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REVIEW OF CONVECTIVELY COOLED STRUCTURES FOR HYPERSONIC FLIGHT

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MAY 1986

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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665

REVIEW OF CONVECTIVELY COOLED STRUCTURES FOR HYPERSONIC FLIGHT

SUMMARY

Resurgent interest in development of Aerospace Plane and "Orient Express" type vehicles promises to stretch structural technology for hypersonic flight vehicles to the uppermost limits. Although much of the structure for such vehicles may consist of hot structural concepts, significant portions of the structure may require active cooling of some type to survive the hostile environment. Despite a lack of recent research activity for cooled structures, a significant body of unclassified knowledge exists concerning such structures. Contractual and in-house research conducted mainly by NASA's Langley Research Center during the decades of the 60's and 70's on vehicles very similar to the proposed "Orient Express" has provided a substantial, though by no means complete, data base for convectively cooled hypersonic flight structures. This data base provides a solid foundation for the extensive maturation program required to bring convectively cooled structures technology to an acceptable state of readiness for hypersonic flight vehicles. Pertinent results from the research conducted in the 60's and 70's are reviewed. Specifically, results are presented for regeneratively cooled structural concepts which have a relatively high heat flux capability and use the hydrogen fuel directly as a coolant; and for structural concepts which use a secondary coolant loop to absorb incident heating and then transfer the absorbed heat to the liquid hydrogen fuel as it flows to the engines. Results are presented to indicate application regions in terms of heat flux capability for various concepts and benefits for each concept. Additionally, experience gained and costs involved with design, fabrication, and testing of full-scale convectively cooled structures are discussed.

INTRODUCTION

Resurgent interest in development of Aerospace Plane and "Orient Express" type vehicles promises to stretch structural technology for hypersonic flight vehicles to the uppermost limits. For such vehicles to become a practical reality, techniques must be developed for the design and fabrication of low-mass airframe structures that can withstand repeated and prolonged exposure to the severe aerodynamic heating encountered in hypersonic flight. Advancement of structural technology for this hostile flight environment has been the object of continuing coordinated research at the NASA Langley Research Center.

A 1966 review of structural prospects for hypersonic vehicles (ref. 1) emphasized hydrogen fuel-cooled structures for engines and passive hot structures of high temperature materials for airframes. Predicated on prospects of hydrogen fueled scramjets with low cooling requirements (ref. 2), convectively cooled airframe structures of conventional low-temperature low-mass materials (e.g. aluminum) that used the hydrogen fuel as the heat sink for all cooling requirements were proposed in 1970 (ref. 3). Figure 1 illustrates both the direct use of the hydrogen fuel as a coolant in the outer vehicle surface structure and the indirect use in a secondary cooling loop. In the indirect application, a secondary coolant flows through a closed-loop circuit with passages in the surface structure to transport the absorbed aerodynamic heating to a heat exchanger where the heat is rejected to the cryogenic hydrogen flowing to the engines. Theoretical heat flux limits based on heat transfer through the exposed surface for superalloy materials and hydrogen coolant range from 4000 to 10000 Btu/ft^2-sec. and for aluminum with ethylene glycol in water as the coolant range from 550 to 7000 Btu/ft^2-sec, practical considerations may reduce these limits by one to two orders of magnitude.

This paper reviews results from contractual and in-house research conducted during the decades of the 1960's and 70's on structures for vehicles similar to the proposed "Orient Express" that has provided a substantial, though by no means complete, data base for convectively cooled structures for hypersonic flight. Both regeneratively cooled (direct hydrogen fuel cooling) structural concepts and secondary cooling circuit structural concepts are discussed. Results are presented to indicate application regions in terms of heat flux capability for various concepts and benefits for each concept. Additionally, experience gained and costs involved with design, fabrication, and testing of full-scale convectively cooled structures are discussed.

CONVECTIVE ACTIVELY COOLED STRUCTURE

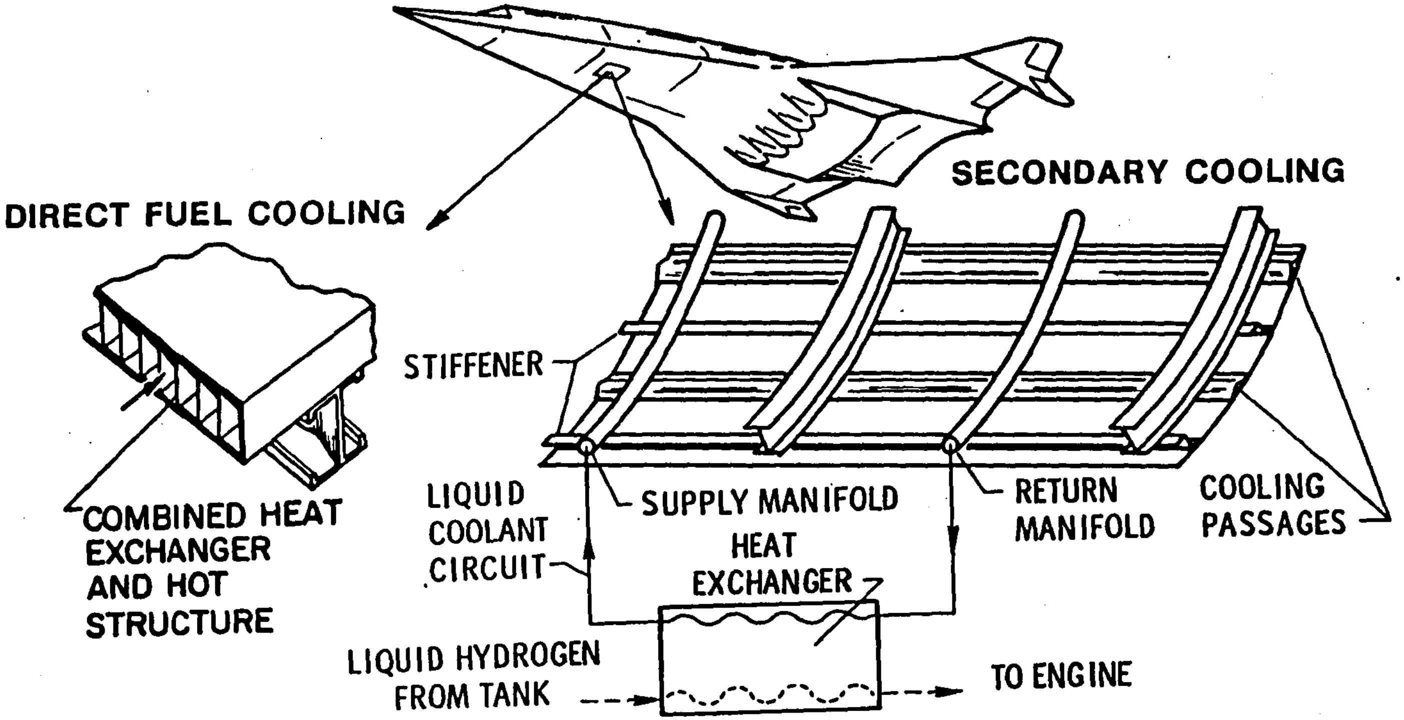


Figure 1

HYDROGEN COOLED ENGINE STRUCTURES

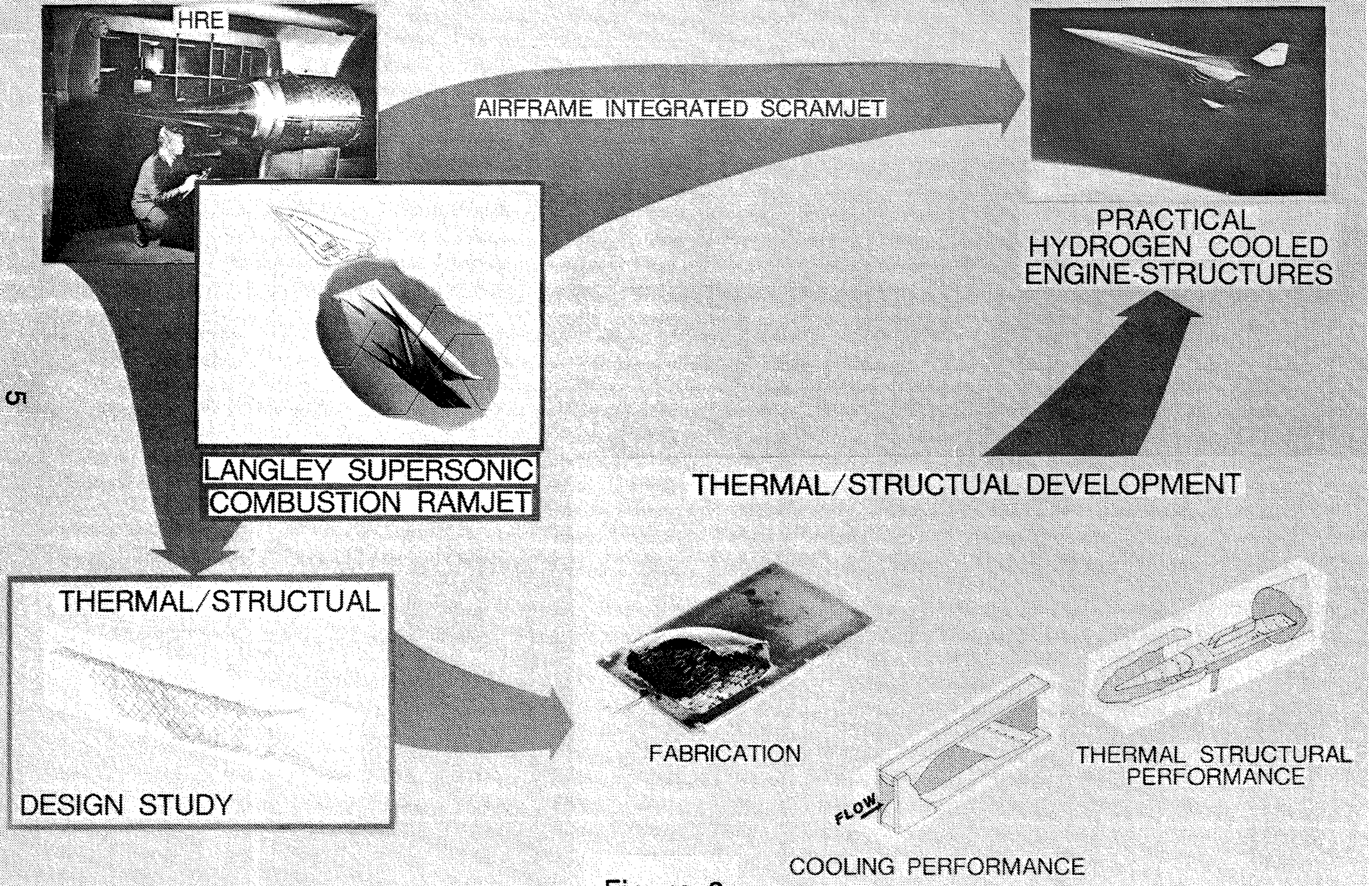
Research on hydrogen-cooled engine structures at the Langley Research Center is depicted in figure 2. In parallel with the Hypersonic Research Engine (HRE) Program of the 1960's, a series of thermal and structural design, fabrication and test evaluation studies (refs. 4-8) were conducted to determine basic characteristics of hydrogen cooled flat panels. Technology from these studies was incorporated into the design and fabrication of a complete flight-weight hydrogen-cooled engine assembly which was tested in the Langley 8-Foot High Temperature Tunnel as described in reference 9. These tests confirmed the suitability of the basic approach for scramjet engines for research purposes. The studies and tests revealed that the coolant requirements for the HRE exceeded the heat capacity of the available hydrogen fuel and the thermal fatigue life was far shorter than needed (HRE had an anticipated fatigue life of only 135 operational cycles). Both the problems stemmed, in part, from the annular design and high compression ratio of the engine which resulted in large areas being exposed to an intense heating environment. A basic goal in the continuing research program was to develop an engine concept which required only a fraction of the total fuel heat sink for engine cooling.

Studies of airframe-integrated scramjets with high potential performance led to the sweptback, fixed geometry, hydrogen-fueled, rectangular scramjet module shown in figure 2. Scramjet modules are integrated with the airframe and use the entire undersurface of the aircraft to process engine flow. The aircraft forebody serves as an extension of the engine inlet, and the afterbody serves as an extension of the engine nozzle. Structural advantages for this concept include the fixed geometry, and reduced wetted surface area and heating rates. Surface area is reduced by the non-annular configuration and by multiple fuel injection planes which promote fuel mixing and combustion and thereby reduces the combustor length. Heat transfer rates are reduced by the lower inlet compression ratio and by the large combustor exit-to-entrance area ratio which reduce pressures.

Thermal/structural design studies described in references 10 and 11 produced viable design concepts for the integrated scramjet with cooling requirements that permit engine operation to Mach numbers of 9-10 without additional hydrogen for engine cooling. However, these studies reemphasized the need for advances in fabrication and materials technology to obtain reasonable structural life. Fabrication studies (ref. 12) to improve thermal fatigue life were successful and a fuel injection strut is currently being built for tests at NASA Langley.

Selected results from the thermal/structural design, fabrication, and testing studies for hydrogen-cooled structures are discussed subsequently.

HYDROGEN COOLED ENGINE STRUCTURES



AIRFRAME INTEGRATED SCRAMJET

PRACTICAL HYDROGEN COOLED ENGINE-STRUCTURES

LANGLEY SUPERSONIC COMBUSTION RAMJET

THERMAL/STRUCTUAL DEVELOPMENT

THERMAL/STRUCTUAL

DESIGN STUDY

FABRICATION

THERMAL STRUCTURAL PERFORMANCE

COOLING PERFORMANCE

Figure 2

COOLED STRUCTURE CONCEPTS

Thermal and structural design studies presented in references 4 and 5 for heat fluxes from 10 to 500 Btu/ft^2-sec. and external pressure loadings of 7 to 250 psi (representative of engine structures) resulted in the three preferred concepts shown in figure 3. For low heat flux and low pressures, an integral concept which combines both the heat absorption and load carrying functions was found to be the preferred concept. For moderate to high heat flux and moderate pressure, a separate heat exchanger brazed to hot primary structure was found to be the preferred concept. For low to high heat flux and high pressure, a non-integral concept which completely separated the heat exchanger from cold primary structure (necessary to carry the high pressure loads) was found to be the preferred concept.

The studies indicated that thermal stresses are a primary concern in the design of regenerativey cooled panels. In-plane thermal stresses were minimized by careful manifold design to prevent maldistributions of flow through the panels and thus avoid large thermal stresses associated with nonlinear in-plane temperature gradients. In-depth thermal stresses, which are unavoidable, were found to be minimized through the use of small coolant passages and high flow velocities which cause high coolant pressure losses through the panels. For the range of coolant flow rates and pressure losses considered, the resulting in-depth temperature differences made thermal fatigue a problem. Pressure containment was found to be a minor problem, and, in general, minimum-gage materials were adequate for the internal pressures considered (300 to 1000 psi).

Material selection was found to be very important in the design of regeneratively cooled panels. For the heat exchanger portion of the concepts, elevated-temperature ductility of the material was found to be a determining factor for thermal fatigue life. Uncoated nickel-base superalloys appeared to be the best candidates for hydrogen cooled panels. Waspalloy was chosen for the integral design. Hastelloy X and Inconel 625 were best choices for the heat exchanger portion of the other two concepts. A later advanced fabrication study (ref. 12) found Inconel 617 and Nickel 201 to offer significant improvements in thermal fatigue life. Inconel 718 was limited to use for the primary structure only.

COOLED STRUCTURE CONCEPTS

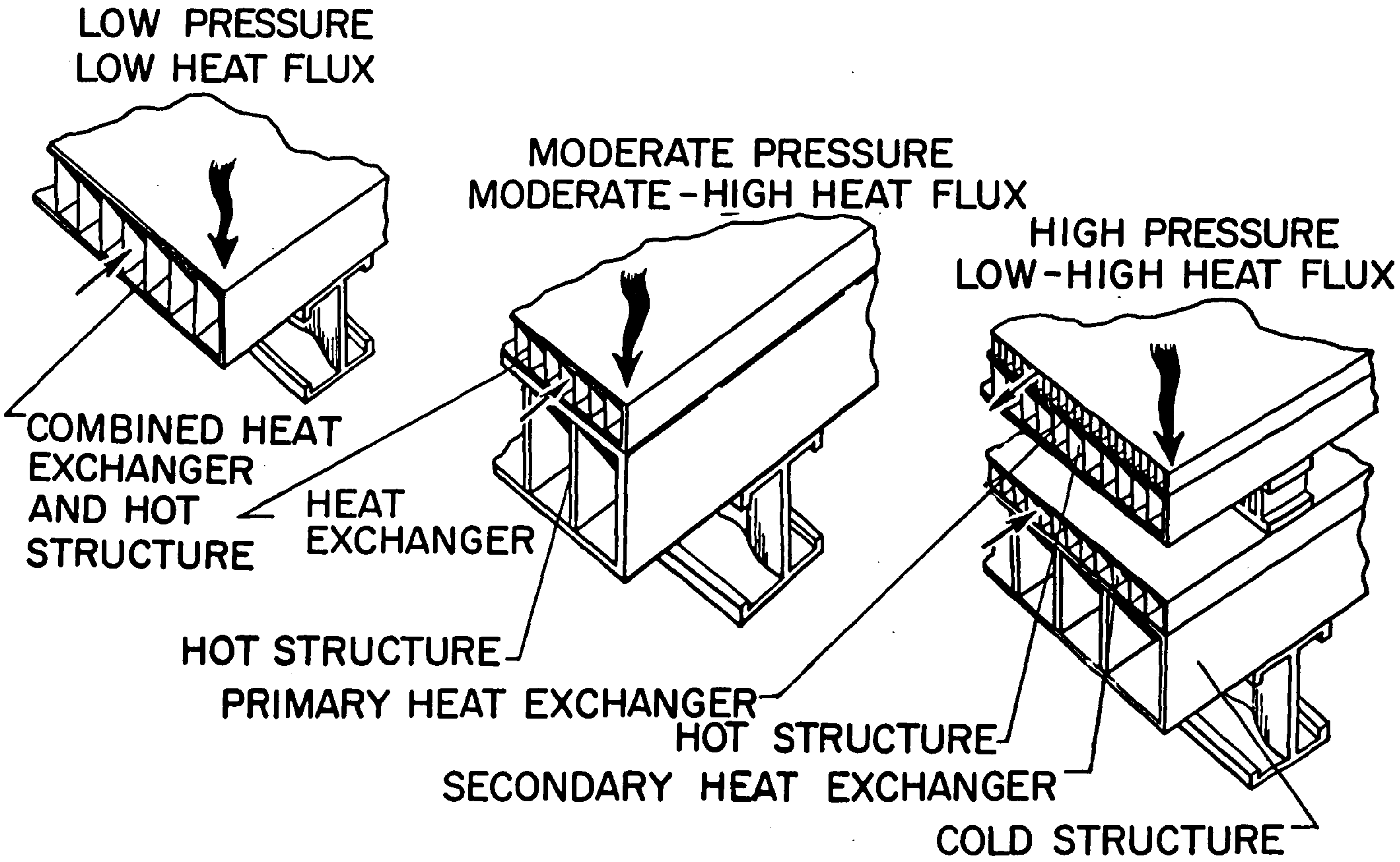


Figure 3

HYDROGEN-COOLED COMPOSITE-STRUCTURE WEIGHTS

Unit weights from the design studies (refs. 4 and 5) are shown for the three concepts as a function of applied heat flux and external pressure loading. The weights are based on a 2- by 2-foot panel and a hydrogen outlet temperature of 1600°R. The weights include the heat exchanger, structural panels and beams, and allowances for manifolds, plumbing, and seals. Since distribution system weights and pumping penalties for the hydrogen coolant would be similar for the three concepts, the impact on concept selection would be small therefore, these weights were ignored in the selection process. Unit weights were found to be a strong function of external pressure and a weak function of heat flux level. Shaded areas on the figure represent the minimum weight concept for specified pressures and heat flux. At low pressures the integral concept has the lowest weight, for higher pressures heat transfer considerations limit the cooling fin height or depth of the panel so that the concept becomes heavier to carry the bending loads associated with higher pressures. At moderate pressures the bonded concept avoids the fin height problem but at the higher heat fluxes, the weight required for the hot primary structure becomes excessive. For combined high heat flux and high pressure, the weight penalty for hot primary structure is greater than the weight for the additional components of the non-integral design so that the non-integral concept becomes the least weight design.

In general, concept selection involves trades among panel weight, coolant flow rate, panel life and other factors unique to a specific mission. References 4 and 5 give detailed design information to assist in the concept selection process.

HYDROGN - COOLED COMPOSITE - STRUCTURE WEIGHTS

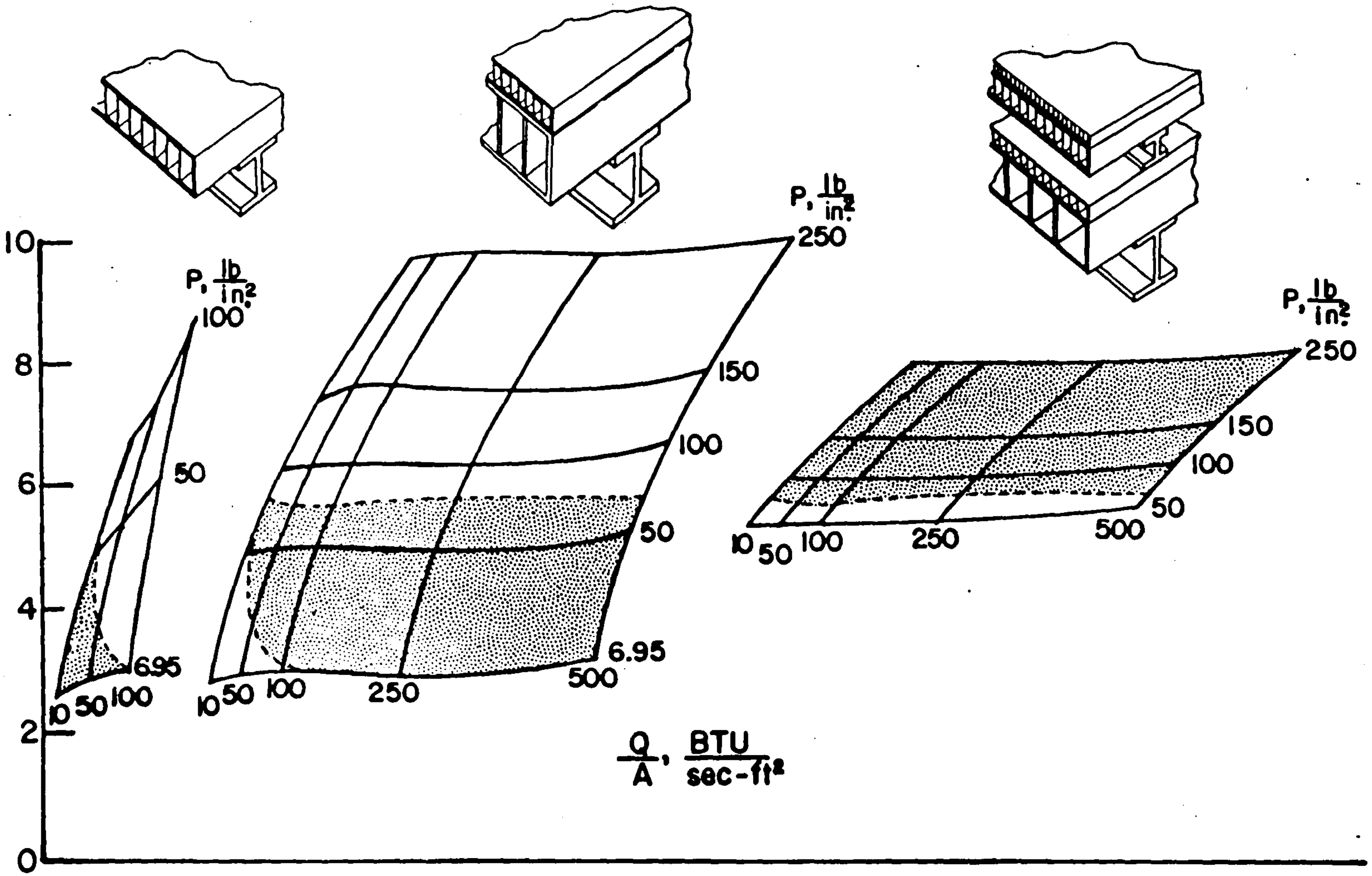


Figure 4

HYDROGEN-COOLED FABRICATION SPECIMEN

Design procedures in references 4 and 5 generally result in heat exchangers with very small coolant passages, as indicated by the photograph in figure 5. An appreciation of the size can be obtained by comparing the passages with the dime. Because of the close spacing of the fins, foil gage materials can be used to contain coolant pressures as high as 1000 psi. The off-set fins promote heat transfer to the coolant and reduce the temperature difference between the heat exchanger surfaces thereby reducing through the depth thermal stresses.

Following the thermal structural design studies, extensive fabrication and structural evaluation studies (refs. 6 and 7) were conducted for the integral and brazed heat-exchanger hot-primary structure concepts. Inconel 625, Hastelloy X, and Waspalloy parent metals and the Palniro family of gold-palladium-nickel braze alloys were used as materials in the studies. Tests included sheet alloy tensile tests, metallographic joint evaluations, and burst, creep rupture, and flexure tests at operational temperatures. A summary of the test results is shown in figure 6.

HYDROGEN-COOLED PROPULSION STRUCTURES

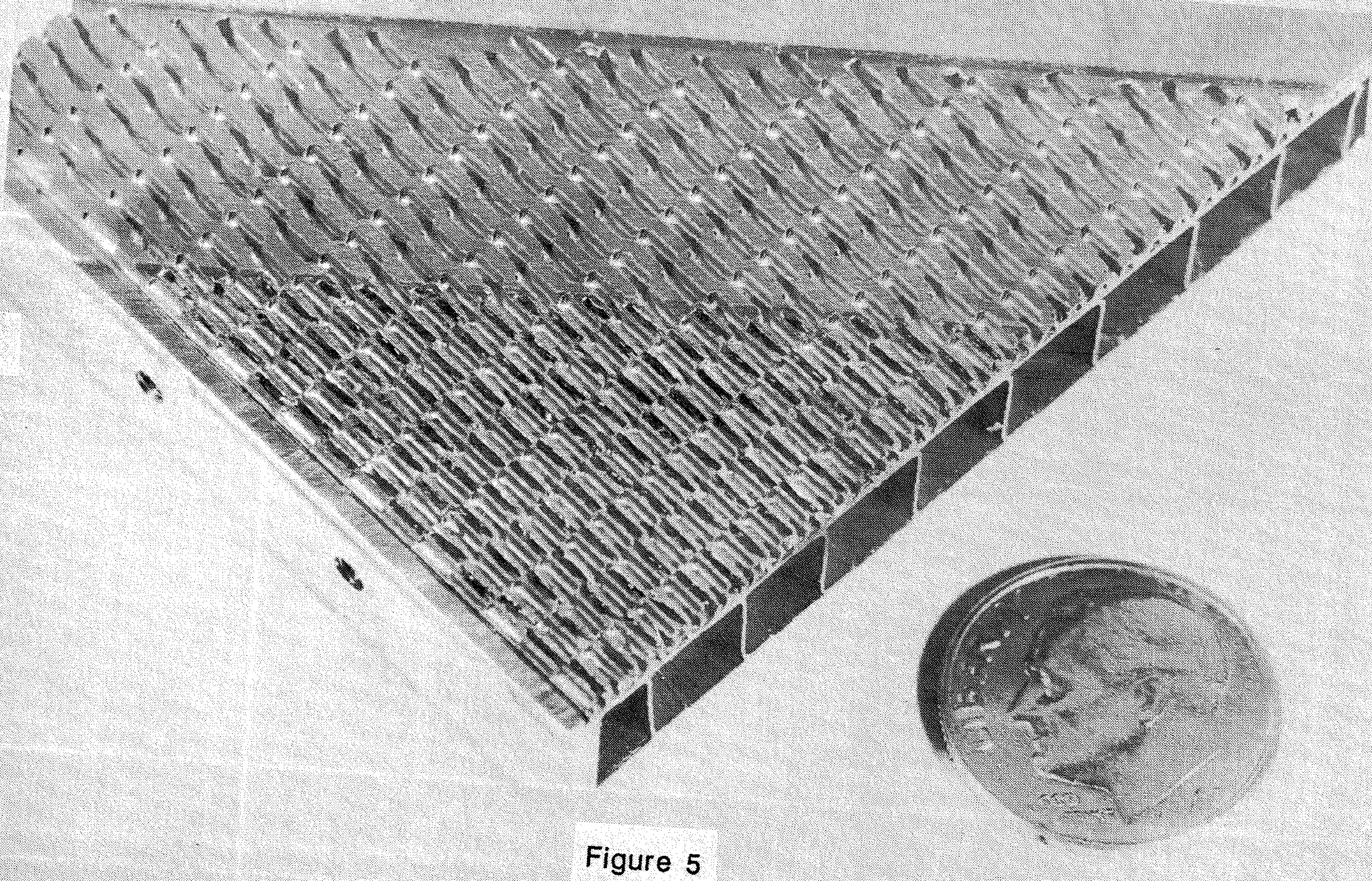


Figure 5

NASA HQ RW72-15141 (2) 9-2-71

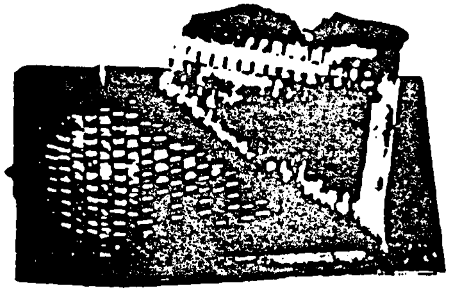
STRENGTH AND FATIGUE TEST RESULTS

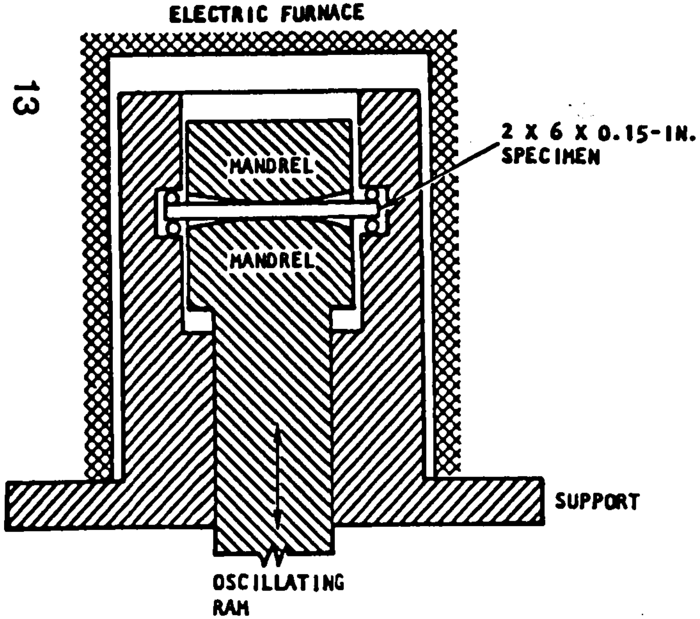
Small 2- by 3-inch specimens were used to determine short-term burst and creep rupture properties for the plate-fin sandwich structures. For both types of tests the specimens were maintained at design operating temperatures in an electric furnace and pressurized with an inert gas. For the short-term burst tests, pressure was increased continuously at 20 psi/sec until failure occurred; for the rupture test, pressure was maintained at fixed levels and the specimens allowed to creep until failure occurred. For the low-cycle fatigue test 2- by 6-inch specimens were maintained at a test temperatures of 1540°F by an electric furnace which enclosed the test apparatus as shown in figure 6. Strains were imposed mechanically by the oscillating ram and circular mandrels. Implicit in this testing method is the assumption that fatigue life depends on the maximum cycle temperature and cyclic strain level independent of whether the strain is mechanically or thermally induced.

Results from the tests are shown as ratios of mechanical properties of the plate-fin assemblies to the parent metal properties. The tests showed that about 85 percent of the parent metal strength was achieved in the burst tests but only 50 percent of the creep rupture strength and only 7 percent of the fatigue life of the parent metal could be achieved by the fabricated specimens. Many factors were found to influence the strength and fatigue life of the fabricated specimens such as time at braze temperature, fin geometry, braze fillet shape, fin shape, faceplate thickness, and material ductility. Creep rupture performance could be improved by increasing material gages; however, improvements in fatigue life (obtained in the integrated-scramjet development program and discussed subsequently) required redesign, new fabrication techniques, and different materials.

STRENGTH AND FATIGUE TESTS

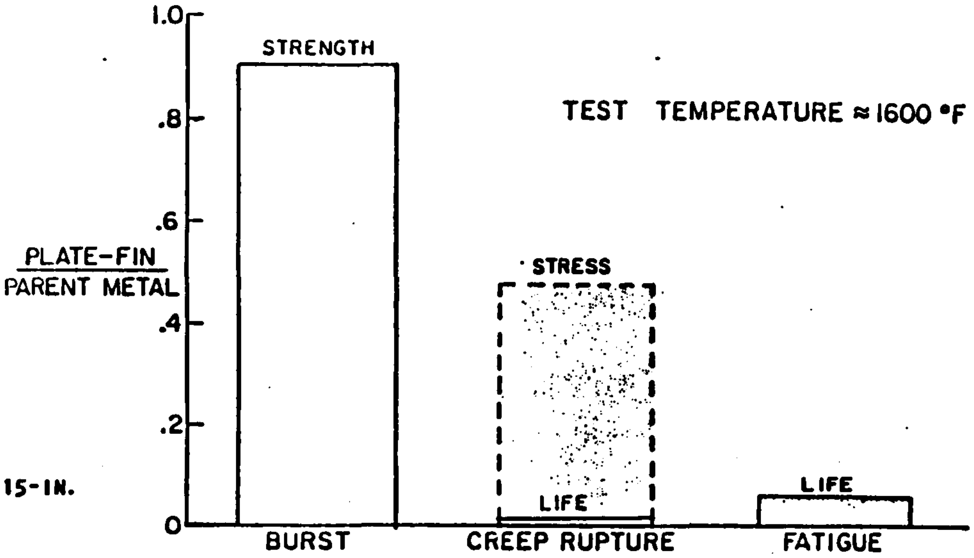
BURST SPECIMEN





FATIGUE APPARATUS

MECHANICAL PROPERTIES RATIOS



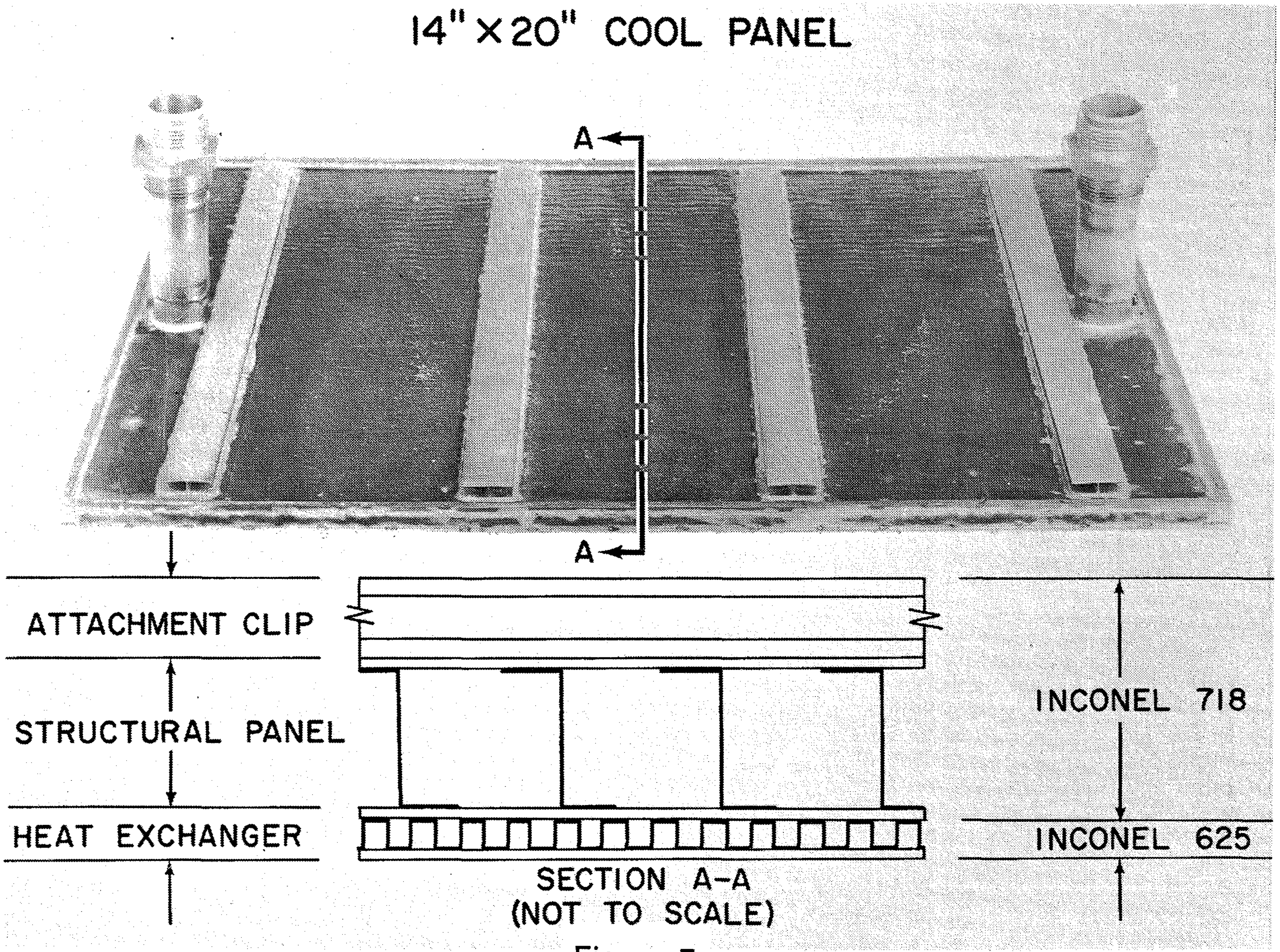
IMPORTANT FACTORS

- BRAZE TIME
- BRAZE FILLET SHAPE
- FIN GEOMETRY
- FIN SHAPE
- FACEPLATE THICKNESS
- MATERIAL DUCTILITY

Figure 6

14- BY 20-INCH COOL PANEL

As a culmination of the hydrogen-cooled panel studies, structural and thermal performance tests (ref. 8) were conducted on the 14- by 20-inch brazed plate-fin panel shown in figure 7. The panel consisted of an Inconel 625 heat exchanger brazed to an Inconel 718 structural panel which was supported by Inconel 718 I-beams not shown. Clips spanning the backside of the structural panel were used to attach the panel to the support beams. Inlet and outlet manifolds for distribution of the hydrogen coolant were integral parts of the structural panel. The panel was designed to sustain a 100 psi uniform surface pressure and a heat flux of 100 Btu/ft^2-sec. The panel was tested in an inert gas atmosphere with a graphite heater to radiantly heat the cooled surface. A maximum heat flux of 103 Btu/ft^2-sec. and a maximum temperature of 1930°R were imposed during the tests. A maximum uniform surface pressure of 115 psi at a maximum temperature of 980°R imposed the most severe loads on the Inconel 718 structural panel. Panel heat transfer performance was generally lower than expected, apparently because of flow and heater non-uniformities. The average overall heat transfer coefficient was 63 percent of the value predicted for uniform hydrogen flow and uniform heating of the panel.



14" X 20" COOL PANEL

Figure 7

HYPERSONIC RESEARCH ENGINE

Technology from the hydrogen-cooled flat panel studies was incorporated in the design and fabrication of a full-scale structures assembly model of the HRE engine for tests in a hypersonic flow stream. Approximately $8 million was expended in further development of hydrogen-cooled structures for the engine. The test model, shown in figure 8, was 7.5 ft long and 18 inches in diameter (ref. 9). The structure was designed for Mach 8 flight conditions and consisted of plate-fin sandwich shells with compound curvature. Hastelloy X brazed with gold-palladium-nickel braze alloys was used in the shell structures. Use of the plate-fin sandwich structure construction with off-set fins tolerated some blockage of flow area, permitted installation of inserts for various purposes, facilitated incorporation of manifolds into the structure, and resulted in smooth aerodynamic surfaces.

The complex assembly of hydrogen-cooled structure was tested in the Mach 7 stream of the Langley 8-Foot High Temperature Tunnel (under non-conbustion conditions) for a total of 55 times to accumulate 30 minutes of exposure which met or exceeded temperatures and temperature differences for the Mach 8 design conditions (ref. 9). Serviceability of the flightweight plate-fin cooled structure was clearly demonstrated although the tests corresponded to only about 60 thermal duty cycles (design life was 100 cycles). The coolant system maintained acceptable temperature levels and tolerated large heating nonuniformities.

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HYPERSONIC RESEARCH ENGINE

STRUCTURAL ASSEMBLY MODEL

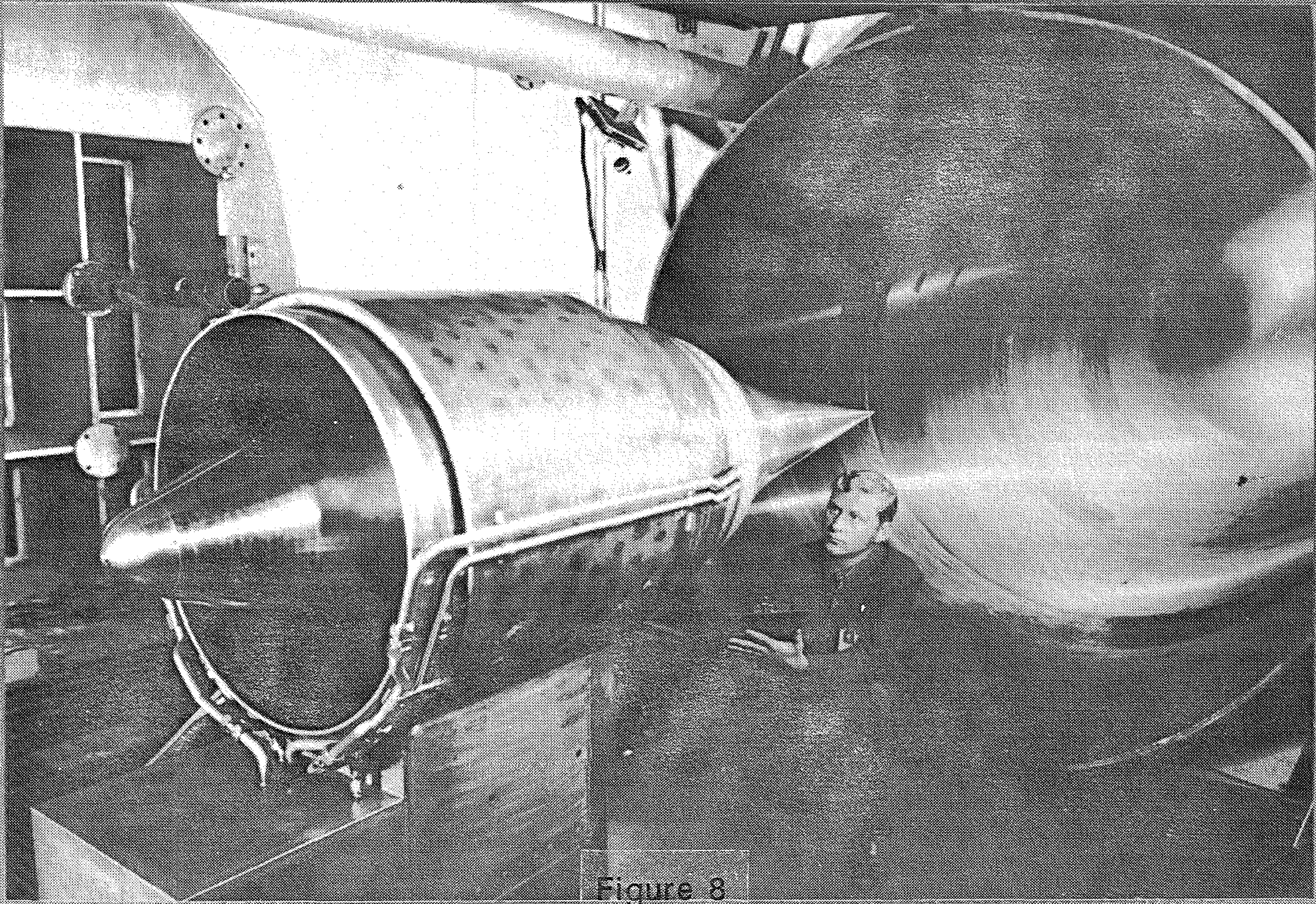


Figure 8

THERMAL FATIGUE LIFE

The fabrication and material technology required to obtain reasonable thermal fatigue life for hydrogen-cooled structures beyond the 100 cycles for the HRE was developed and experimentally validated (ref. 12). The goal in the airframe-integrated scramjet program is 1000 hours and 10,000 cycles of hot operation (cross-hatched region of fig. 9) which represents an improvement of two orders of magnitude over the HRE. Analytical predictions of the fatigue life as a function of the temperature difference between the hot aerodynamic skin and the back surface are shown in figure 9. Life goals appear attainable through a number of factors such as engine design, fabrication, and material selection. Improvements attributable to these factors are graphically illustrated in the figure. The bottom curve indicates anticipated life of the Hastelloy X coolant jacket on the HRE. Analytical predictions of the fatigue life as a function of the temperature difference between the hot aerodynamic skin and the back surface are shown in figure 9. The solid symbol at the right denotes the HRE design point and the open symbols indicate experimental data. A fundamental change in engine design to decrease the heat flux intensity and thus the temperature difference, as indicated by the horizontal arrow, is the first factor to increase the life of the airframe-integrated scramjet. An additional increase, as indicated by the vertical arrow, is obtained through an advanced fabrication technique. In this technique, the fin coolant passages are photo-chemically etched into the aerodynamic skin which eliminates the strain concentration caused by local thickening of the skin by the fin and eliminates the hot skin to fin braze joint configuration. However, the braze joint to the cooler primary structure remains. The photo-chemical etching process can be used for a wide variety of plate-fin configurations, two candidate configurations fabricated by this process are shown in the figure. Finally, another increment in life is attained though the selection of a material with high thermal conductivity which decreases the temperature difference, and with high ductility which increases the fatigue life directly. Nickel 201 and Inconel 617 specimens were fabricated and tested and the results for Nickel 201 as indicated by the upper curve met the goal of 10,000 cycles for a design heat flux of 500 Btu/ft^2-sec.

THERMAL FATIGUE LIFE

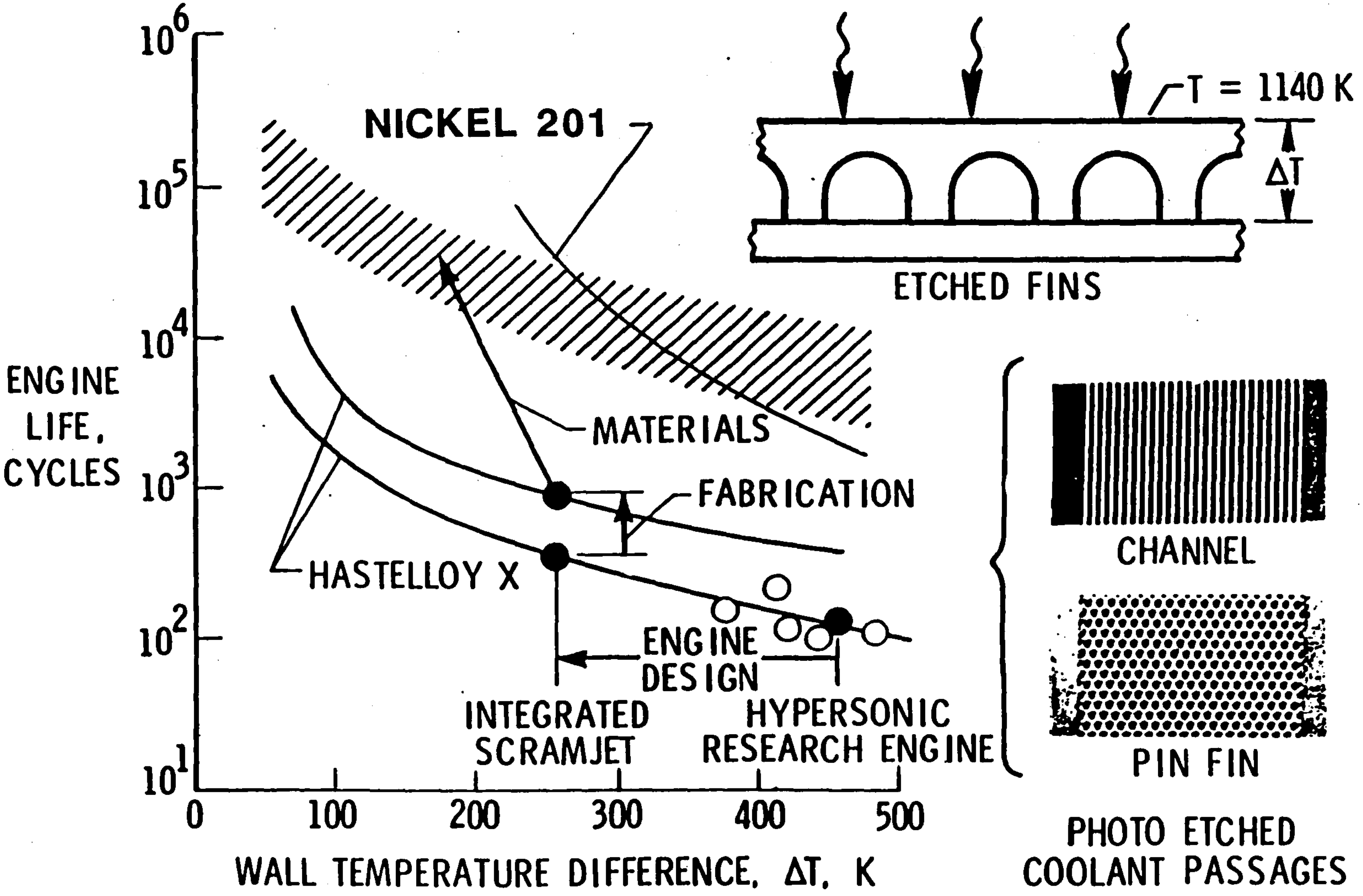


Figure 9

HYDROGEN-COOLED PANELS SUMMARY

Design, fabrication, and testing of hydrogen-cooled panels conducted from 1965 to 1971 at a total cost of $700 thousand (circa 1968) established a data base for such structures. The studies defined the best concepts for uniform surface pressures ranging from 7 to 250 psi and uniform heat fluxes from 10 to 500 $\mathrm{Btu/ft^2}$-sec. Technology developed in these studies was employed and enhanced during the Hypersonic Research Engine Project which expended $8 million (circa 1968) in structures and cooling development and resulted in successful wind tunnel tests of a full scale structures assembly model of the engine. Fabrication processes and details, material selection, and thermal loading significantly impact low-cycle thermal fatigue for hydrogen-cooled structures and the goal of 10,000 cycles was finally achieved by advanced fabrication techniques (program costs were $418 thousand) in 1985.

SUMMARY - HYDROGEN-COOLED STRUCTURE

0 DATA BASE ESTABLISHED FOR DESIGN, FABRICATION, AND TESTING ($700K CIRCA 1968)

0 HYPERSONIC SCRAMJET ENGINE BUILT AND TESTED INCLUDED $8 MILLION FOR STRUCTURES AND COOLING DEVELOPMENT (CIRCA 1968)

0 LOW-CYCLE THERMAL FATIGUE SIGNIFICANT PROBLEM AFFECTED BY
- FABRICATION PROCESSES AND DESIGN DETAILS
- MATERIAL SELECTION
- THERMAL LOADING

0 ADVANCED FABRICATION PROGRAM ACHIEVED 10,000 CYCLES ($418K CIRCA 1982)

FIGURE 10

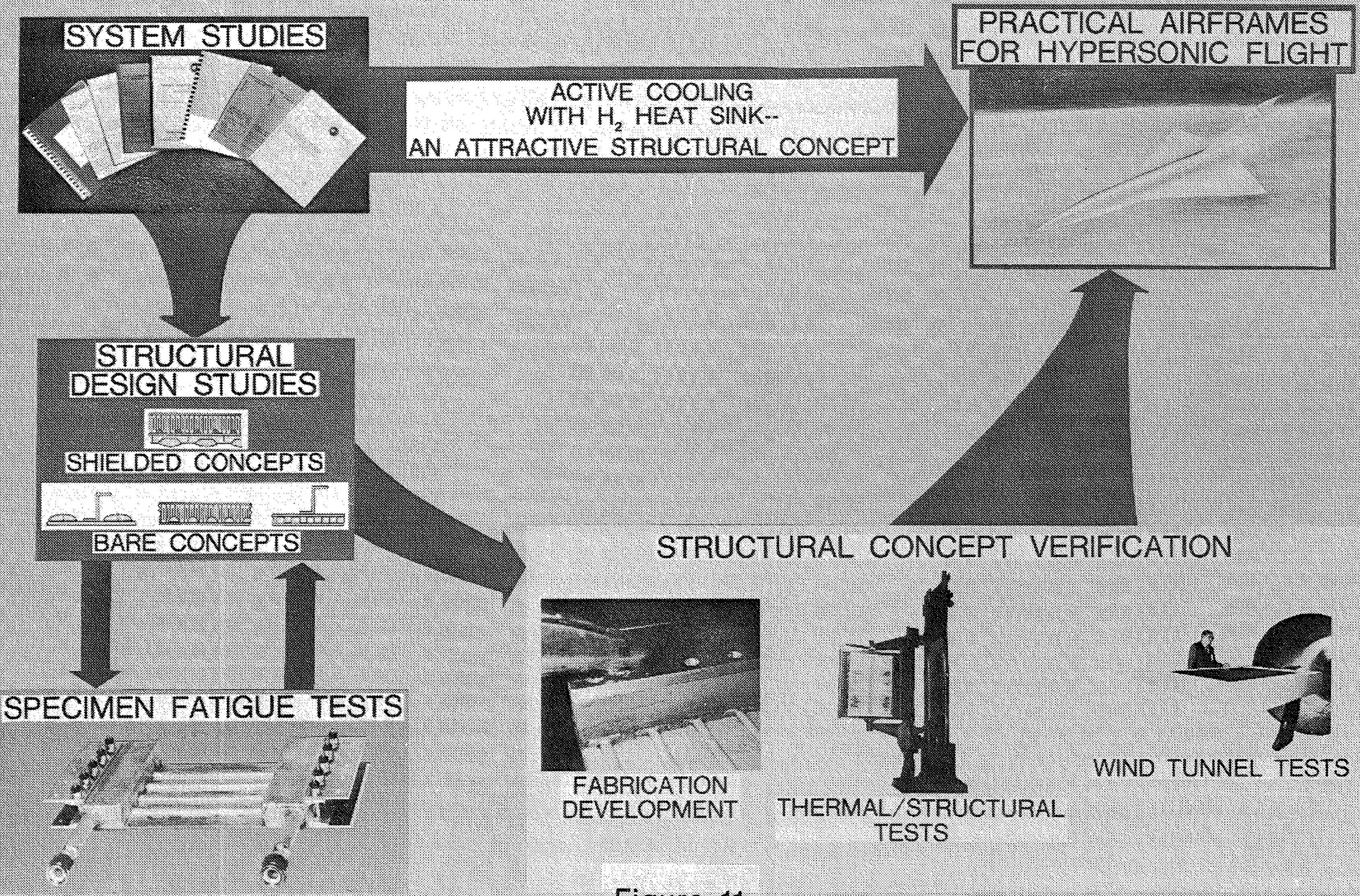
ACTIVELY COOLED AIRFRAME STRUCTURES

Extensive efforts have also been expended on development of secondary cooling circuit structural concepts for airframe structures (fig. 11). Systems studies indicated initial feasibility of the convective cooling approach and defined initial concepts. A series of design and fabrication studies were then conducted to further develop specific concepts. These studies included thermal-structural design, small specimen fatigue tests, fabrication development, and static and wind tunnel thermal-structural verification tests.

Although early studies for actively cooled airframe structures recognized problems in matching the instantaneous aerodynamic heat load with the heat sink capacity of the hydrogen fuel flowing to the engines and proposed partial heat shielding to reduce the absorbed heat load, both system studies (refs. 13-18) and hardware studies (refs. 19 and 20) concentrated on bare cooled structures with high-level cooling. Later studies (refs. 21-23) yielded a better understanding of the significance of heat sink matching and the mass penalties associated with high-level cooling.

Selective general results from the actively cooled airframe structures studies are discussed next.

ACTIVELY COOLED AIRFRAME STRUCTURES



SYSTEM STUDIES

ACTIVE COOLING
WITH H_2 HEAT SINK--
AN ATTRACTIVE STRUCTURAL CONCEPT

PRACTICAL AIRFRAMES
FOR HYPERSONIC FLIGHT

STRUCTURAL
DESIGN STUDIES

SHIELDED CONCEPTS

BARE CONCEPTS

SPECIMEN FATIGUE TESTS

STRUCTURAL CONCEPT VERIFICATION

FABRICATION
DEVELOPMENT

THERMAL/STRUCTURAL
TESTS

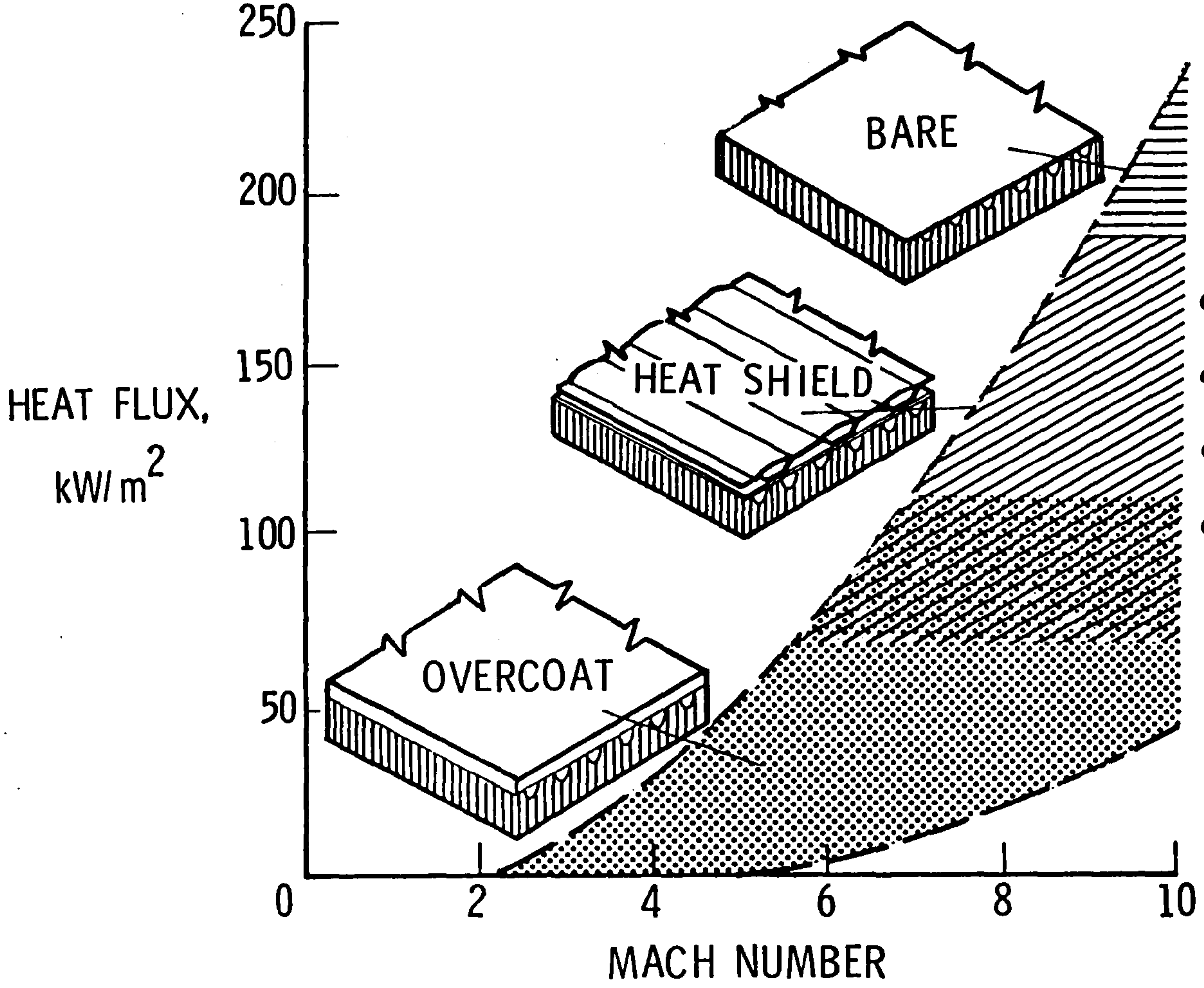
WIND TUNNEL TESTS

Figure 11

CONVECTIVELY COOLED CONCEPT SELECTION

Systems and hardware studies conducted in the mid 1970's yielded a coherent and consistent definition of the most attractive convectively cooled structural approach that combined both passive and active thermal protection. Recommended application regions for airframe concepts that combine passive and convective cooling are indicated in figure 12. The limits shown are approximate, and precise definition depends on the intended application. At lower incident heat fluxes, an overcoated cooled structure is the favored concept. The overcoat, a moderate-temperature elastomeric material applied to the outer surface of the structure, is an outgrowth of the fail-safe abort studies described in reference 24. At higher heat fluxes the overcoat is replaced by high temperature insulation and heat shields. This approach represents a marriage of convective active cooling with the radiative heat shield technology developed for entry vehicles. Only at the highest heat flux levels where heat shields reach excessive temperatures would bare convectively cooled structures be used. Recent advances in lightweight durable heat shield concepts promise extension of the shielded concept to heat fluxes perhaps as high as 150 Btu/ft^2-sec. Use of hot surface thermal protection with convectively cooled structure reduces total mass, provides improved heat-load/heat-sink compatibility, increases safety and reliability, improves tolerance to off-design conditions, and eases fabrication difficulties.

CONVECTIVELY COOLED CONCEPT SELECTION



FACTORS

- TOTAL MASS
- COOLANT REQUIREMENT
- SAFETY
- FABRICABILITY

Figure 12

PANEL MASSES - NONUNIFORM HEAT FLUX

Effects of nonuniform heating for bare, overcoated and heat shielded convectively cooled panels from reference 11 are shown in figure 13. Results are presented for panel unit masses as a function of the uniform heat flux that would be absorbed by a bare cooled structure with a surface temperatures of 250°F. For the uniformly heated panels, an additional heat load with a half-cycle sine-wave distribution and a peak intensity five times the uniform intensity was assumed to exist over 15 percent of the panel surface; thus, the average heat flux to the panel was 1.4 times the uniform flux. The overcoated configurations exhibit a clear mass advantage over bare configurations for both uniform and nonuniform heating. The figure also illustrates the low sensitivity of the heat shielded configurations to heat flux level and nonuniformity. Slopes of the curves for heat shielded panels are less than 10 percent of the minimum slopes for bare configurations. Similarly, a change to nonuniform heating with 1.4 times the average heat flux increases shielded panel mass by less than eight percent and bare configuration mass by 16 to 50 percent.

COOLED PANEL MASSES

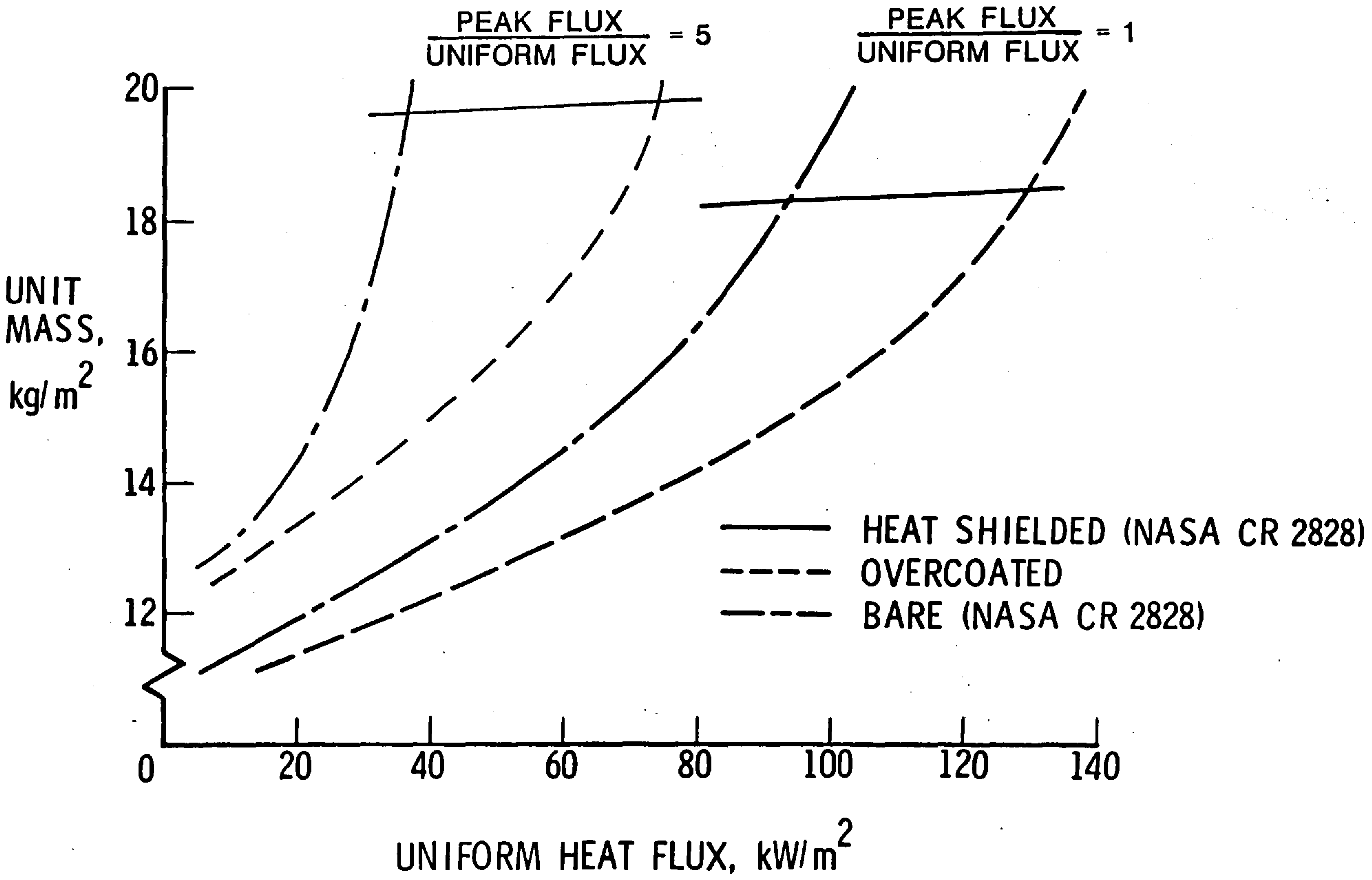


Figure 13

SENSITIVITY TO TRANSIENT HEATING

Besides accommodating heating nonuniformities, insulation (both overcoats and heat shields) decreases the sensitivity of convectively cooled structures to transients as indicated in figure 14. The figure (from ref. 11) shows the structural temperature response to the transient heat pulse for a 90° - 2g turn of bare and heat-shielded convectively cooled panels designed for an aerodynamic heating environment that would produce a heat flux of 12 Btu/ft^2-sec. to a 300°F surface. For the factor of two increase in aerodynamic heat transfer coefficient the temperature of the heat shielded structure slowly increases by an insignificant 18°F and the heat shielded temperature increases about 270°F to 1760°F. (A temperature within the use range of superalloy shields.) In contrast, the bare structure responds rapidly and increases about 100°F to 400°F which is unacceptable for aluminum. The lower sensitivity of the shielded structure simplifies cooling system controls and may make it possible to size the shielded structures for steady-state heat loads, whereas bare configurations must be sized for the most severe maneuver heat load.

COOLED STRUCTURES TRANSIENT RESPONSE

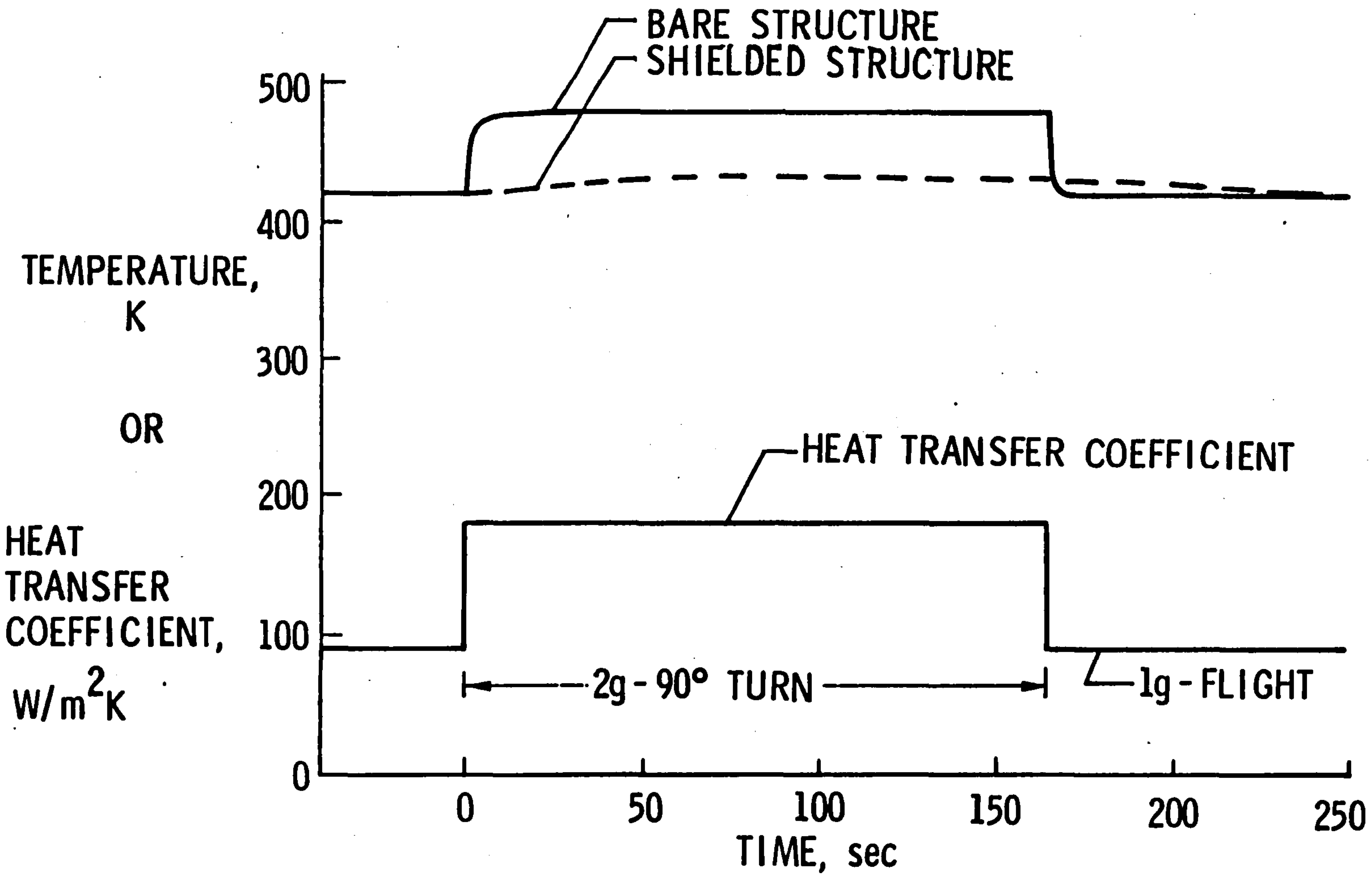


Figure 14

SENSITIVITY TO BOND-LINE CONDUCTANCE

The conductance of the bond-line between cooling tubes and the structural skin is a critical concern for bare convectively cooled structures which absorb virtually all of the incident heat flux, but is a minor concern for shielded configurations which absorb only a small fraction of the incident flux. The importance of conductance is illustrated in figure 15 (from ref. 11), which shows maximum skin temperature use for bare and shielded convectively cooled configurations. Both configurations were designed for the same aerodynamic heating environment and used similar construction with discrete tubes an inch apart. Skin temperatures for the bare structure are excessive at conductances representative of available adhesives. Thus, bond-line conductance was the controlling factor which led to soldering as the joining process for the bare structure and ultimately was the Achilles heel of the bare panel design. Fabrication of this concept was abandoned after two unsuccessful attempts to solder a large panel. At lower heat fluxes, adhesive bonding yields acceptable temperatures and was used to successfully fabricate a shielded configuration.

BOND-LINE CONDUCTANCE EFFECTS

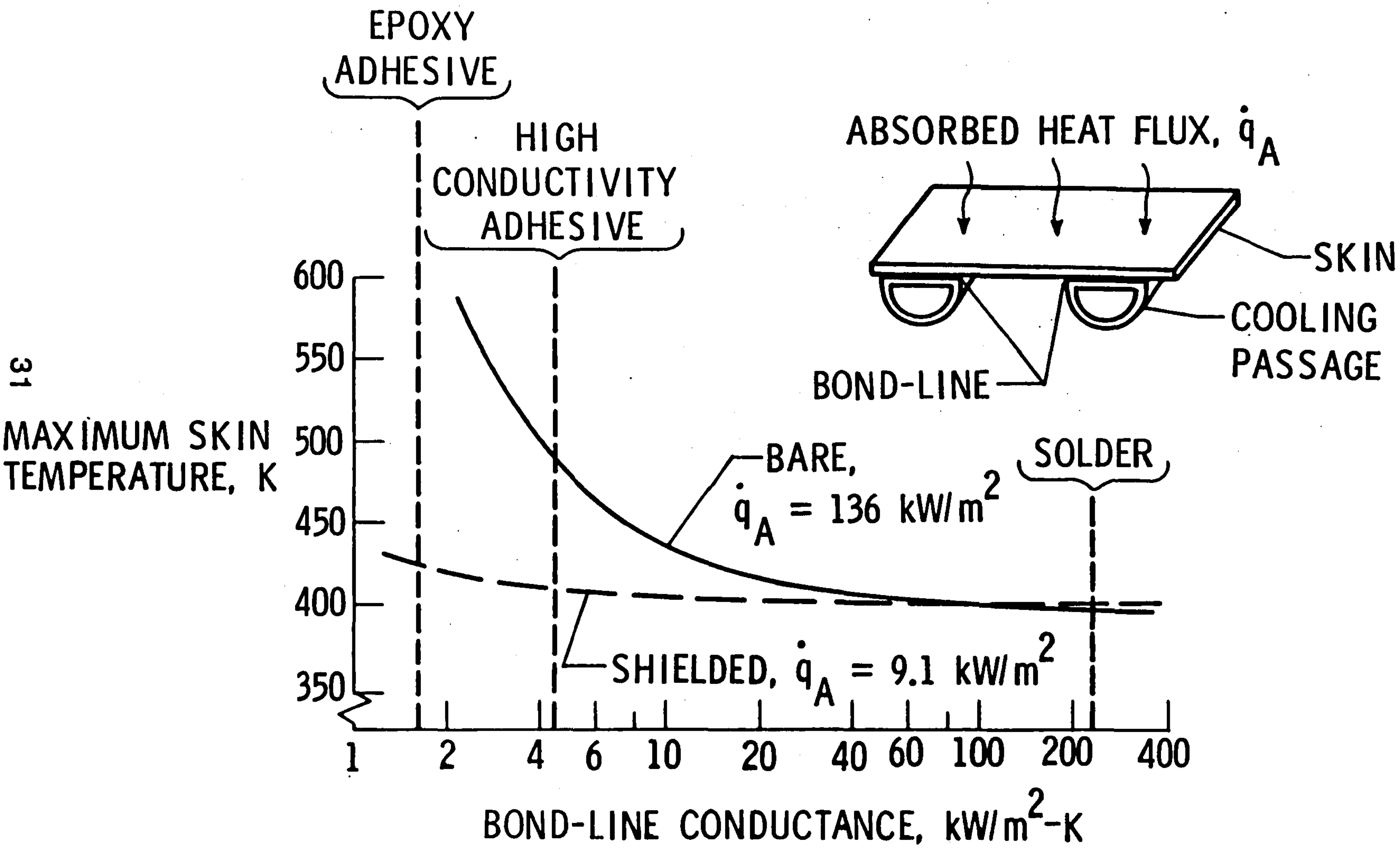


Figure 15

HEAT FLUX LEVEL COMPLICATES JOINT DESIGN

Another advantage of shielded configurations over bare configurations occurs in the design of the bolted joints at the end of a structural panel. As shown in figure 16 (from ref. 11), for a bare panel (heat flux = 12 Btu/ft^2-sec.) a single row of fasteners was used to avoid excessive temperature at the joints which were cooled by conduction to the manifold. However, this type of joint permitted excessive motion and fretting in tests of small fatigue specimens (ref. 19) and was redesigned for the shielded structure (ref. 23) (heat flux = 0.8 Btu/ft^2-sec.). The redesign took advantage of the lower temperature rise at the end of the panel associated with the lower absorbed heat flux to add an additional row of fasteners which alleviated the motion problem.

JOINT DESIGN

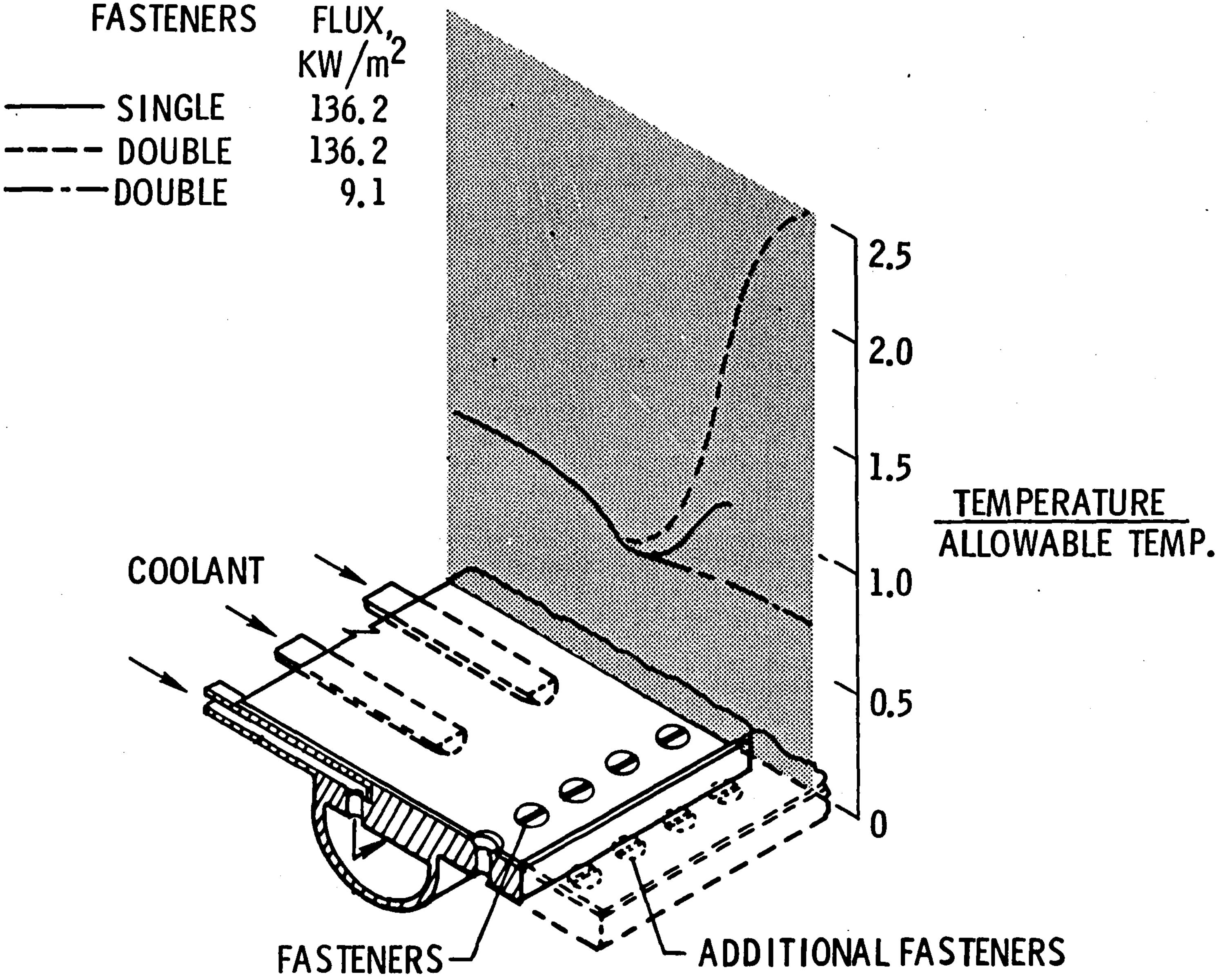


Figure 16

ACTIVELY COOLED PANEL PROGRAM - ALUMINUM CONCEPTS

To complement the system studies a series of design and fabrication studies was undertaken to provide both bare and heat shielded full-scale structural specimens for thermal-structural testing by NASA. Three bare concepts and one shielded concept were included in the studies. The 20 ft long panels were designed to meet Mach 6 to 8 transport characteristics and to have 10,000 hours of life and to survive 20,000 fully reversed limit load cycles. Each panel was designed to accommodate 12 Btu/ft^2-sec., a uniform pressure of ± 1 psi, and a uniaxial limit load of ± 1200 lb/in.

The Bell Aerospace bare concept is a skin-stringer structure with dual (redundant) counterflow cooling passages, and uses glycol/water as a coolant. Coolant passages are quarter ellipse tubes with wire crack arresters next to them adhesively bonded between a flat outer skin and a formed inner skin. The tubes contain the coolant pressure and eliminate peel stresses between the bonded skins. Both sets of cooling passages operate to maintain design temperatures during normal flight; should one of the redundant systems fail, either in the panel or distribution system, the panel has a life expectancy of 1/2 hour at normal operating conditions. The unit mass (includes panel, coolant inventory, pumping penalty, and coolant distribution system) for this concept was 4.25 lbm/ft^2.

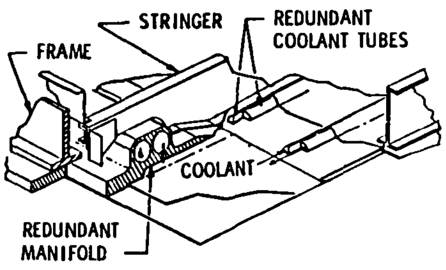
The McDonnell Aircraft bare concept has a single pass nonredundant cooling system (half-circle tubes) embedded in a honeycomb sandwich, which is designed to contain internal coolant leaks. The coolant tubes are brazed to a manifold with double chambers to get full coolant flow along the transverse edge. The tube-manifold assembly is then soldered to the outer skin. Methanol-water is used as the coolant. The unit mass for this concept was 4.84 lbm/ft^2. The heat shielded concept (not shown) is very similar to the bare honeycomb panel in that it uses small half-round tubes and adhesively bonded honeycomb sandwich structure plus a layer of high temperature insulation and metallic heat shields. Since the insulation and corrugation stiffened Rene'41 heat shields operate around 1450°F, most of the incident heat is radiated away and the heat absorbed by the cooled panel is reduced by a factor of 10. As a result, the mass of the secondary cooling system is greatly reduced and the shielded concept has a unit mass of 4.52 lbm/ft^2 or 7 percent less than the corresponding bare concept. The much lower heat flux to the cooled panel permits use of adhesives to bond the cooling tubes to the outer facesheet rather than the soldering process needed for the bare panel. Difficulties with the soldering process eventually led to abandonment of fabrication of the bare honeycomb sandwich.

The LRC-Rockwell International concept uses a stringer-stiffened, brazed plate-fin sandwich (similar to hydrogen-cooled panels) with a rectangular fin core for the main coolant passages. An auxiliary coolant passage outboard of the edge fasteners plus a thickened conduction plate provide longitudinal edge cooling. Stringers are adhesively bonded to the inner skin between frames. Glycol-water is used as the coolant. The unit mass for this concept was 4.46 lbm/ft^2.

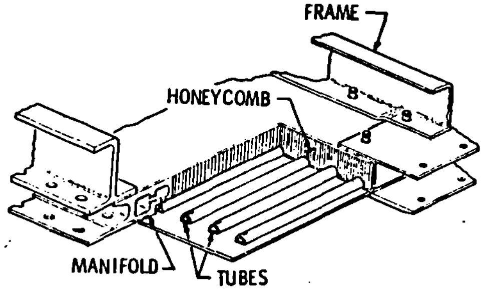
References 11, 19, 20, 23, 25 and 26 discuss the design and fabrication of the concepts in detail.

ACTIVELY COOLED PANEL PROGRAM – BARE ALUMINUM CONCEPTS

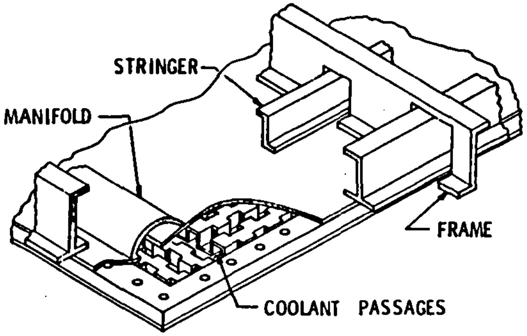
GOALS:
- ESTABLISH THERMAL PERFORMANCE
- ESTABLISH STRUCTURAL PERFORMANCE/FATIGUE LIFE



BELL AEROSPACE
- Z-STIFFENED SHEET
- REDUNDANT TUBES



McDONNELL AIRCRAFT
- HONEYCOMB STIFFENED
- NONREDUNDANT TUBES



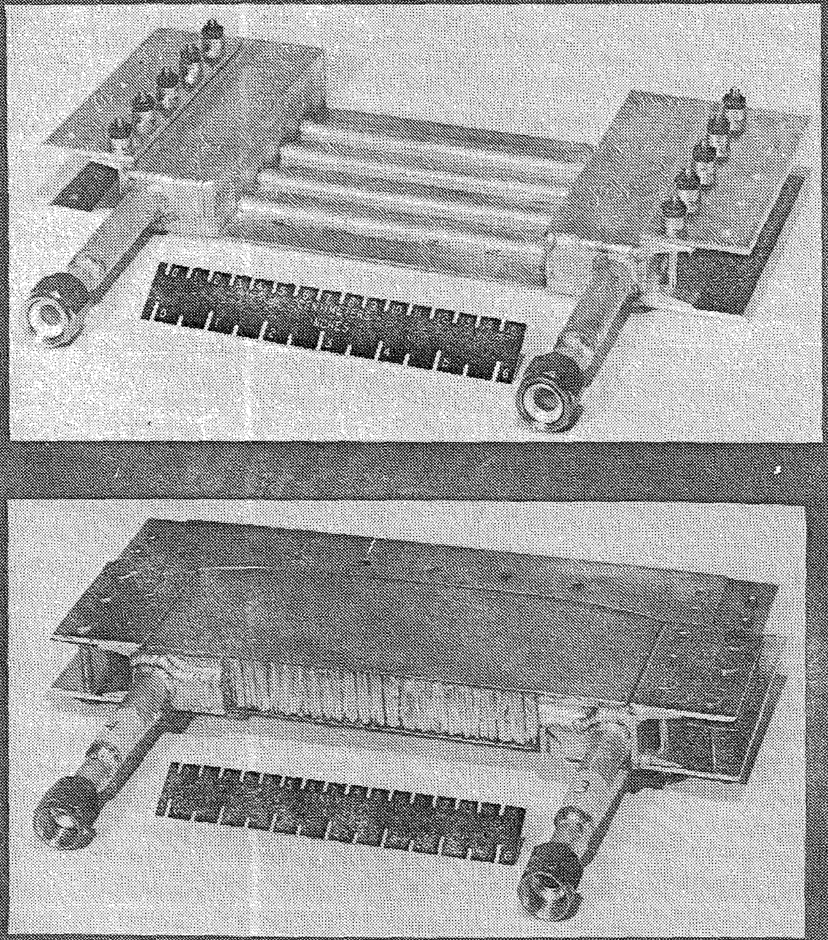
LRC/ROCKWELL INTERNATIONAL
- Z-STIFFENED SANDWICH SKIN
- PLATE-FIN COOLANT PASSAGES

Figure 17

ACTIVELY COOLED HONEYCOMB SANDWICH AMBIENT TEMPERATURE FATIGUE TESTS

As part of the hardware design and fabrication studies, small specimens were fabricated and tested to determine fatigue life characteristics for each concept. Two of the bare honeycomb sandwich fatigue specimens are shown in figure 18. The upper specimen was used to check cooling tube/facesheet characteristics and the lower was used to check the assembled panel characteristics. Results from the fatigue test indicated that the fatigue life of 20,000 cycles was exceeded, the cooling tubes acted as crack arrestors for cracks induced in the facesheets, cracks in the facesheets bypassed the coolant tubes, and when leaks were purposely introduced in the cooling tubes the honeycomb contained the internal leakage for operational pressures. Finally, the tests also showed that there was a need to redesign the transverse joints to avoid excessive joint motion. Similar results were found for the transverse joints for the discrete tube concept and the plate fin concept and indicate that the need to cool the joints further complicates a difficult design task.

ACTIVELY COOLED HONEYCOMB SANDWICH AMBIENT TEMPERATURE FATIGUE TESTS



- EXCEEDED DESIGN FATIGUE LIFE (20000 CYCLES)
- COOLANT TUBES ACTED AS CRACK ARRESTORS
- CRACKS IN FACE SHEET BYPASSED COOLANT TUBES
- HONEYCOMB CONTAINED INTERNAL LEAKAGE
- TRANSVERSE MECHANICAL JOINT IMPROVEMENT NEEDED

NASA
LCD-77-93

Figure 18

BARE PLATE-FIN CONVECTIVELY COOLED PANEL

Figure 19 shows a 2- by 4-foot convectively cooled plate-fin test panel. The brazed assembly consists of two facesheets, a corrugated interior core, and the inlet and outlet manifolds. All elements were brazed together in a single braze operation (ref. 26). The facesheets are 0.032 in. thick No. 23F braze sheets composed of 6951 aluminum alloy clad with 4045 aluminum/silicon braze alloy. The core or fin material is 0.005 in. thick aluminum alloy corrugated to a fin height of 0.1 in. with a fin pitch of 0.1 in. The sandwich panel is stiffened with adhesively bonded longitudinal stiffeners. The panel is cooled by a 60 percent solution of ethylene glycol-water at a mass flow rate of 30,000 lb/hr with an inlet temperature of 60°F to accommodate the 12 Btu/ft^2-sec. incident heating rate. Load adaptors at either end of the plate were required to interface with NASA test facilities and properly introduce uniaxial inplane loading into the test panel.

BARE ACTIVELY COOLED PANEL

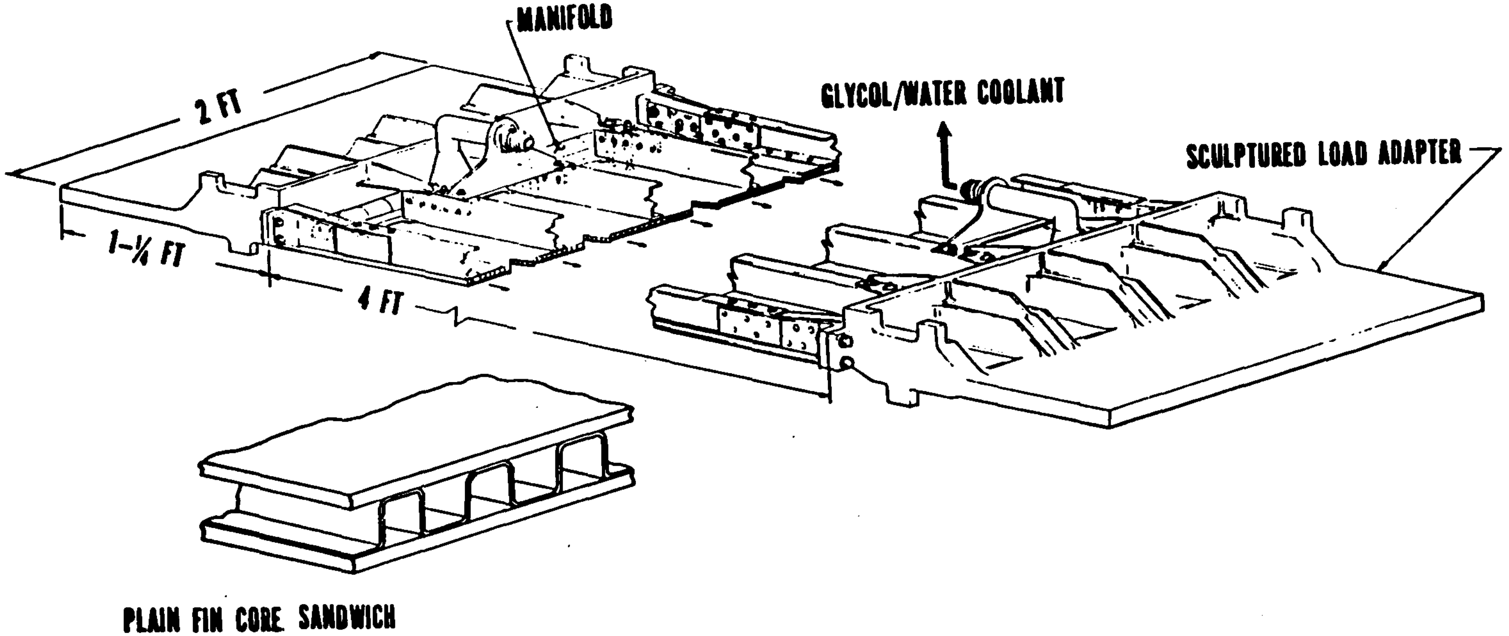


Figure 19

BARE PLATE-FIN PANEL TEST RESULTS

Figure 20 summarizes the test results to date for the bare plate-fin convectively cooled panel. The panel has successfully withstood 7 hours at the design heat flux of 12 Btu/ft^2-sec. to a 300°F surface. A total of 5 thermal cycles and 1100 load cycles of ± 1200 lb/in. while at operational temperatures have been imposed on the panel. The thermal and structural performance of the panel has been within 10 percent of the predicted performance. Thus far, there has been no evidence of structural damage or leaks in the panel. Plans call for completion of 5000 load cycles at temperature (design life for the panel).

BARE PLATE-FIN PANEL TEST RESULTS

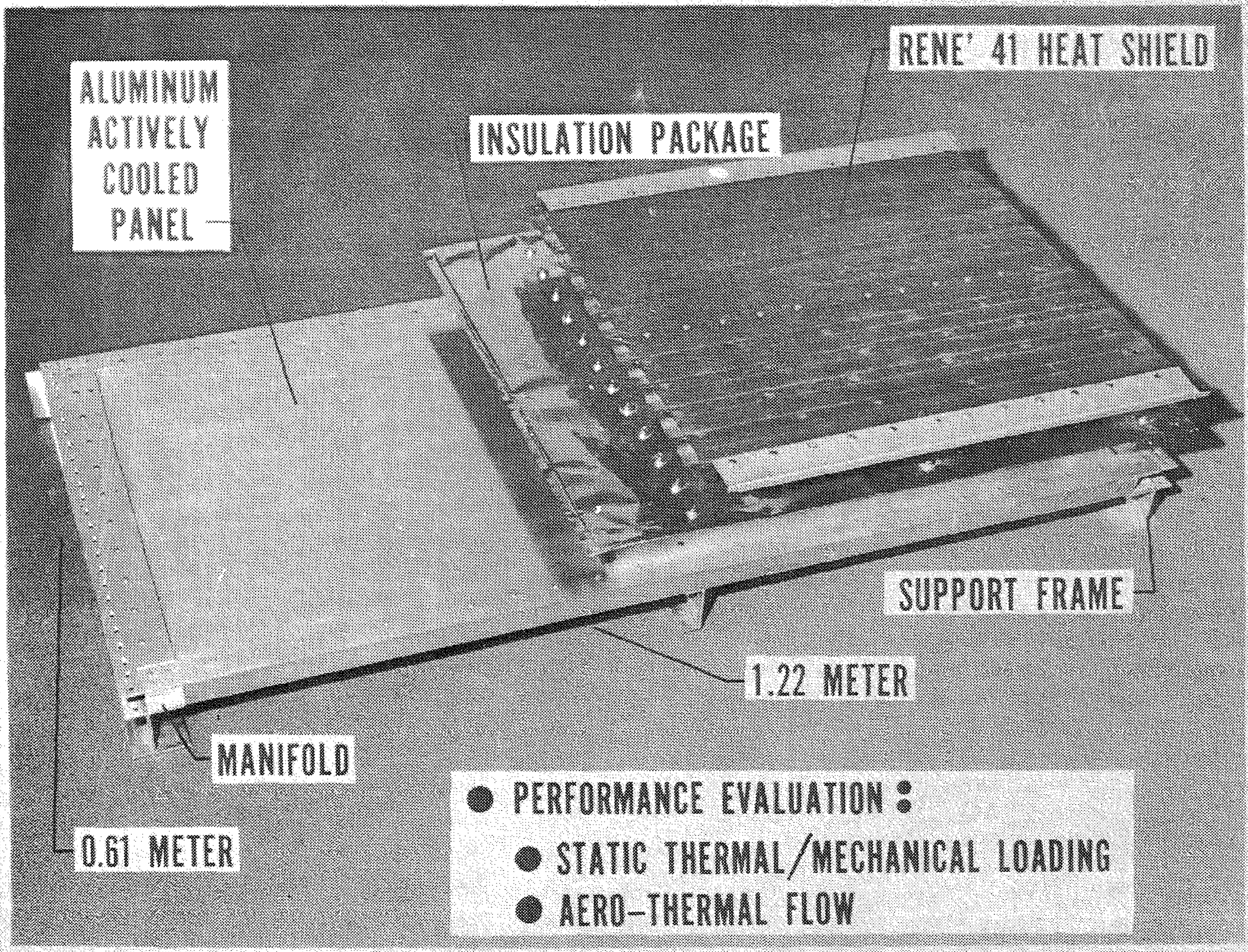
- 7 HOURS AT DESIGN HEATING CONDITIONS
- 5 THERMAL CYCLES
- 1100 LOADS CYCLES AT TEMPERATURE
- THERMAL AND STRUCTURAL PERFORMANCE WITHIN 10-PERCENT OF PREDICTED PERFORMANCE
- NO EVIDENCE OF DAMAGE OR LEAKS
- PLAN TO COMPLETE 5000 LOAD CYCLES AT TEMPERATURE

FIGURE 20

SHIELDED HONEYCOMB TEST PANEL

Figure 21 shows a 2- by 4-foot flightweight test panel which includes radiant heat shields and a convectively cooled adhesively bonded honeycomb panel. The panel was designed to accommodate a heat flux of 12 Btu/ft^2-sec. and consists of corrugation stiffened heat shields of 0.01 in. thick Rene'41 backed by a 0.125 in. thick layer of foil-encapsulated high-temperature insulation and a honeycomb structural panel. The aluminium honeycomb sandwich structural panel has 0.040 in. thick 2024-T81 facesheets adhesively bonded to 5056-H39 Aluminum honeycomb. Half-round aluminum tubes bonded to the outer facesheet at 1 in. intervals serve as passages for the 60 percent mass solution of ethylene glycol/water coolant which flows through the panel at a rate of 1824 lb/hr to absorb the heat to the structural panel (0.8 Btu/ft^2-sec.).

RADIATIVE AND ACTIVELY COOLED PANEL (RACP)



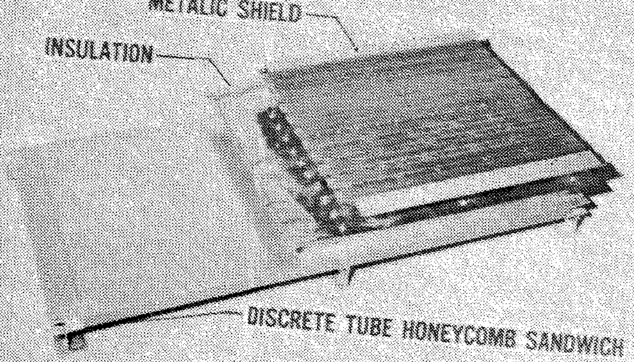
- PERFORMANCE EVALUATION :
  - STATIC THERMAL/MECHANICAL LOADING
  - AERO–THERMAL FLOW

Figure 21

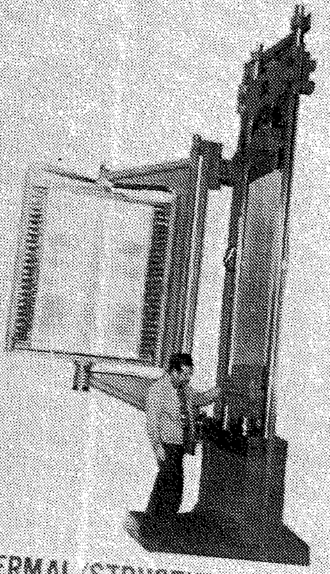
SHIELDED PANEL TEST RESULTS

As described in references 27 and 28 and shown in figure 22, the flightweight heat shielded convectively cooled panel was subjected to thermal/structural tests representing design flight conditions for a Mach 6.7 transport and off-design conditions simulating flight maneuvers and cooling system failures. A total of 32 tests exposed the panel to 65 thermal cycles and multiple cycles of mechanical loading. The panel successfully withstood 55 hours of radiant heating simulating 12 Btu/ft^2-sec. and 5000 cycles of uniaxial in-plane limit loading of ± 1200 lb/in. at operational temperatures. Additionally, the panel withstood off-design heating conditions for a simulated 2g maneuver from cruise conditions and simulated cooling system failures without excessive temperatures on the structural panel. Wind tunnel tests exposed the panel to 15 aerothermal cycles for a total of 137 seconds in a Mach 6.7 test stream. The panel responded as predicted and survived the extensive aerothermal/structural testing without significant damage to the structural panel, coolant leaks, or hot-gas ingress to the structural panel. However, the foil covering on the insulation packages sustained damage sufficient to destroy their function of preventing water ingress to the layer of high-temperature insulation.

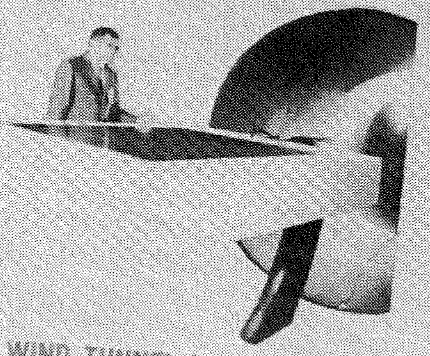
RADIATIVE-ACTIVELY COOLED PANEL TEST RESULTS



- 55 HOURS AT DESIGN HEATING CONDITIONS
- 65 THERMAL CYCLES
- 5000 LOAD CYCLES AT TEMPERATURE
- THERMAL AND STRUCTURAL PERFORMANCE WITHIN 10-PERCENT OF PREDICTED PERFORMANCE
- 132 SECONDS (TOTAL) IN M = 7 AEROTHERMAL ENVIRONMENT
- WITHSTOOD SIMULATED ABORT (COOLANT LOSS) HEATING TRAJECTORY
- NO EVIDENCE OF HOT GAS INGRESS OR STRUCTURAL FAILURE OR COOLANT LEAKS



THERMAL/STRUCTURAL TESTS



WIND TUNNEL TESTS

Figure 22

SHIELDED PANEL RESPONSE TO 2-g MANEUVER HEATING

To simulate heating during a 2-g maneuver from design cruise conditions, temperatures on the heat shield were rapidly increased from 1450°F to 1740°F (corresponding to doubling the aerodynamic heat-transfer coefficient to the heat shield), maintained for 240 seconds, then returned to design values. Figure 23 shows the temperature response to the increased heating. Temperatures are shown for the heat shield, the outer and inner surfaces of the high-temperature insulation and the structural panel. A calculated response for a bare panel under similar heating condition is shown for comparison. The increased heating caused the structural-panel temperature to increase 30°F compared to a 130°F increase for an unshielded convectively cooled panel and verifies that the shielded configuration is relatively insensitive to off-design thermal conditions compared to a bare configuration designed for the same aerodynamic heating environment.

SHIELDED PANEL RESPONSE TO 2-g MANEUVER HEATING

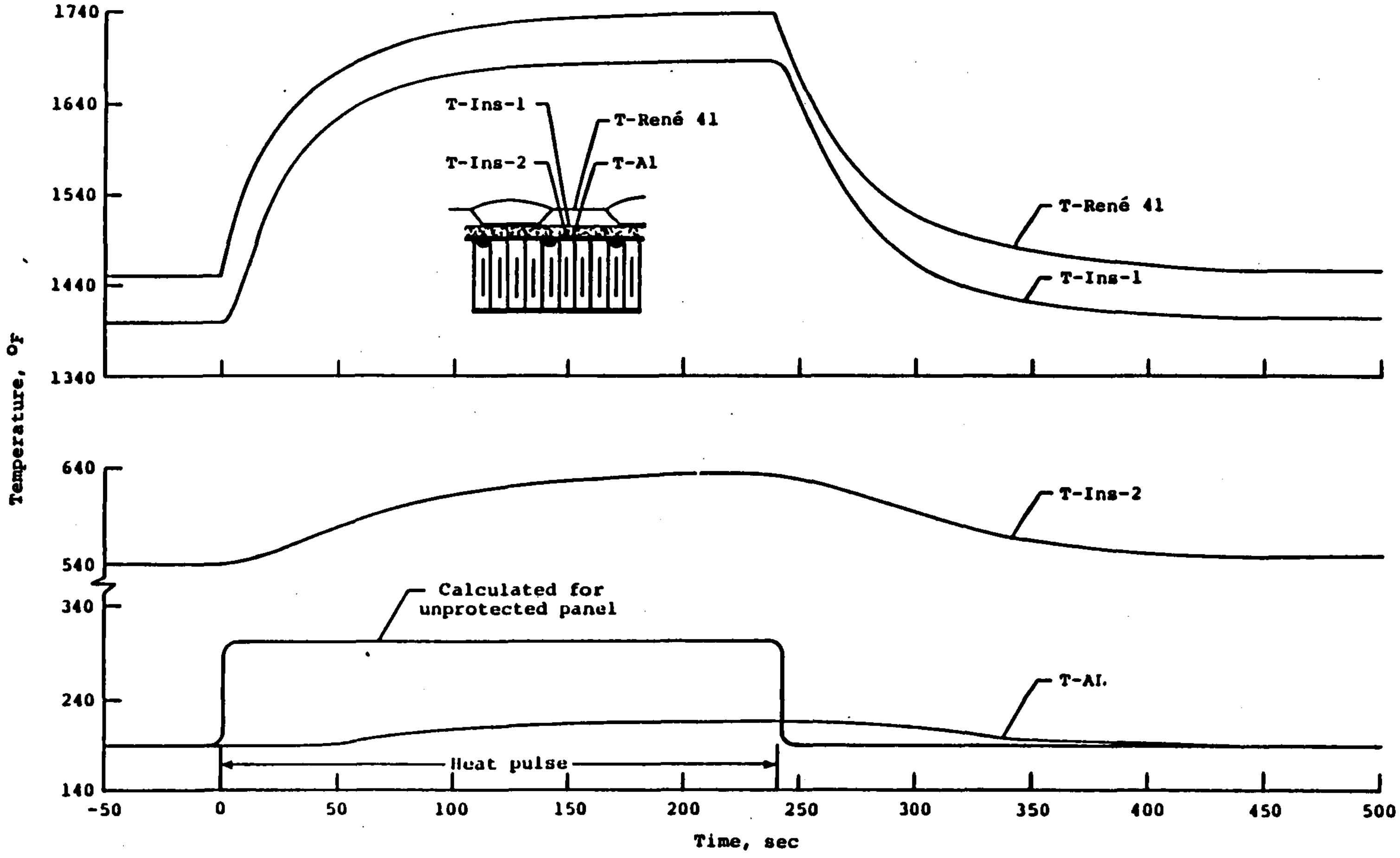


Figure 23

SHIELDED PANEL RESPONSE TO ABORT HEATING

A failure mode for convectively cooled panels is a total loss of coolant flow. One method to cope with this problem (ref. 24), predicated on early detection of loss of coolant flow, is to follow a load-factor limited trajectory which minimizes the heat load until flight speeds are decreased to values where aerodynamic heating is negligible. To determine the heat shielded configuration response to such a procedure, the panel was subjected to a heating cycle corresponding to the minimum-heat-load trajectory.

Figure 24 shows temperature histories of the shielded panel response to the abort heating simulation. Average measured temperatures are shown for the heat shields and the cooled structural panel. Also shown for comparison are heat-shield and cooled-panel temperature histories from a one-dimensional transient heat-transfer analysis for the abort heating profile starting from steady-state conditions. A calculated response for an unshielded aluminum cooled panel is also shown. Maximum temperature for the shielded structural panel reached 325°F, only 25°F above the panel maximum design temperature indicated by the tic mark on the ordinate. By comparison an unprotected panel would very quickly reach temperatures where aluminum has virtually no strength.

RACP RESPONSE TO ABORT HEATING

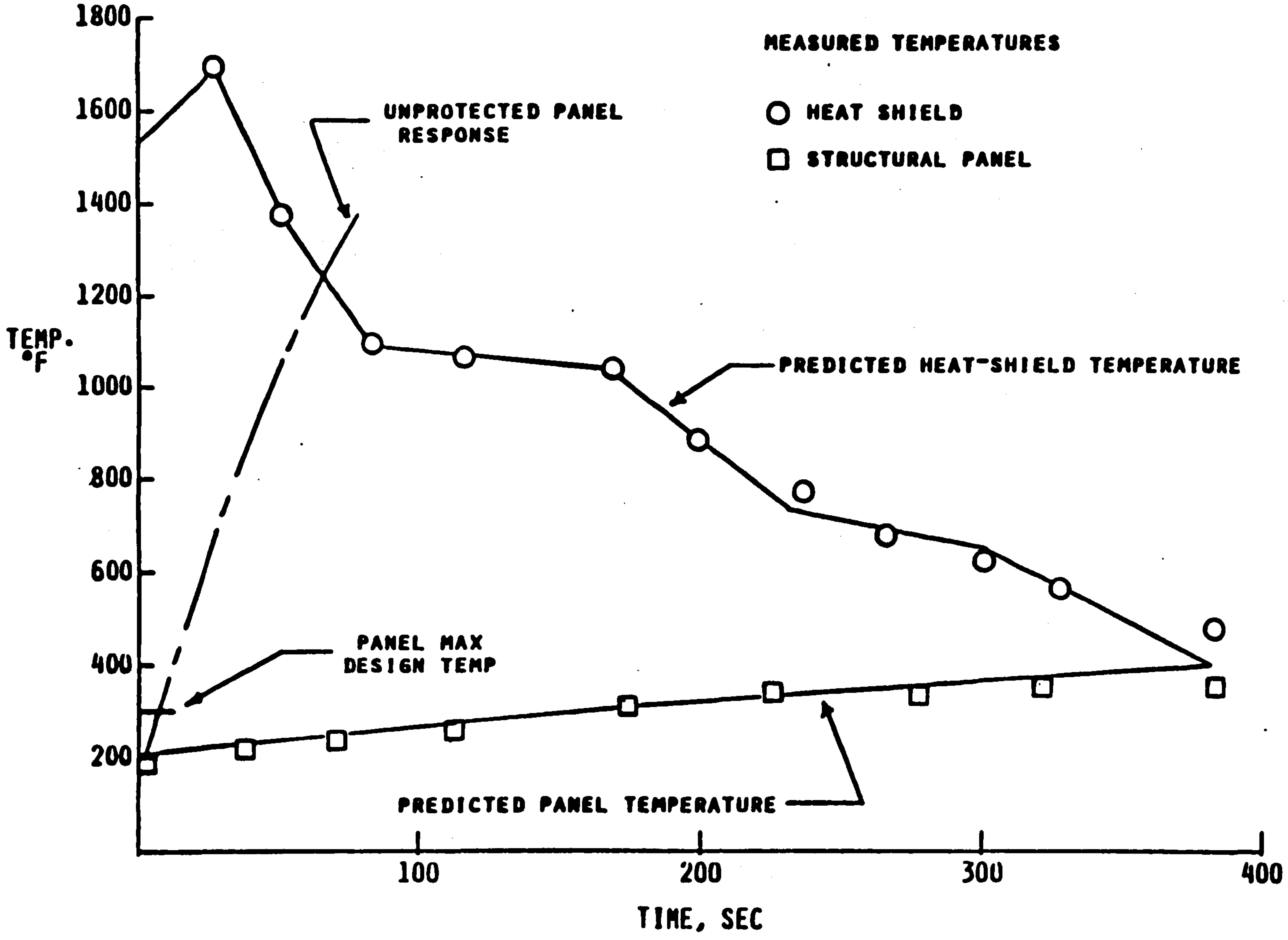


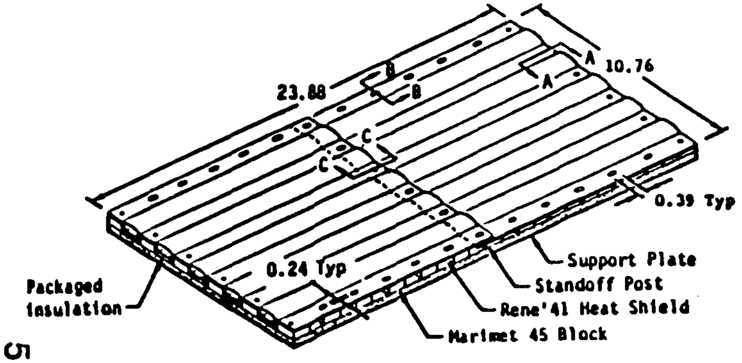
Figure 24

HEAT SHIELD THERMAL FATIGUE TESTS

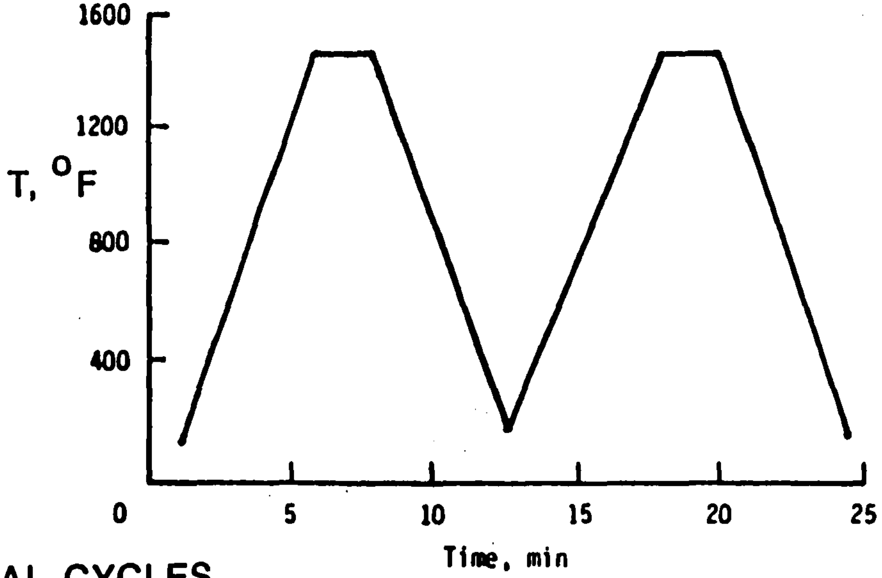
As part of the evaluation of the heat-shielded convectively cooled configuration, a thermal fatigue model of the heat shield design was subjected to a series of thermal cycles (ref. 29). As shown in figure 25, the model consisted of two corrugation-stiffened beaded-skin Rene'41 heat shields supported by an 0.5 in. thick aluminum plate. The overall configuration was 10.8 in. wide by 23.9 in. long. Rigidized insulation blocks were used to support the heat shields away from the aluminum plate and the space between the shields and the plate was filled with a layer of high-temperature insulation. The mid-panel joint was representative of the slip joint used in the full-scale design as were the other details of the heat shields. Thermal cycles indicated by the temperature histories shown on the figure were imposed by radiant heaters. The maximum expected temperature differential in the heat shields was 193°F; the tests imposed a 191°F maximum temperature differential. After 20,040 simulated flights (thermal cycles) were imposed, the heat shields were still intact. However, a one percent shrinkage in the heat shield caused cracks and excessive wear to occur around the elongated fastener holes. Shrinkage of the heat shield panels, which resulted from thermal creep and/or metallurgical changes in the alloy must be considered to properly design Rene' 41 heat shields. Tensile tests of specimens machined from the heat shield showed an 80 percent loss in ductility and a 20 percent increase in yield strength compared to Rene'41 in the aged condition which must also be considered in the design of the heat shields.

HEAT SHIELD THERMAL FATIGUE TEST

TEST ARTICLE



TEMPERATURE CYCLE



RESULTS

- PANEL INTACT AFTER 20000 THERMAL CYCLES
- 1% SHRINKAGE CAUSED CRACKS AND EXCESSIVE WARE AROUND FASTENER HOLES

Figure 25

SUMMARY OF ACTIVELY COOLED AIRFRAME STRUCTURE

Extensive work was done on actively cooled (secondary cooling circuit) airframe structures in the 1970's but little has been done since then. Systems studies revealed best concepts as a function of heat flux with coated concepts best for low values of heat flux. A heat shielded cooled concept (cooled structure with metallic radiation shields rejecting most of the heat input) was found to be the best concept for moderate values of heat flux. For very high values, bare aluminum concepts where the coolant absorbs virtually all of the heat input were best.

Systems studies identified actively cooled structure as attractive since it would be conventional aluminum structure. Design and in particular fabrication studies proved this to be incorrect; the structure was aluminum but not conventional. Major airframe manufacturers experienced fabrication difficulties, discovered a need for high conductivity adhesives, and learned that the difficult task of designing joints is greatly increased for actively cooled panels.

A bare actively cooled panel was subjected to radiant heating and cyclic mechanical loading and performed well and in the manner predicted. A heat-shielded actively cooled panel was subjected to similar tests as well as aerothermal loading and also performed as predicted. The heat-shielded system used fibrous insulation encapsulated in metal foil, and the foil was found to have unacceptable limited life; this problem has not been totally resolved. Systems studies identified an abort trajectory that minimizes heat load as one solution to the obvious concern of what happens when the cooling system fails. Coolant was cutoff to the heat shielded cooled panel and an abort heating profile applied to the panels. The panel performed as predicted.

No major show stoppers were found during the investigations and the biggest concern with this concept is the overall system complexities and the high reliability required.

Total program costs for four design and fabrication studies that resulted in three 2- by 4-foot test specimens were $1.25 million (circa 1975).

SUMMARY OF ACTIVELY COOLED AIRFRAME STRUCTURE

- DEFINED BEST CONCEPTS
  - COATED FOR LOW HEAT FLUX
  - METALLIC TPS FOR MODERATE HEAT FLUX
  - BARE ALUMINUM FOR HIGH HEAT FLUX

- COOLED ALUMINUM STRUCTURE NOT TYPICAL AIRFRAME CONSTRUCTION
  - HAD FABRICATION PROBLEMS
  - NEED HIGH CONDUCTIVITY ADHESIVES
  - JOINTS ARE A PROBLEM

- TESTED RADIATIVE - ACTIVELY COOLED PANEL
  - GOOD, PREDICTABLE PERFORMANCE
  - FOIL ENCAPSULATING INSULATION HAD LIMITED LIFE
  - NO MAJOR SHOW STOPPERS FOUND

- OVERALL SYSTEM COMPLEXITIES MAJOR DESIGN CONCERN

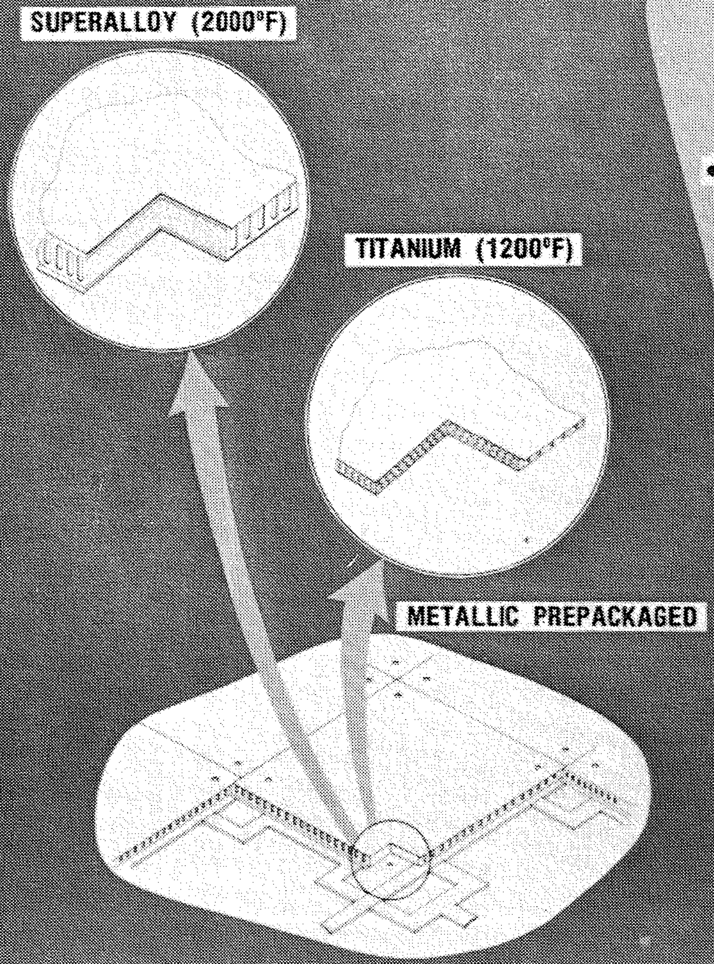
- PROGRAM COSTS   \$1.25 MILLION CIRCA 1975

Figure 26

ADVANCED TPS CONCEPTS

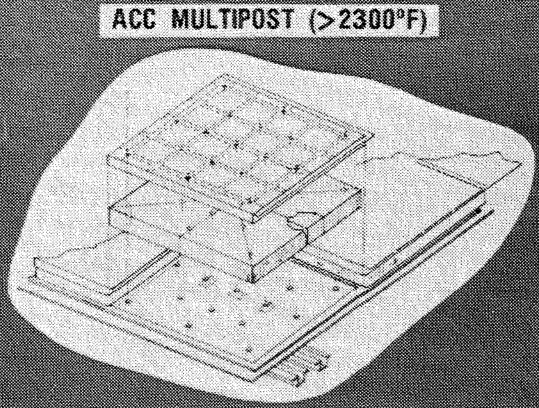
Design of the heat shields for the shielded convectively cooled panel was based on 1972 technology and although durable the heat shields had a high unit mass. Recent efforts have been directed toward developing durable thermal protection systems (TPS) with a low unit mass. Figure 27 summarizes a program to develop a durable TPS using metallic concepts for surface temperatures from 700°F to 2000°F and using Advanced Carbon-Carbon (ACC) above 2000°F (ref. 30). The goals of the program are to develop TPS that has durable surfaces, is mechanically attached, has covered gaps between panels to reduce gap heating, and is mass competitive. The graph in the figure shows that the durable TPS concepts indicated by the symbols are mass competitive with shuttle RSI indicated by the cross-hatched area.

DURABLE TPS CONCEPTS



GOALS

- DURABLE SURFACE
- MECHANICALLY ATTACHED
- COVERED GAPS
- MASS COMPETITIVE



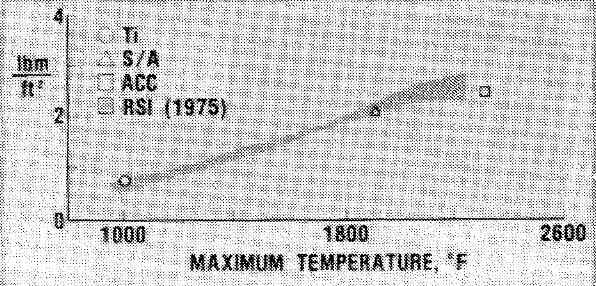


Figure 27

METALLIC TPS CONCEPTS

The two metallic prepackaged concepts shown in figure 28 are discrete panels that have a strip of RTV-covered Nomex felt beneath the perimeter of each panel to prevent hot gas flow beneath the panels. The titanium multiwall concept (maximum surface temperature <1200°F) consists of layers of dimpled titanium foil Liquid Interface Diffusion (LID)* bonded together at the dimples with a flat foil sheet sandwiched between the dimpled sheets. The superalloy honeycomb concept (maximum surface temperature <2000°F) consists of an Inconel 617 honeycomb outer surface panel, layered fibrous insulation, and a titanium honeycomb inner surface panel. The edges of the two metallic concepts are covered with beaded closures to form discrete panels nominally 12 inches square. Thermal expansion considerations limited panel sizes to 12 inches. The titanium multiwall and superalloy honeycomb panels are described in detail in references 31 and 32, respectively.

The two types of attachments shown in figure 28 can be applied to either of the TPS concepts. The bayonet-clip attachment, shown with the titanium concept, consists of two clips and a metal tab (bayonet) LID bonded to the lower surface of the panel. One clip is mechanically attached to the vehicle surface, and one clip is LID bonded to the lower surface of an adjacent panel. Thus, a single bayonet attaches a corner from each of two adjacent panels. The through panel fastener (most likely to be used), shown with the superalloy concept, consists of a thin-walled cylinder through the panel that allows access to a bolt which fastens the panel corner to the vehicle structure. The cylinder which contains fibrous insulation, is covered with an Inconel 617 threaded plug. These fasteners are described in detail in reference 32.

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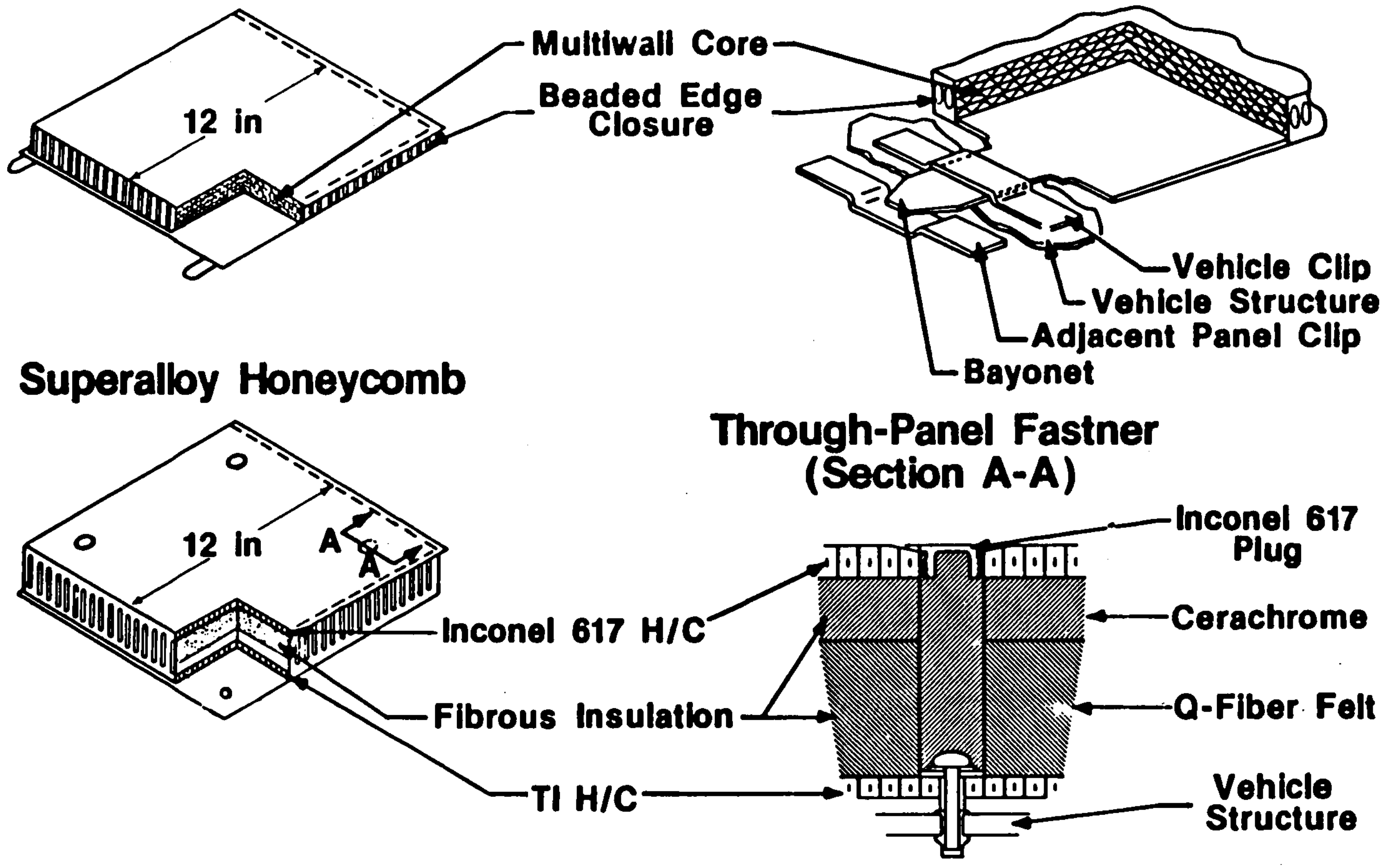
* Proprietary joining process of Rohr Industries

METALLIC TPS CONCEPTS



Titanium Multiwall

Bayonet-Clip Attachment

Superalloy Honeycomb

Through-Panel Fastner (Section A-A)

Figure 28

ADVANCED CARBON-CARBON MULTIPOST STANDOFF TPS CONCEPT

The Advanced Carbon-Carbon (ACC) multipost (maximum surface temperature <2000°F) shown in figure 29 consists of a rib-stiffened ACC sheet attached to the vehicle primary structure by posts with fibrous insulation packaged in a ceramic cloth between the ACC panel and the vehicle structure. The surface of the single ACC panel is nominally 36 inches square. The use of a larger unit than that for the metal concepts results because of the relatively low coefficient of thermal expansion of carbon-carbon. The shield is supported by 17 stand-off attachment posts, 14 of which are mounted with spherical attachments that permit unrestrained thermal expansion of the heat shield and 3 are attached with single axis pivots oriented to permit thermal expansion but restrained rigid body movement of the shield. The ACC multipost concept is described in detail in reference 33, and fabrication of an ACC test model used to obtain test results is described in reference 34.

ADVANCED CARBON-CARBON MULTIPOST STANDOFF TPS CONCEPT

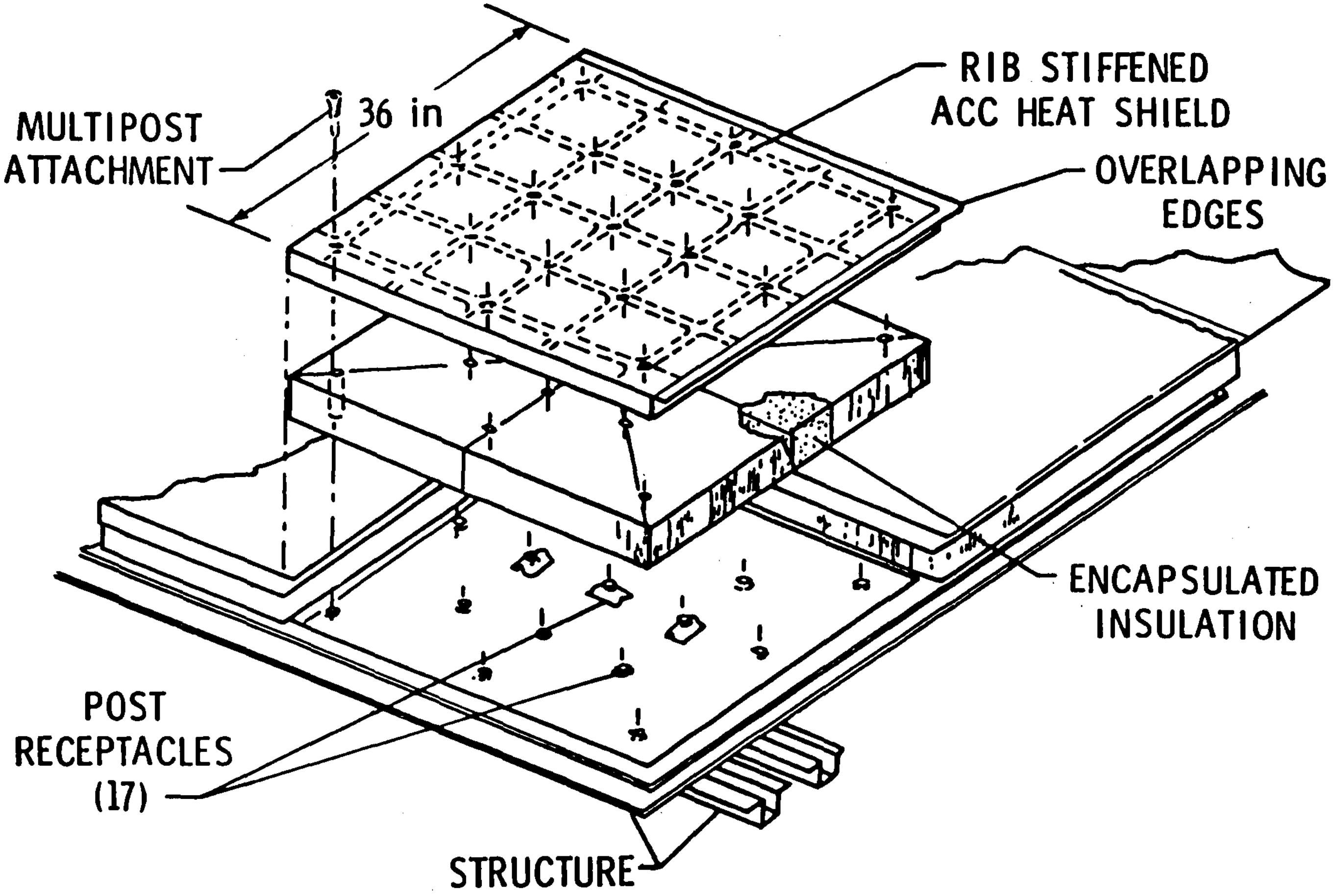


Figure 29

VERIFICATION TEST FACILITIES

NASA test facilities at Johnson Space Center (JSC), Kennedy Space Center (KSC), and Langley Research Center (LaRC) were used for verification test of the TPS concepts. Figure 30 summarizes the types of tests, shows representative test facilities, and identifies the NASA Centers where the tests were conducted.

TPS test models were exposed to combined temperature and pressure conditions to obtain thermal response characteristics at the concepts using thermal/vacuum test facilities at JSC, KSC, and LaRC. These facilities consist of radiant heaters enclosed in an environmental chamber.

Dynamic response of metallic TPS concepts was evaluated by shaker-table vibration tests and by acoustic exposure in a sound chamber of JSC and a progressive wave facility at LaRC. Acoustic levels were representative of those experienced during Shuttle lift-off. The LaRC facility uses air modulation to generate noise which propagates through a horn to the test section. Test panels are attached to the side wall of the test section. Graphite heaters are added to the test section side wall opposite the test panel to provide radiant heating capability.

Environmental tests to assess water retention and the effects of atmospheric contamination on metallic TPS were conducted near the Space Shuttle NASA launch site at KSC. Additional water retention tests were conducted with a wind/rain machine at JSC.

Lightning strike tests were conducted at LaRC to determine how much damage lightning impact causes on metallic panels. The facility operates by charging a bank of capacitors and rapidly discharging the capacitors to a grounded test model. The maximum capability of the facility is a peak current of 100 kA and an action integral of 0.25 x10^6 A^2-sec. This strike intensity meets space shuttle criteria for lightning strikes on acreage surfaces.

The metallic TPS concepts were tested in the LaRC 8-Foot High Temperature Tunnel (8' HTT) and the ACC concept was tested in the LaRC 20 MW Aerothermal Arc Tunnel to evaluate the performance of the concepts in an aerothermal environment. Details of these investigations are presented in reference 30.

NASA
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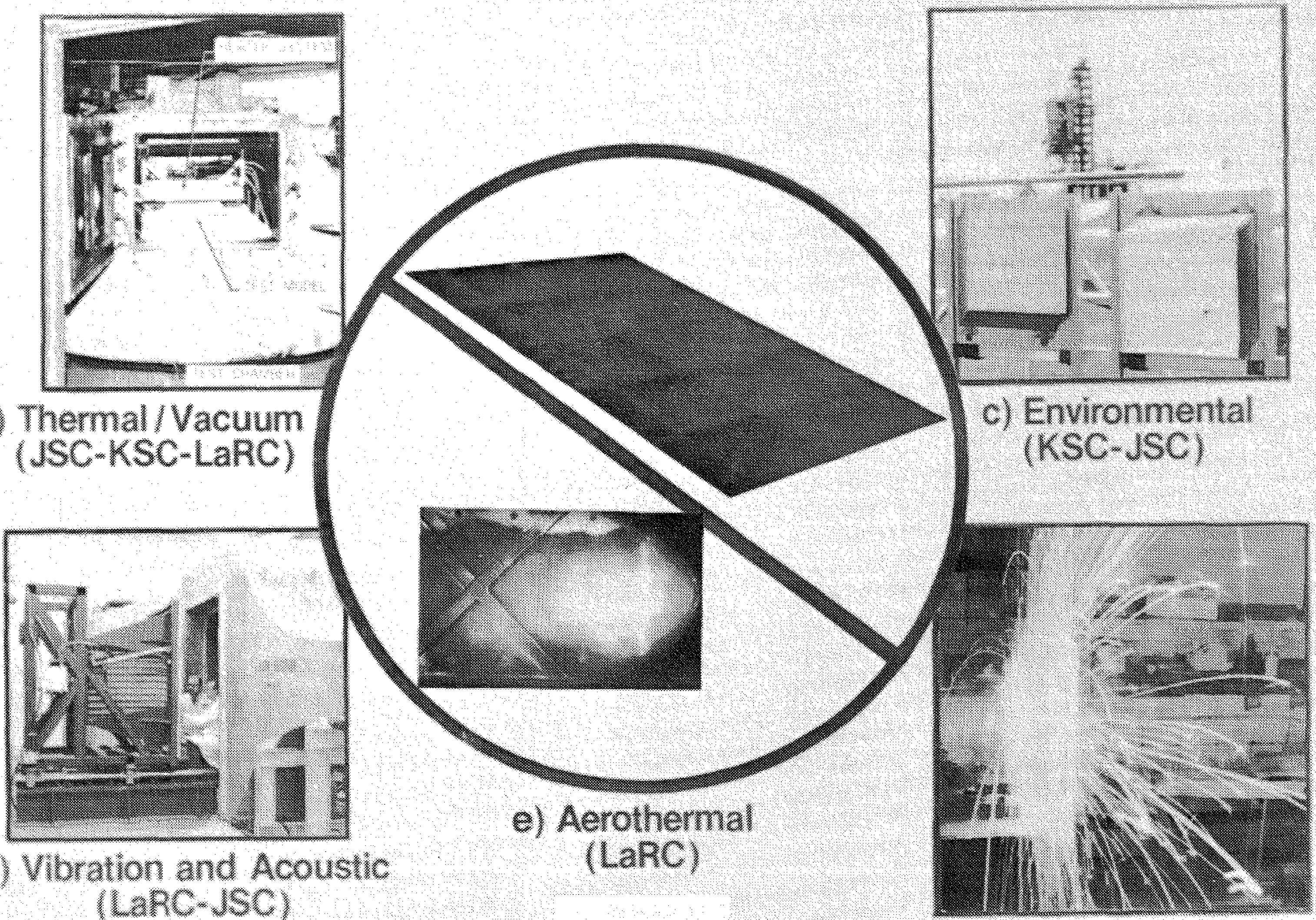
VERIFICATION TEST FACILITIES



a) Thermal / Vacuum
(JSC-KSC-LaRC)

b) Vibration and Acoustic
(LaRC-JSC)

c) Environmental
(KSC-JSC)

d) Simulated Lightning
(LaRC)

e) Aerothermal
(LaRC)

Figure 30

SUMMARY - ADVANCED TPS

Results from a variety of verification tests indicate that metallic TPS concepts are viable over a temperature range from 700°F to 2000°F and are mass competitive with current RSI thermal protection used on the Shuttle. Verification tests included thermal and aerothermal performance vibration and acoustic exposure, and exposure to simulated lightning strikes.

Advanced carbon-carbon is a promising material for acreage TPS applications at high temperatures. A multipost concept has been built and subjected to limited radiant heating and arc jet aerothermal tests with surface temperatures up to 2300°F. The specific concept tested may need a design change to prevent hot gas ingress at panel joints. The material is subject to oxidation and thus must be coated. Tests have shown that impact damage of the coatings may be a problem. Materials research suggests use temperatures of 3000°F should be achievable now, 3500°F in the near term, and 4000°F may be obtainable. The complex process required to make carbon-carbon makes these TPS concepts very expensive.

For both the metallic and advanced carbon-carbon TPS, hot gas ingress in the covered gaps was found to be a problem. For the metallic TPS, flow blockers have been incorprated in an array of curved panels which will be tested in an aerothermal environment to assess their effectiveness in a flow field with large pressure gradients. A similar local design change may be necessary for the advanced carbon-carbon TPS.

Total program costs for durable TPS development has been about $1.6 million.

SUMMARY - ADVANCED TPS

METALLIC TPS

0 METALLIC TPS MASS COMPETITIVE WITH CURRENT SHUTTLE RSI TPS DEMONSTRATED FOR TEMPERATURES UP TO 2000°F
- THERMAL/AEROTHERMAL
- VIBRATION
- ACOUSTIC
- LIGHTNING STRIKE

ACC TPS

0 MULTIPOST CONCEPT FOR ACREAGE APPLICATIONS SURVIVED REPEATED THERMAL EXPOSURES TO 2300° F

0 ARCJET TESTS SUGGEST JOINT-SEAL DESIGN CHANGE MAY BE REQUIRED

0 IMPACT DAMAGE TO COATINGS MAY BE A PROBLEM

0 MATERIALS RESEARCH SUGGESTS HIGHER USE TEMPERATURES POSSIBLE
- 3000° F, NOW
- 3500° F, NEAR TERM
- 4000° F, MAYBE

0 PROGRAM COSTS - $1.6 MILLION (CIRCA 1982)

FIGURE 31

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16. Abstract

Resurgent interest in development of Aerospace Plane and "Orient Express" type vehicles promises to stretch structural technology for hypersonic flight vehicles to the uppermost limits. Significant portions of the structure may require active cooling of some type to survive the hostile environment. Despite a lack of recent research activity for cooled structures, a significant body of unclassified knowledge exists concerning such structures. Contractual and in-house research conducted mainly by NASA's Langley Research Center during the decades of the 60's and 70's on vehicles very similar to the proposed "Orient Express" has provided a substantial data base for convectively cooled hypersonic flight structures. Pertinent results from the research conducted in the 60's and 70's are reviewed. Specifically, results are presented for regeneratively cooled structural concepts which have a relatively high heat flux capability and use the hydrogen fuel directly as a coolant; and for structural concepts which use a secondary coolant loop to absorb incident heating and then transfer the absorbed heat to the liquid hydrogen fuel as it flows to the engines. Results are presented to indicate application regions in terms of heat flux capability for various concepts and benefits for each concept. Additionally, experience gained and costs involved with design, fabrication, and testing of full-scale convectively cooled structures are discussed.

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