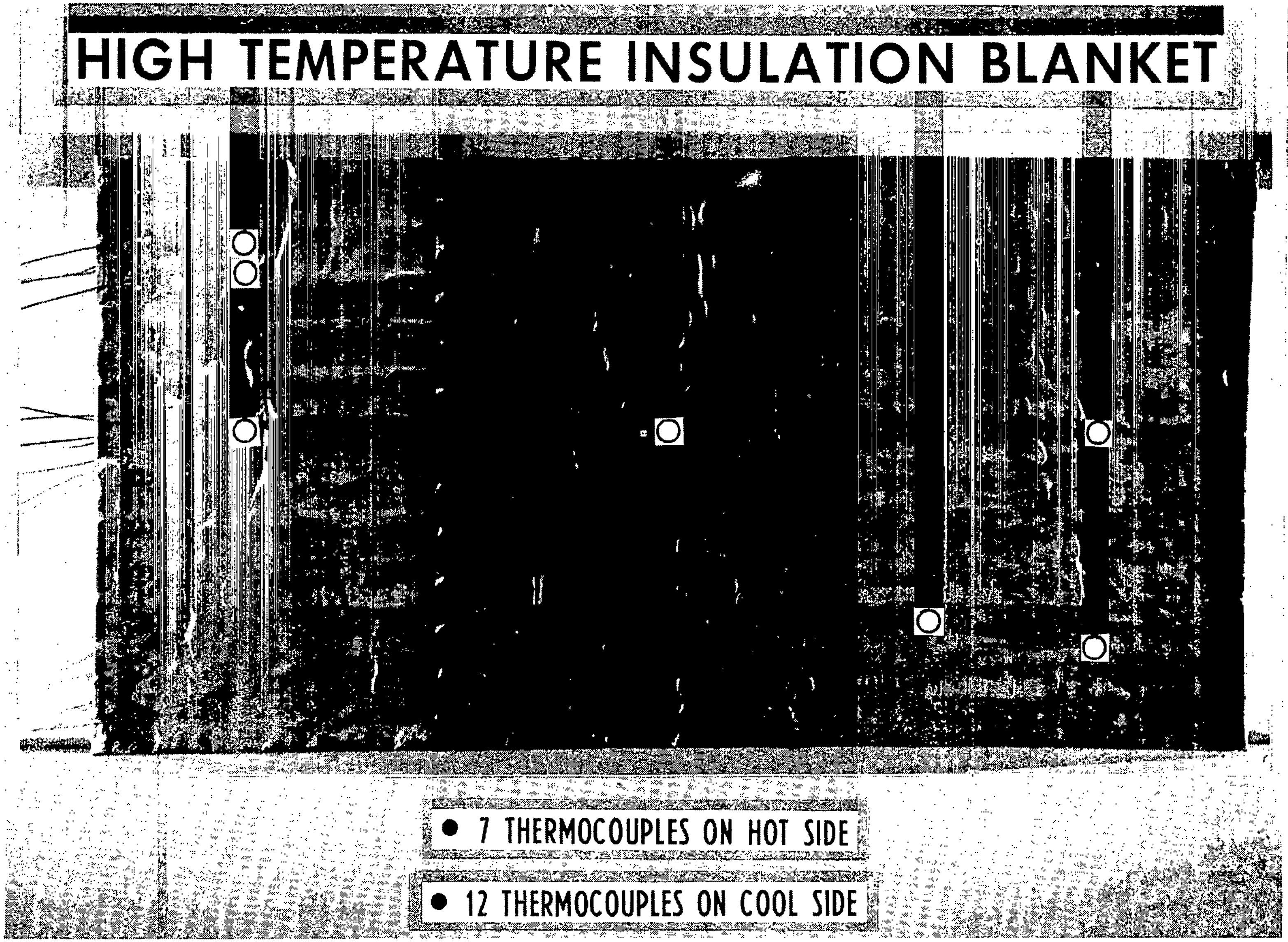

HIGH TEMPERATURE INSULATION BLANKET
• 7 THERMOCOUPLES ON HOT SIDE
• 12 THERMOCOUPLES ON COOL SIDE

Figure 6

COOLED ALUMINUM HONEYCOMB PANEL

(Figure 7)

A total of 120 thermocouples were used to monitor temperatures over the surface of the cooled panel. The thermocouples were bonded to the aluminum surfaces to avoid possible crack starters from welding or peening. To monitor both thermal and mechanical stresses, longitudinal and transverse strain gage pairs were bonded to the panel surfaces at the eleven locations denoted by the white spots on the figure. Before testing, the panel was heated in an oven to 422 K (300°F) to calibrate the temperature sensitivity of the strain gages.

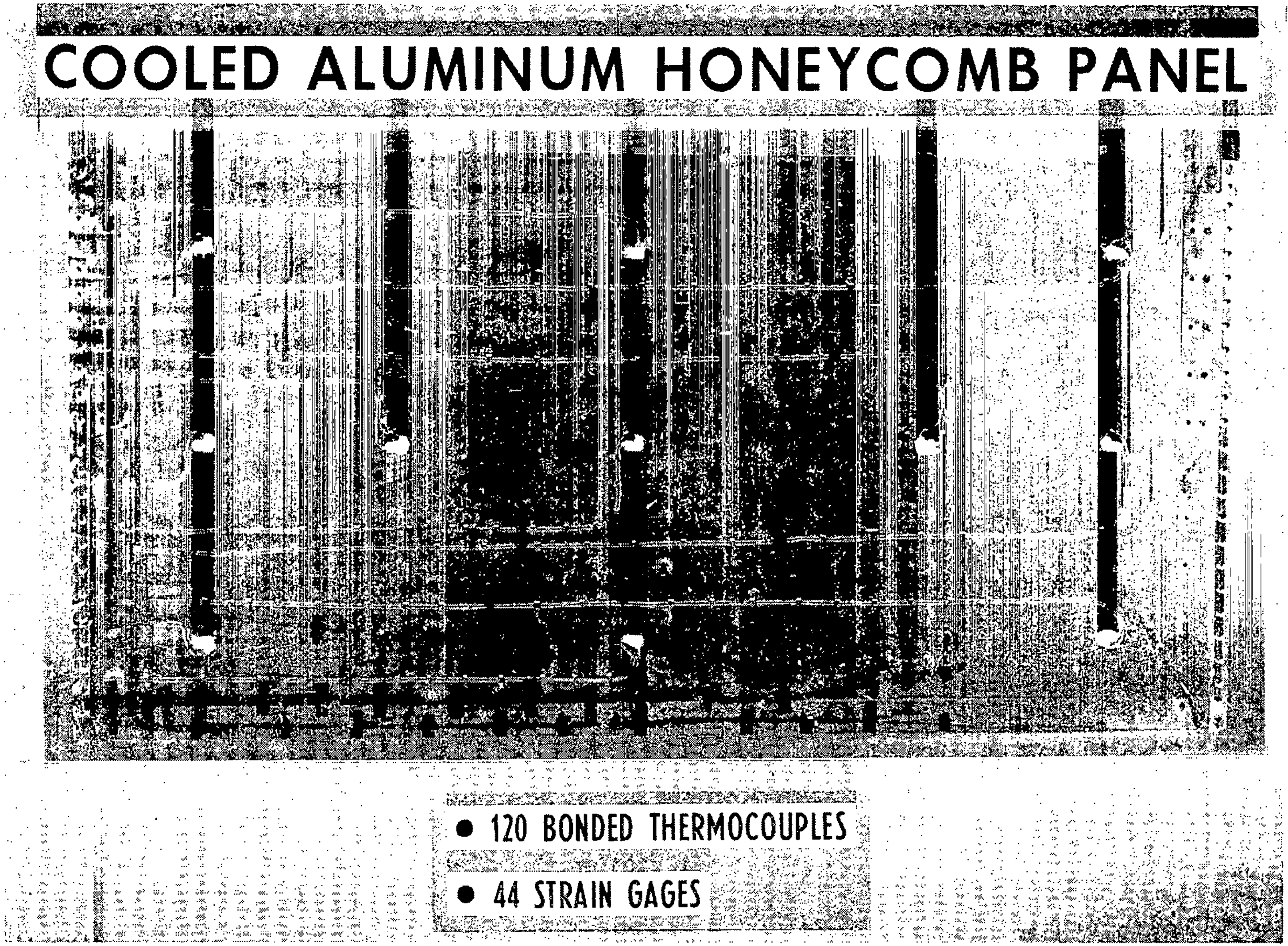

COOLED ALUMINUM HONEYCOMB PANEL
• 120 BONDED THERMOCOUPLES
• 44 STRAIN GAGES

Figure 7

ACTS HEATER SYSTEM

(Figure 8)

This figure shows the ACTS heater in place over the RACP during a hot test. Heater coolant air enters the manifolds on either side of the heater from the supply lines near the bottom of the heaters and is collected by the center manifold and subsequently vented by the large diameter hose at the top of the heaters. Other lines visible in the picture are supply and return lines for the water cooled reflector which encases the heaters. Calibration of the heaters indicated the heat flux variation over the test panel surface was about 10 percent.

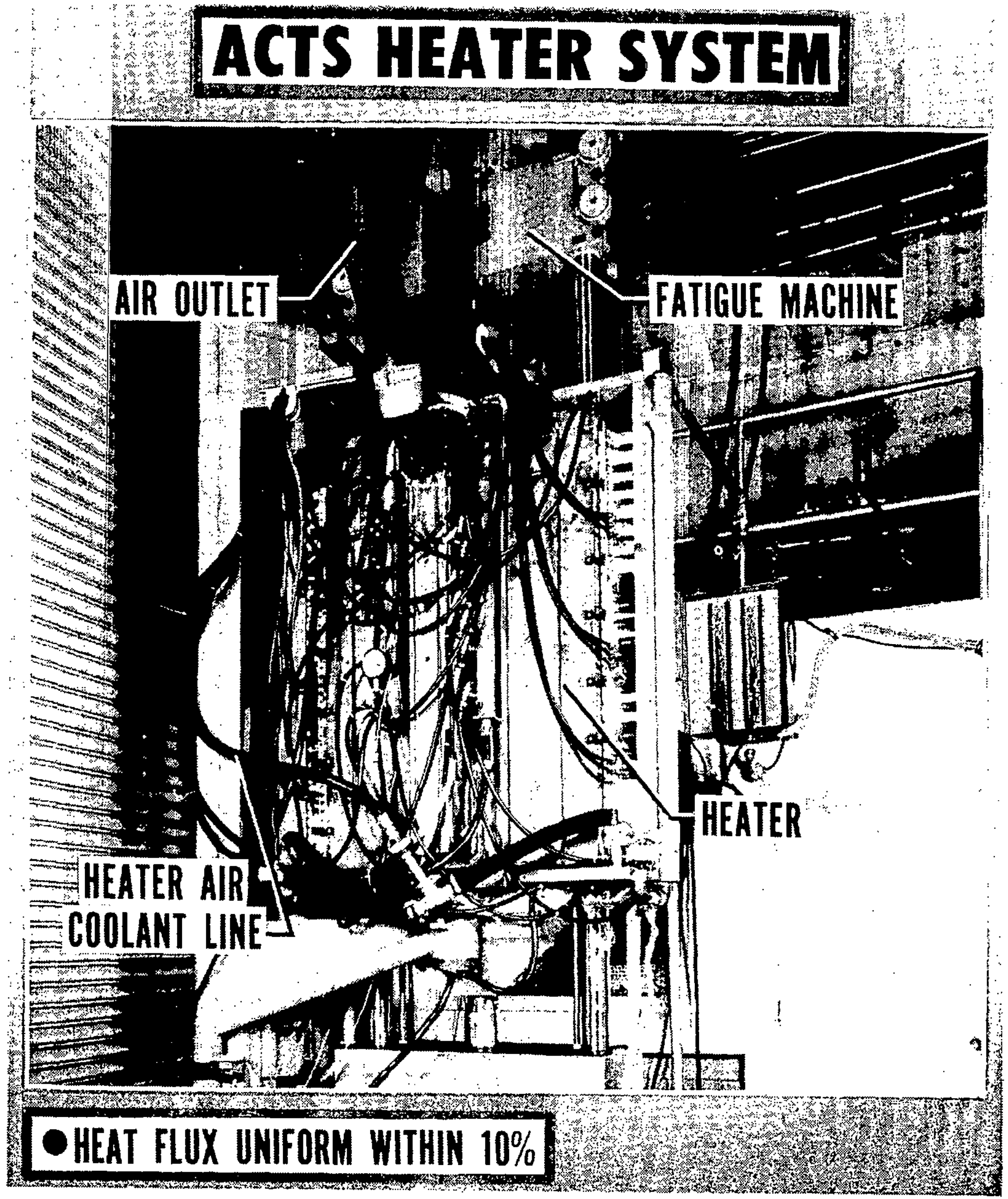

ACTS HEATER SYSTEM
AIR OUTLET
FATIGUE MACHINE
HEATER
HEATER AIR
COOLANT LINE
● HEAT FLUX UNIFORM WITHIN 10%

Figure 8

ACTS PANEL LOADING SYSTEM

(Figure 9)

This figure shows the rear of the RACP during a hot test and illustrates some additional features of the test set-up. The glycol/water coolant supply and return lines are shown on the right side of the figure. The loading heads of the fatigue testing machine are visible at the center top and bottom of the figure. Additional support of the test panel is provided by the linear bearings (denoted frame supports) which are attached to the panel frames. These bearings prevent out-of-plane motion of the frames but permit unrestrained longitudinal thermal expansion of the panel since the bearings are free to move along the vertical rods on either side of the test fixture. Transverse thermal growth is accommodated by slots in the vertical rod supports.

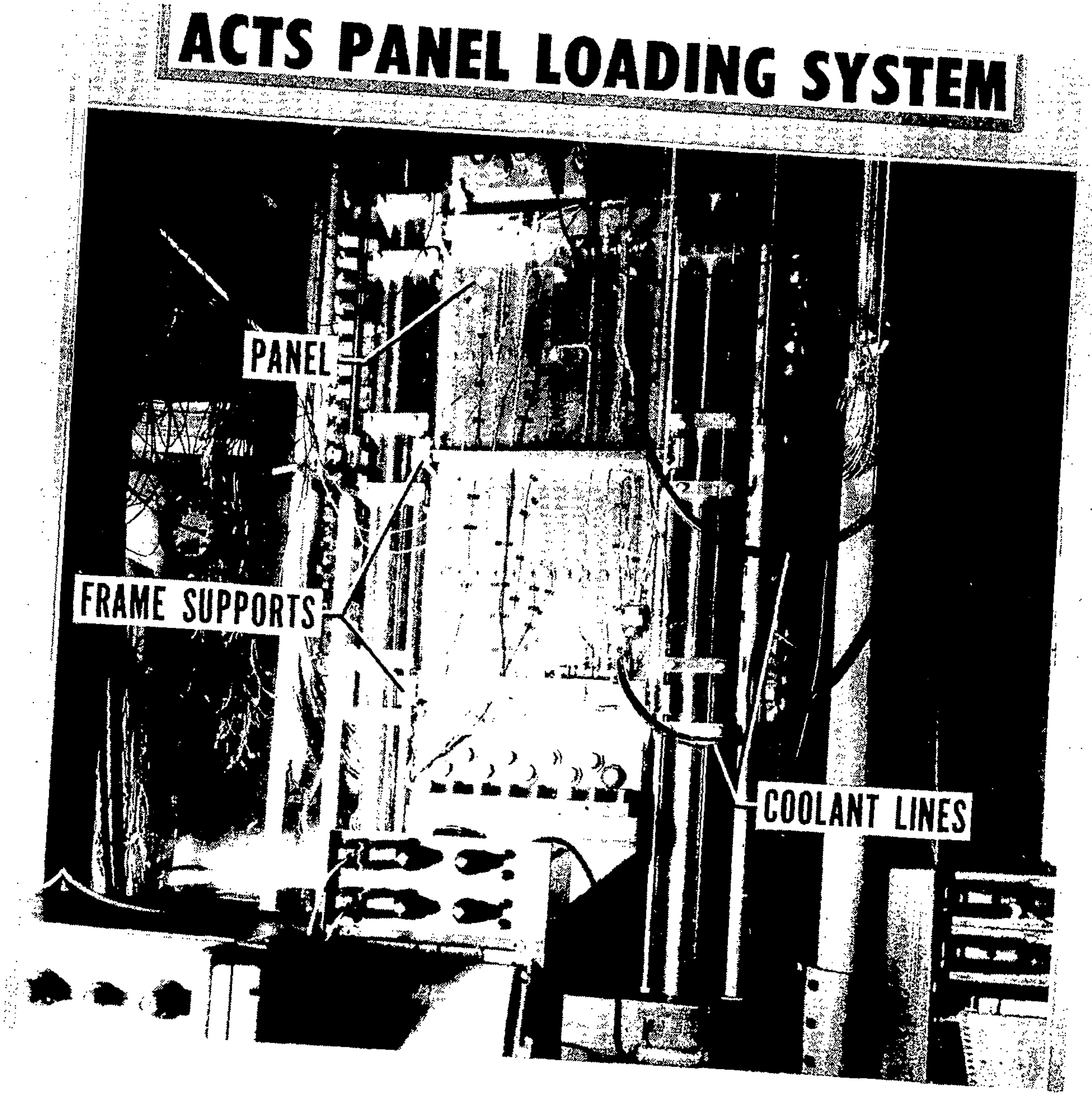

ACTS PANEL LOADING SYSTEM
PANEL
FRAME SUPPORTS
COOLANT LINES

Figure 9

SUMMARY OF RACP TESTS IN ACTS

(Figure 10)

During the preliminary static thermal/structural check-out tests six thermal cycles and 17 limit load cycles (±210 kN/m (±1200 lb/in.)) were imposed on the RACP for a total of 4.8 hours at operating temperature. The performance of the RACP was within 90 percent of predicted values for heat shield temperatures, cooled panel temperatures, heat flux absorbed by the cooled panel and mechanical stresses in the aluminum panel skins. Although strain measurements were taken under heated conditions, time constraints have prevented analysis of these data to determine thermal stresses in the cooled panel. Post test examination of the RACP components revealed no apparent structural degradation and the tests revealed no test-to-test degradation of thermal performance. Additionally, no evidence of coolant leakage was found during the 4.8 hours of operation.

SUMMARY OF RACP TESTS IN ACTS

- 6 THERMAL CYCLES
- 17 LOAD CYCLES
- 4.8 HOURS AT OPERATING TEMPERATURE
- PERFORMANCE WITHIN 90% OF PREDICTED VALUES
  - HEAT SHIELD TEMPERATURE: 978 VERSUS 1081 K
  - COOLED PANEL TEMPERATURE: 326 VERSUS 340 K
  - ABSORBED HEAT FLUX: 8.2 VERSUS 9.1 kW/m^2
  - MECHANICAL STRESS: 81.7 VERSUS 86.0 MPa
- NO APPARENT THERMAL/STRUCTURAL DEGRADATION
- NO COOLANT LEAKAGE

Figure 10

PANEL TEMPERATURES

(Figure 11)

Typical RACP test temperatures are shown as a function of distance from the coolant inlet. Temperatures are shown for the heat shields and cooled panel and at the coolant inlet and outlet. The bars connecting the symbols for the heat shields indicate the lateral variation in heat shield temperatures. Center line temperatures only are shown for the cooled panel. Although there is some scatter in the measured heat shield temperatures the overall level agrees well with predicted values. The cooled panel temperatures are in good agreement with predicted values. The measured coolant temperature rise of 8.9 K (16°F) along with the measured mass flow gave a calculated average absorbed heat flux of 8.2 kW/m^2 (0.72 Btu/ft^2-sec) compared to the design flux of 9.1 kW/m^2 (0.8 Btu/ft^2-sec). The predicted temperatures on figure 11 are calculated values based on the measured absorbed heat flux.

The figure inset shows a temperature distribution through the thickness of the RACP and indicates that although the heat shields are operating at 985 K (1313°F), the cooled panel, less than 1.27 cm (0.5 in.) away, is operating at about 331 K (136°F) and that the majority of this temperature drop occurs through the 0.32 cm (0.125 in.) thick insulation package.

After the preliminary static thermal/structural check-out tests in ACTS the RACP was tested in the Langley 8-foot high-temperature structures tunnel. A schematic of the tunnel is shown in figure 12.

PANEL TEMPERATURES

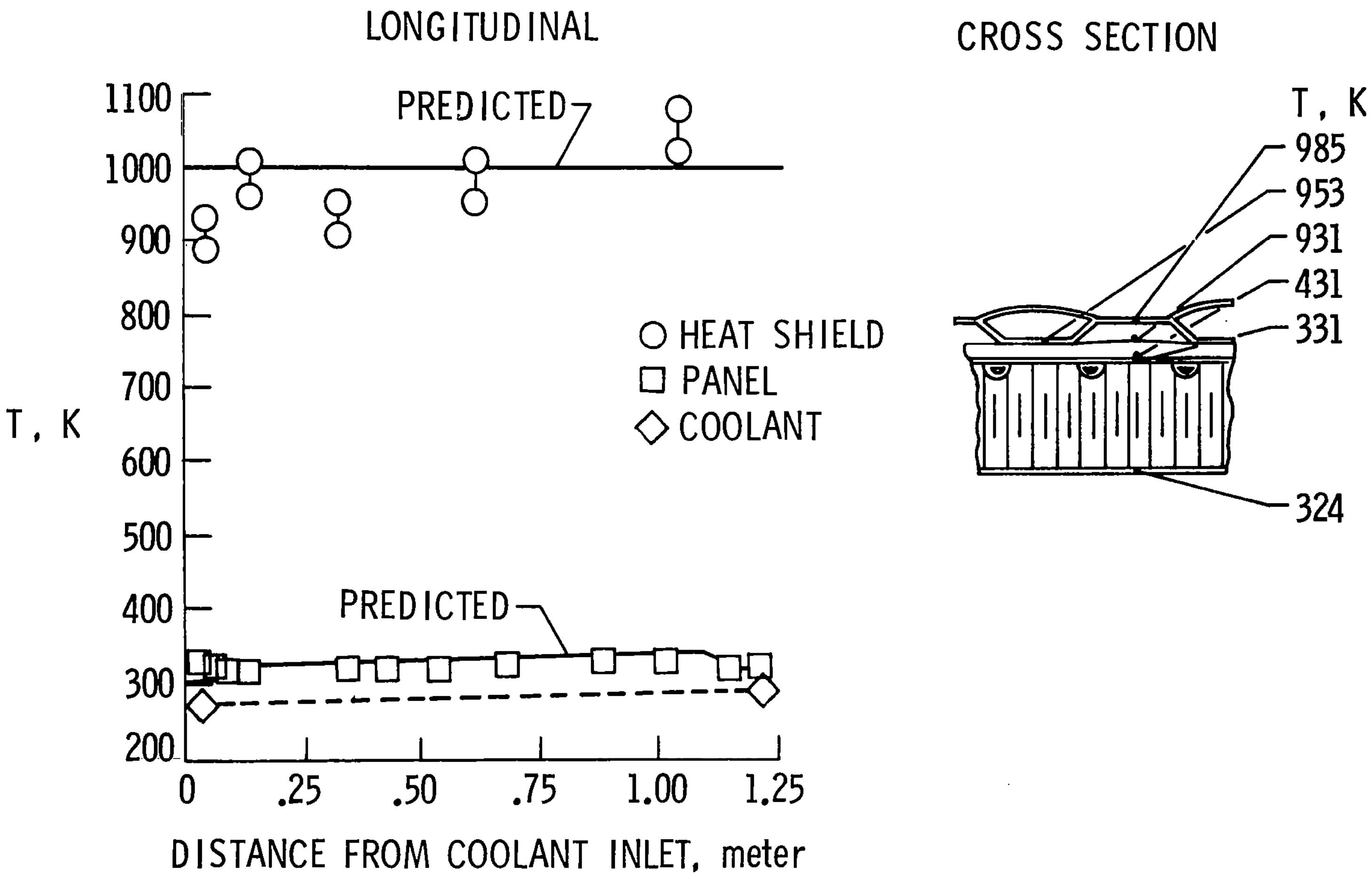


Figure 11

LANGLEY 8-FOOT HIGH-TEMPERATURE STRUCTURES TUNNEL

(Figure 12)

The tunnel is a blowdown facility which uses products of combustion as a test medium. Fuel and air are burned in the combustor and the combustion products are expanded in the nozzle to a nominal free stream Mach number of 7; flow continues through the test section and diffuser sections and into the ambient atmosphere. The air ejector is used to lower the pressure in the test section and thereby reduce starting loads on the test article which is stored in the pod beneath the test section while the tunnel is started. The test article is then injected into the stream once flow is established. Since the tunnel is a blowdown facility with limited run time, radiant preheaters are used to bring test articles to thermal equilibrium before exposure to the test stream. Some details of the heater apparatus are shown in figure 13.

LANGLEY 8-FOOT HIGH-TEMPERATURE STRUCTURES TUNNEL

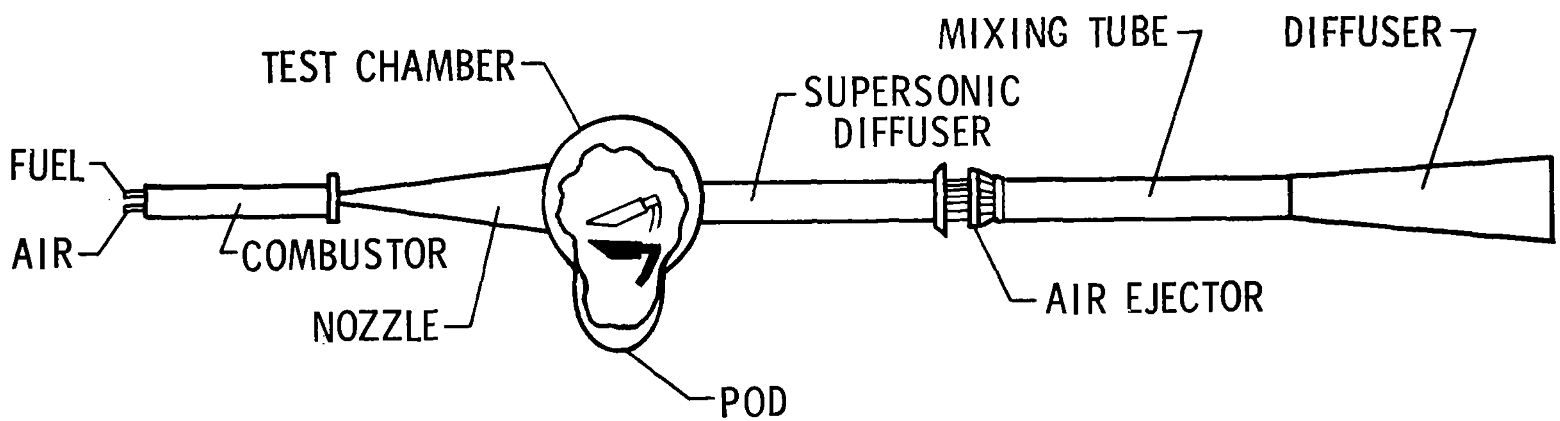


Figure 12

8-FT HTST RADIANT PREHEATING APPARATUS

(Figure 13)

Before the tunnel test begins the test article is located in the pod beneath the test section. The inset on the right shows the radiant preheaters in place over the test article. After desired thermal equilibrium is reached the tunnel is started. Once flow is established the heaters are retracted (lower left inset) and the test article is raised to the test position (upper left inset). At the end of the test the procedure is reversed and the heaters may be used to follow a preselected cool-down rate for the test article.

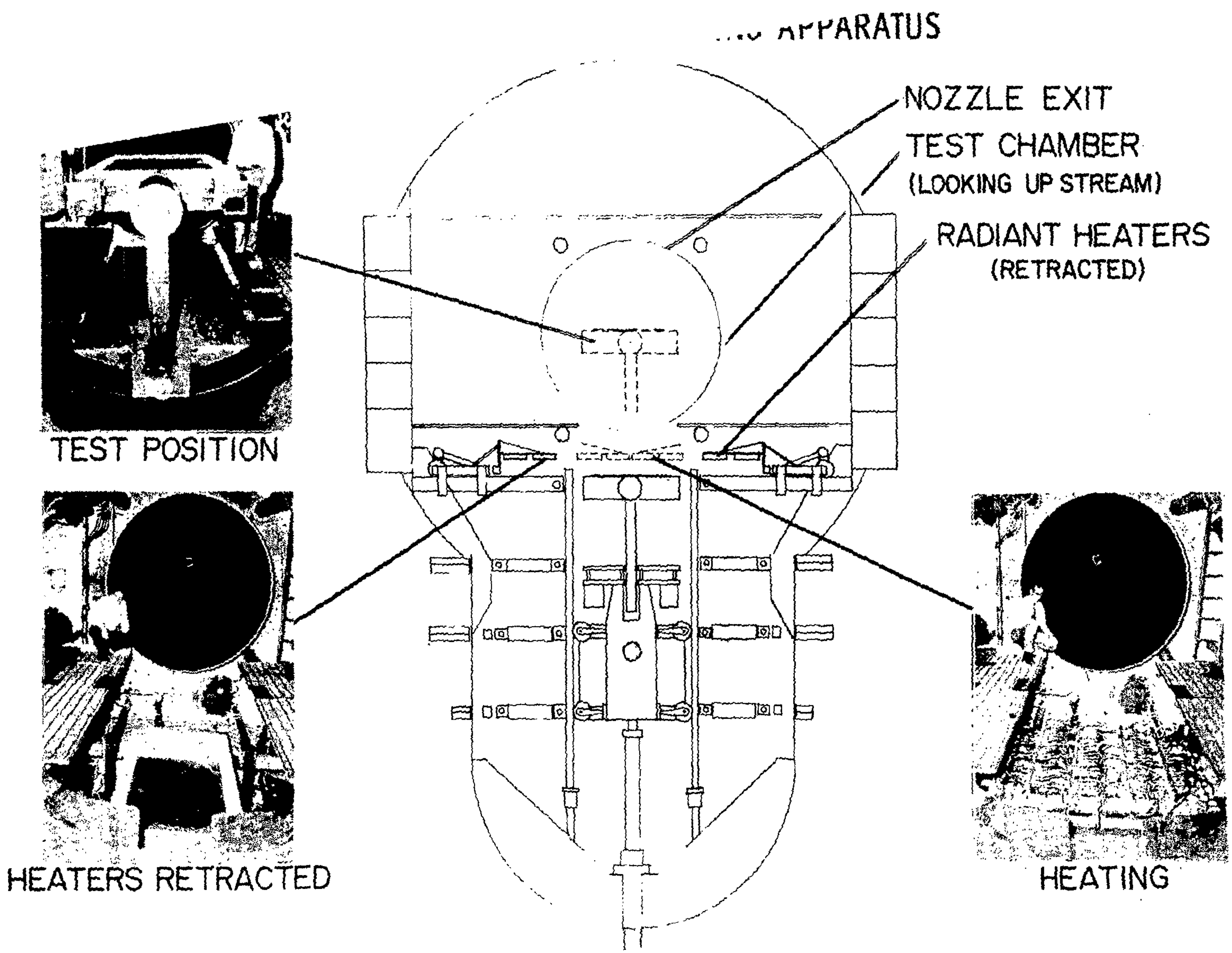

APPARATUS
NOZZLE EXIT
TEST CHAMBER
(LOOKING UP STREAM)
RADIANT HEATERS
(RETRACTED)
TEST POSITION
HEATERS RETRACTED
HEATING

Figure 13

RACP MOUNTED IN WIND TUNNEL

(Figure 14)

For tests in the 8-foot high-temperature structures tunnel the RACP was mounted in a fixture known as the 2-D test sled. The RACP is located in a test cavity near the center of the fixture. Aerodynamic fences along either side of the test sled maintained nominally two-dimensional flow over the test cavity. A row of small metal spheres near the leading edge of the test sled tripped the flow boundary layer to insure turbulent flow over the test panel. The heating rate was controlled by preselected values of the tunnel total pressure (17 MPa, (2500 psia)), stagnation temperature (1920 K (3000°F)) and test sled angle of attack. For these tests the sled was pitched down approximately 8°.

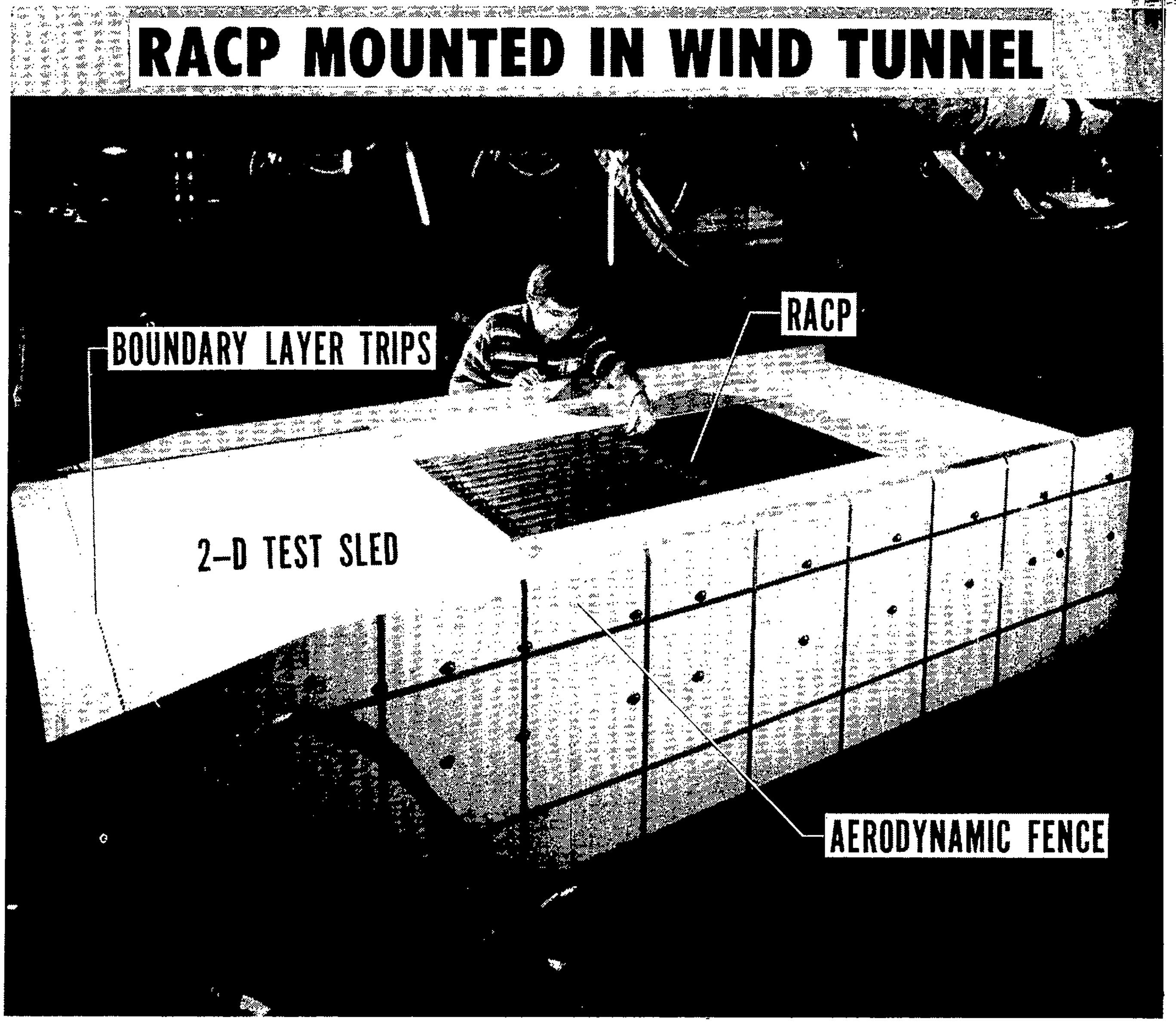

RACP MOUNTED IN WIND TUNNEL
BOUNDARY LAYER TRIPS
RACP
2-D TEST SLED
AERODYNAMIC FENCE

Figure 14

TEMPERATURE PROFILE FOR TYPICAL TUNNEL RUN

(Figure 15)

This figure illustrates the RACP temperature response for a typical tunnel run. While the RACP was located in the tunnel pod, the desired coolant inlet temperature and pressure and flow rate through the cooled panel were established. The RACP was then radiantly heated at 2.8 K/sec (5°F/sec) until the heat shields reached 1061 K (1450°F). The RACP was then allowed to come to thermal equilibrium. After the RACP reached equilibrium the tunnel starting process was begun and after flow was established (note change in time scale) the heaters were retracted and the RACP injected into the stream. During this process the heat shields cooled to about 950 K (1250°F). The aerodynamic heating provided by the stream rapidly reheated the heat shields to a near equilibrium temperature of about 1090 K (1500°F). However, because of the short run time and lag in thermal response of the cooled panel provided by the insulation, the cooled panel did not begin to recover to its initial equilibrium temperature. At the end of the run the RACP was retracted from the stream, the tunnel shut down, and the preheaters used to control the RACP cool-down rate. During the time in the stream an infrared scanner was used to monitor temperatures on the heat shield surface. Some typical data from these scans are shown in figure 16.

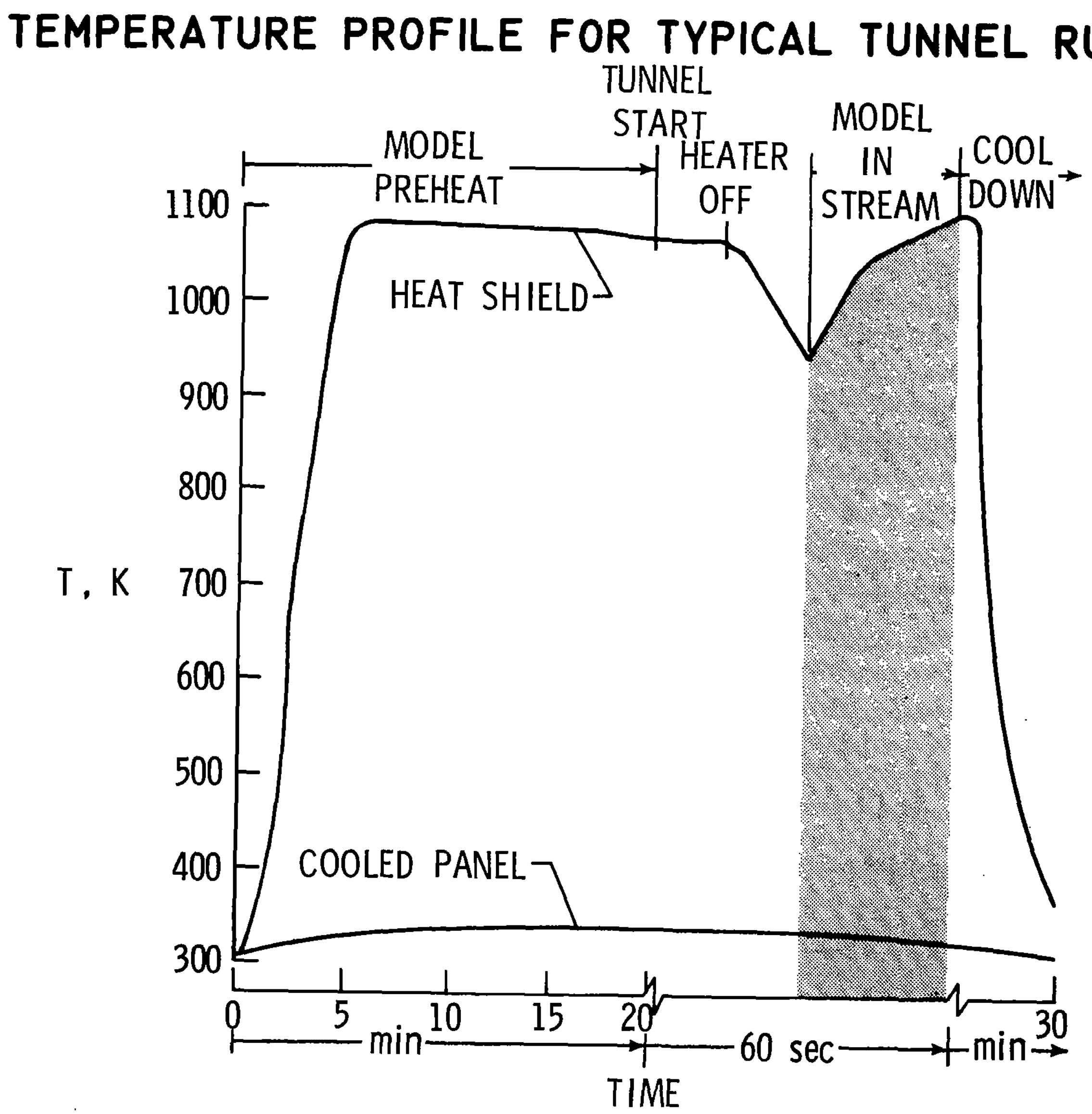

TEMPERATURE PROFILE FOR TYPICAL TUNNEL RUN
TUNNEL START
MODEL PREHEAT
HEATER OFF
MODEL IN STREAM
COOL DOWN
HEAT SHIELD
COOLED PANEL
T, K
1100
1000
900
800
700
600
500
400
300
0
5
10
15
20
30
min
60 sec
min
TIME

Figure 15

INFRARED TEMPERATURE DATA FROM HEAT SHIELD

(Figure 16)

The infrared system provides immediate pictorial temperature data which can later be electronically digitized to yield quantitative temperature data. Three different types of output are indicated on the figure. The contour plot shows the overall temperature level attained by the heat shields and also indicates hot spots caused by fastener heads which protrude into the stream. The temperature relief map shows the transition from the cooler regions of the test sled to the hotter heat shield and clearly shows the variation of heating across the shields caused by the beaded heat shield surface. The single temperature profile corresponds to a slice across the heat shields at a row of fasteners and indicates that the fastener heads are about 28 K (50°F) hotter than the surrounding surface.

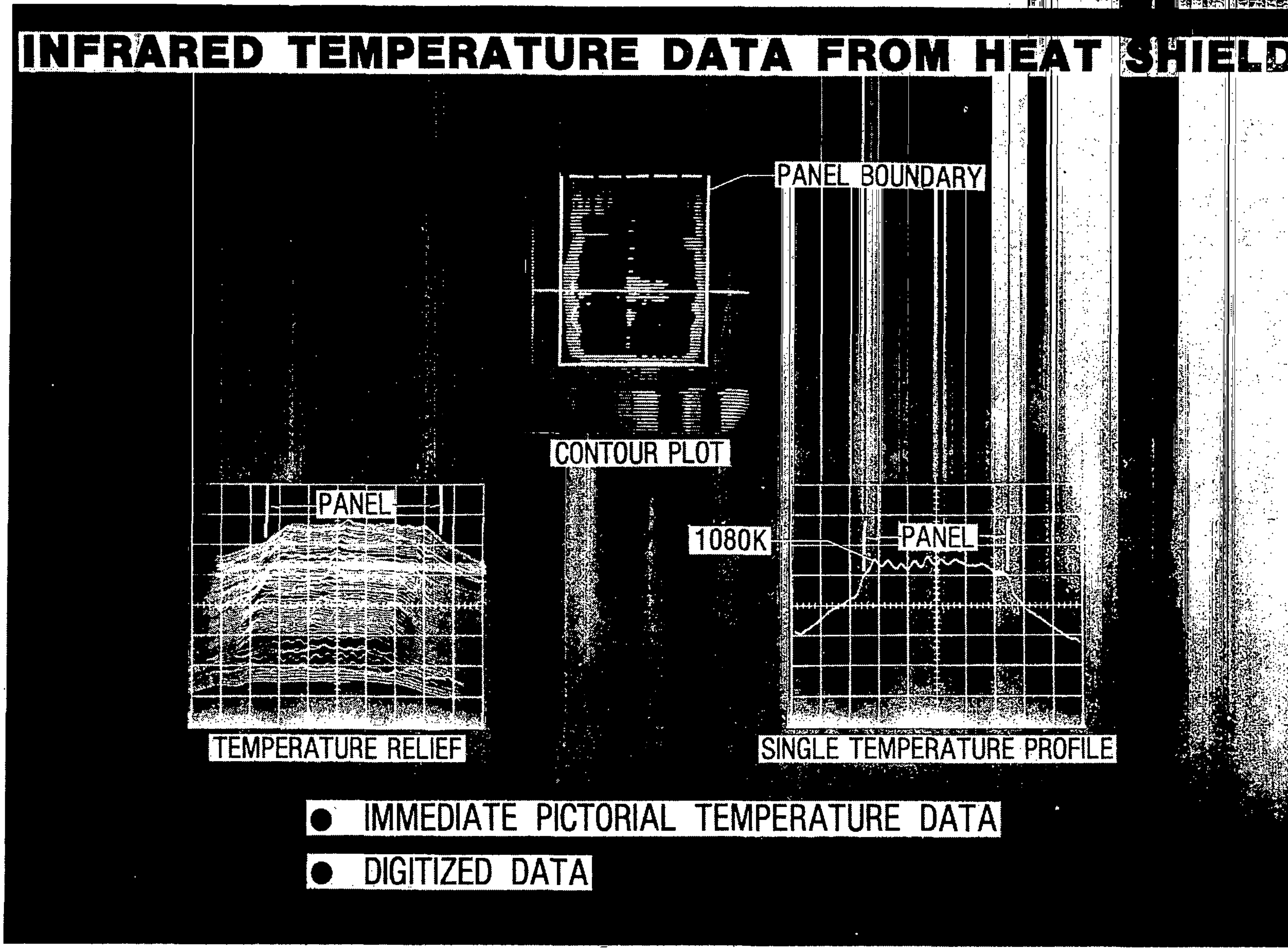

INFRARED TEMPERATURE DATA FROM HEAT SHIELD
PANEL BOUNDARY
CONTOUR PLOT
PANEL
TEMPERATURE RELIEF
1080K
PANEL
SINGLE TEMPERATURE PROFILE
● IMMEDIATE PICTORIAL TEMPERATURE DATA
● DIGITIZED DATA

Figure 16

RENÉ 41 SHIELD AFTER WIND TUNNEL TESTS

(Figure 17)

The photos show the post test condition of the heat shields and indicate that there was no structural degradation to the heat shields as a result of the preliminary static tests in ACTS or the aerodynamic tests in the wind tunnel. Scratch marks at the heat shield joints indicate 0.6 cm (0.25 in.) movement which is consistent with the 790 K (1420°F) temperature change from ambient conditions. Additionally, there was no evidence of binding at the joints or of buckling or wrinkling of the heat shield skins.

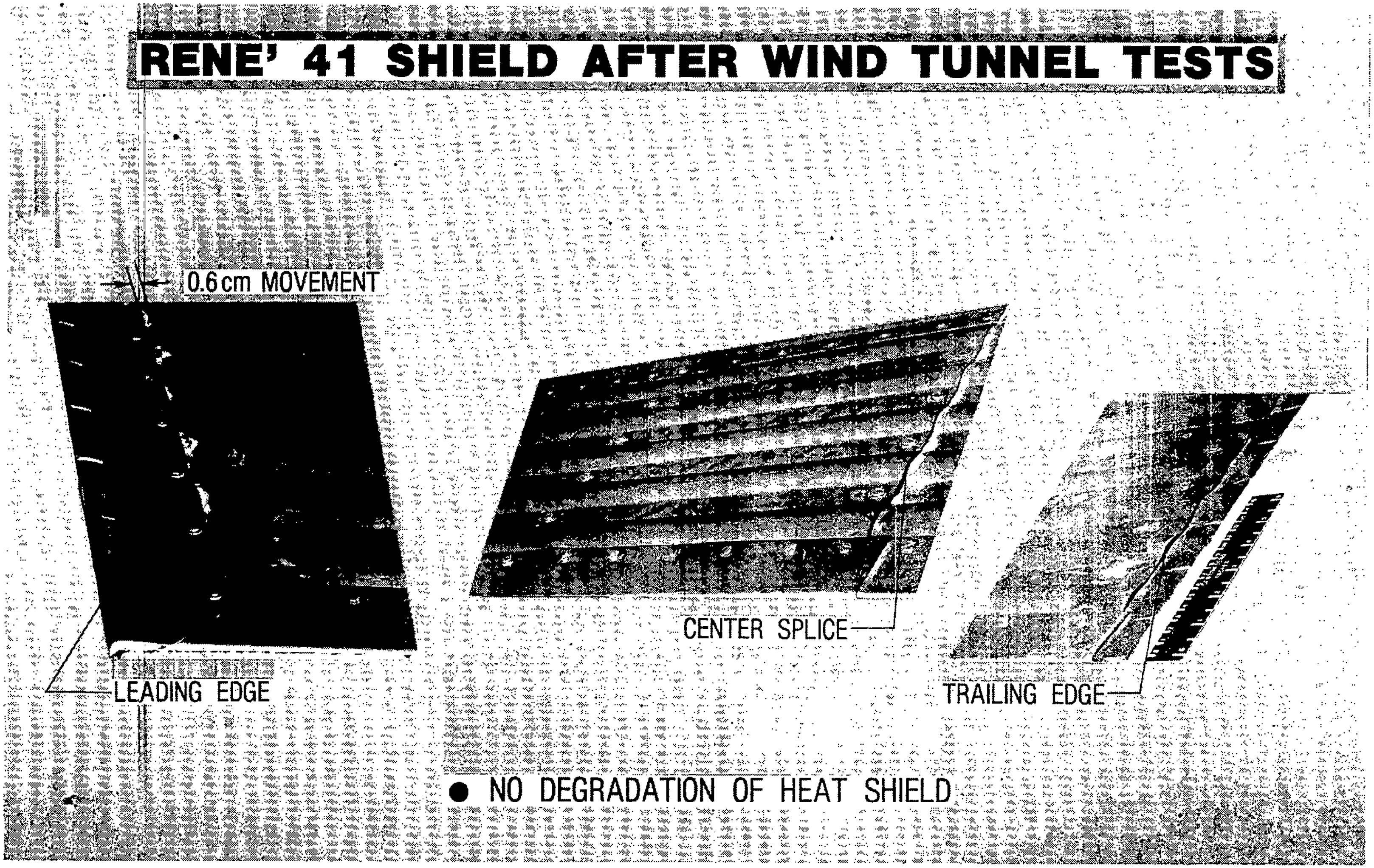

RENE' 41 SHIELD AFTER WIND TUNNEL TESTS
0.6 cm MOVEMENT
LEADING EDGE
CENTER SPLICE
TRAILING EDGE
● NO DEGRADATION OF HEAT SHIELD

Figure 17

SUMMARY OF RACP TESTS IN 8-FT. HTST

(Figure 18)

The tunnel tests imposed an additional 15 thermal cycles, 3.5 hours at operating temperatures and 2.2 minutes exposure to M=7 flow on the RACP. The panel responded to aerodynamic heating as predicted: the heat shields reached 1090 K (1500°F), the cooled panel reached a maximum temperature of 367 K (200°F) and the cooled panel absorbed heat flux was 11.1 kW/m^2 (0.98 Btu/ft^2-sec). There were no unexpected hot spots and no evidence of hot gas ingress to the cooled panel. Additionally, there was no evidence of coolant leakage.

SUMMARY OF RACP TESTS IN 8–FT HTST

- 15 THERMAL CYCLES
- 3.5 HOURS AT OPERATING TEMPERATURES
- 2.2 MINUTES EXPOSURE TO MACH 7 FLOW
- PANEL RESPONSE TO AERO CONDITIONS AS PREDICTED
  - MAX HEAT SHIELD TEMPERATURE: 1089 K
  - MAX PANEL TEMPERATURE: 367 K
  - ABSORBED HEAT FLUX: 11.1 kW/m^2
- NO UNEXPECTED HOT SPOTS
- NO HOT GAS INGRESS TO COOLED PANEL

Figure 18

FUTURE TESTS FOR RACP

(Figure 19)

The RACP will be reinstalled in ACTS for some detailed thermal/structural tests including simulated inlet and outlet conditions for the full scale panel, simulated coolant system failure, simulated flight maneuvers and cyclic mechanical loading at temperature. The panel will not be tested to failure since it may be used as a test bed for alternate heat shield concepts. Thermal fatigue tests will be conducted on a seperate heat shield specimen. These tests are described in figure 20.

FUTURE TESTS FOR RACP

- DETAILED THERMAL/STRUCTURAL TESTS IN ACTS
  - FULL SCALE PANEL SIMULATION
    - INLET CONDITIONS
    - OUTLET CONDITIONS
  - COOLANT SYSTEM FAILURE SIMULATION
    - ABORT HEATING TRAJECTORY
    - ONE-HALF COOLANT FLOW RATE
  - SIMULATED FLIGHT MANEUVER
  - CYCLIC MECHANICAL LOADING AT TEMPERATURE
- THERMAL FATIGUE TESTS ON SEPARATE HEAT SHIELD SPECIMEN

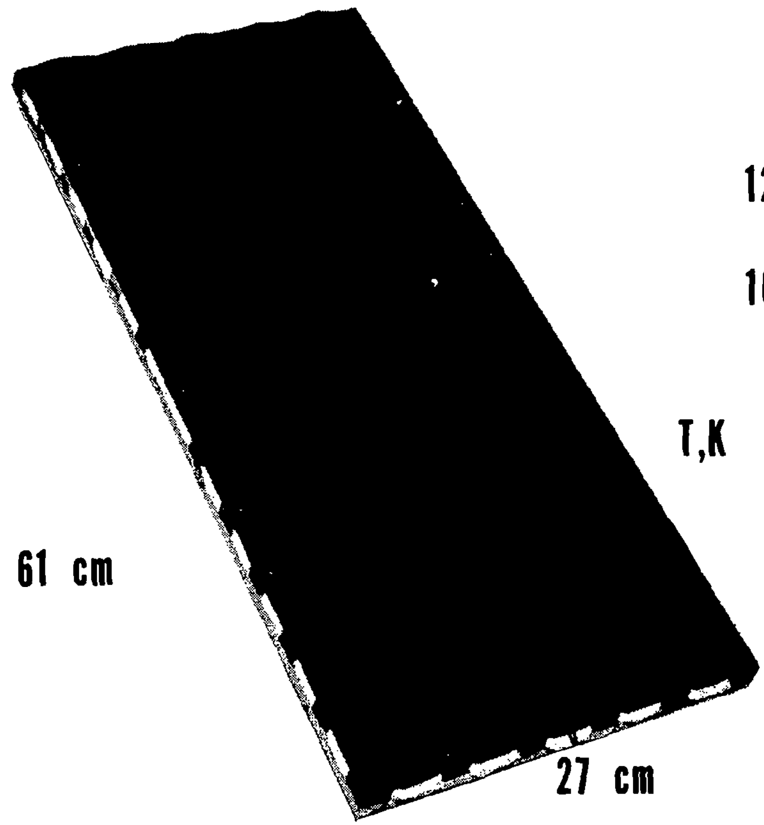
Figure 19

HEAT SHIELD THERMAL FATIGUE TESTS

(Figure 20)

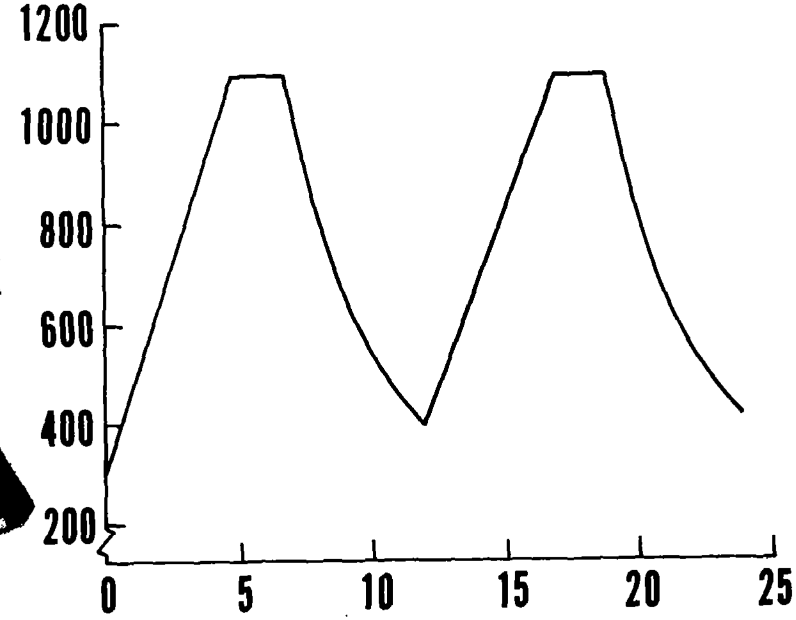
Most heat shields have been designed for hundreds of thermal cycles rather than the thousands of cycles required for hypersonic transport vehicles. Since little thermal fatigue data exist beyond about a hundred cycles, the specimen shown on the left in figure 20 will be thermally cycled to determine its thermal fatigue characteristics. The specimen will be heated at 2.8 K/sec (5°F/sec) to 1090 K (1500°F), allowed to come to equilibrium and then cooled as indicated by the curve on the left of figure 20. Tests will be run until the specimen fails or accrues 5000 thermal cycles.

HEAT SHIELD THERMAL FATIGUE TESTS



TEST SPECIMEN

- GOAL = 5000 CYCLES



CYCLIC TEMPERATURE

Figure 20

CONCLUSIONS

(Figure 21)

The preliminary tests of the RACP were successful in that the mechanical loading gave predicted mechanical stresses, the panel responded thermally as predicted, the overall panel behavior was acceptable and the tests revealed no surprises. Future tests will check the detailed thermal/structural response of the panel and will address the life characteristics of both the cooled panel and the heat shields.

CONCLUSIONS

- PRELIMINARY TESTS WERE SUCCESSFUL
  - MECHANICAL LOADING GAVE PREDICTED STRESSES
  - THERMAL RESPONSE AS PREDICTED
  - PANEL BEHAVIOR GOOD
  - AEROTHERMAL TESTS GAVE NO SURPRISES

- FUTURE TESTS WILL CHECK DETAILS
  - THERMAL/STRUCTURAL
  - FATIGUE OF PANEL
  - HEAT SHIELD FATIGUE

Figure 21

REFERENCES

1. Ellis, D.A.; Pagel, L.L.; Schaeffer, D.M.: Design and Fabrication of a Radiative Actively Cooled Honeycomb Sandwich Structural Panel for a Hypersonic Aircraft. NASA CR-2957, 1978.

2. Koch, Leland C.: Design and Fabrication of a Radiative Actively Cooled Honeycomb Sandwich Panel. Recent Advances in Structures for Hypersonic Flight, NASA CP-2065, 1978. (Paper no. 13 in this compilation.)

3. Deveikis, William D.; Bruce, Walter E., Jr.; and Karns, John R.: Techniques for Aerothermal Tests of Large, Flightweight Thermal Protection Panels in a Mach 7 Wind Tunnel. NASA TM X-71983, 1974.

*U.S. GOVERNMENT PRINTING OFFICE: 1979 - 636-808