RECENT ADVANCES IN CONVECTIVELY COOLED ENGINE AND AIRFRAME STRUCTURES FOR HYPERSONIC FLIGHT*

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Abstract

The paper reviews Langley Research Center sponsored research on convectively cooled engine and airframe structures. The first section focuses on a hydrogen-cooled structure for a fixed-geometry, airframe-integrated scramjet; however, the thermal/structural problems, concepts, design features, and technological advances are applicable to a broad range of engines. The second section describes the most attractive convectively cooled airframe structural concepts that have evolved from an extensive series of investigations, the technology developments that have led to these concepts, and the benefits that accrue from their use.

Introduction

For hypersonic aircraft to become a practical reality, techniques must be developed for the design and fabrication of low-mass, airframe and engine structures that can withstand repeated and prolonged exposure to the severe aerodynamic heating encountered in hypersonic flight. The advancement of structural technology for this hostile flight regime has been the objective of continuing coordinated research at the NASA Langley Research Center.

At the 5th Congress of the International Council of the Aeronautical Sciences, September 1966, Heldenfels(1) reviewed the structural prospects for hypersonic vehicles. Emphasis then was on 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(2), Becker, at the 7th ICAS Congress(3) proposed convectively cooled airframe structures of conventional low-temperature, low-mass materials (e.g., aluminum) that used the hydrogen fuel as the ultimate heat sink for all cooling requirements. Subsequently, status reports on convectively cooled structures technology were presented by Wieting and Guy(4) for scramjet structures and Nowak and Kelly(5) for airframe structures.

The present paper reviews recent advances in convectively cooled structures for both engine and airframe applications. The paper is divided into two main sections. The engine section is somewhat narrowly focused on a hydrogen-cooled structure for the Langley airframe-integrated scramjet described in detail by Jones and Huber(6). However, the baseline thermal structural configuration, design features, technology advances, and fundamental problems investigated are applicable to a broader range of engine structures. The airframe section describes the most attractive convectively cooled airframe structural concepts that have evolved from a series of investigations, the technology developments that have led to these concepts, and the benefits that accrue from their use. In addition, experience gained in fabrication of several airframe panel concepts is documented.

Engine Structures

Work on hydrogen-cooled engine structures at the Langley Research Center began with the Hypersonic Research Engine (HRE) Program of the 1960's and culminated, from a thermal/structural standpoint, in tests of a complete flight-weight hydrogen-cooled engine assembly in the Langley 8-foot high-temperature structures tunnel (fig. 1). These tests(7) and others(8) confirmed the suitability of the basic approach for research purposes. However, two major thermal/structural problems were uncovered that must be solved before a hydrogen-cooled scramjet can become a practical reality: (1) the coolant requirements must be reduced (the HRE required almost three times as much hydrogen for coolant as for fuel) and (2) the thermal fatigue life must be increased (HRE had an anticipated fatigue life of only 135 operational cycles). Both these problems stemmed, at least 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 fundamental goal of the continuing research program was to develop an engine concept which required only a fraction of the total fuel heat sink for engine cooling.

Airframe-Integrated Scramjet

Studies of airframe-integrated scramjets with high potential performance led to the sweptback, fixed-geometry, hydrogen-fueled, rectangular scramjet module shown in figure 2. Two inner scramjet modules are shown; the sidewall of one module is removed to reveal the internal engine surfaces. The scramjet modules are integrated with the airframe and use the entire undersurface of the aircraft to process engine airflow. The aircraft forebody serves as an extension of the engine inlet, and the afterbody serves as an extension of the engine nozzle. A number of aerodynamic/propulsion advantages are obtained with this concept.(6) Structural advantages include the fixed geometry and reduced wetted surface area and heating rates. Surface area is reduced by the nonannular configuration and by the multiple fuel injection planes which promote fuel mixing and combustion and thereby reduce 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.

By 1971 propulsion technology for the airframe-integrated scramjet had advanced sufficiently to warrant development of the thermal/structural

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technology. A preliminary thermal/structural design analysis study[4] based on HRE technology indicated viability from both an engine structural mass and coolant requirement standpoint. This study revealed a number of critical areas (e.g., panel-to-panel seals, fuel injection struts) and reemphasized the need for advances in fabrication and materials technology to obtain reasonable structural life.

Recently, a more detailed study[9] of this scramjet concept was undertaken by a major engine manufacturer while the effort at Langley concentrated on the fuel-injection strut. As a focal point, the scramjets for these studies were sized for a conceptual hypersonic research aircraft and each module is approximately 46 cm high, 37 cm wide, and 315 cm long. Salient features from the thermal/structural design and analysis studies are presented in this paper.

Aerothermal Environment

The scramjet is designed to operate over a flight Mach number range of 4 to 10, and a dynamic pressure range of 24 kPa to 72 kPa. The maximum loading conditions occur during 2g maneuvers at a dynamic pressure of 72 kPa. The maximum thermal loading (heating rates up to 6 MW/m^2 on plane surfaces) occurs at Mach 10. The maximum pressure loading occurs at Mach 5.2.

The loading is characterized by the heat flux and pressure distribution along the longitudinal centerline of the sidewall component shown in figure 3. The heating is highly nonuniform because of boundary-layer transition, shock-boundary-layer interactions, and combustion. The critical pressure loads occur during an engine unstart (i.e., transition from supersonic to subsonic flow) which results if thermal choking occurs in the combustor. When the initial design study[4] was undertaken, the operational flow system was well understood; however, the unstarting process was not. Consequently, the basic unstart phenomena and loading were characterized experimentally[10].

The unstarting process is highly transient as indicated by the shaded area on the typical pressure history shown in the insert on figure 3. The peak pressure occurs during the unstart and is an order of magnitude higher than the normal operating pressure (p_o) and may be 2 to 7 times higher than the steady state unstarted pressure levels, which have typically been used in prior engine designs such as the HRE. These peak levels are conservatively predicted by normal shock wave theory. Since the complete dynamic characteristics of the transient pulse are not known, the envelope of the peaks along the engine (p_x on figure 3) currently serves as the basis for the engine structural design. The transient loading is particularly critical for the slender airfoil-like struts.

Shell Structure

To provide in-service accessibility and replaceability of parts, each scramjet module has detachable major structural components (see figs. 2, 4, and 5): a top wall, cowl, and two sidewalls, which form the basic shell structure, and the three fuel-injection struts.

Coolant System. All engine surfaces wetted by the airstream are regeneratively cooled by circulating the hydrogen fuel through a cooling jacket before injecting the fuel into the combustor. The cooling jacket, which is brazed to the primary structure, consists of the aerodynamic skin and multiple straight-fin or pin-fin coolant passages; straight-fin passages are shown as part of figure 4.

Although a fundamental design goal was the minimization of coolant requirements, the coolant routing scheme, depicted in figure 5, results primarily from requirements to minimize thermal stresses and deflections to yield the least complex thermal/structural and seal concepts. In general, the coolant enters each component leading and trailing edge (low heat load areas) and flows longitudinally toward the component center (highest heat load area), where it is collected in manifolds and routed to a fuel plenum. (Leading edge stagnation heating is intense but the heat load is low because of the small area). From there it is dispersed to the fuel manifolds in each strut and injected into the airstream. This routing scheme reduces the temperature variation transverse to the flow direction, the temperature differential through the cooling jacket, and to a lesser extent the total aerodynamic heat load thereby reducing the cooling requirements. Two coolant circuits per component were necessitated by the fuel pressure requirements, as frictional pressure losses with only one circuit would be excessive. The aerodynamic skin temperature distribution for each of the basic shell components is given in figure 6. A common outlet manifold location was selected to minimize thermal mismatch and simplify seals between components; although minimization of coolant flow rate and pressure drop would dictate different locations for the outlet manifold of each component.

All leading edges exposed to stagnation heating from the airflow are impingement cooled. The coolant is injected through a slot in the coolant inlet manifold and impinges on the inside surface of the leading edge, which then turns the coolant around to flow along the component surface (section A-A of fig. 7). This technique permits the use of the total sidewall coolant flow for impingement cooling. Even though the impingement cooling technique augments the coolant heat transfer characteristics along the stagnation line by a factor of two to three, the total circuit flow is required because of the high stagnation line heating.

A unique feature of the coolant routing scheme is the commonality of the cooling circuits for the sidewalls of adjoining modules. This scheme minimizes temperature gradients across the sidewall component and thus reduces thermal stresses and warpage in the sidewall. However, the primary structure is not common to the adjoining module sidewalls in that the frames are split as shown in section B-B of figure 7 to relieve top wall and cowl thermal stress by allowing the sidewalls to translate laterally relative to each other. The seal design is also simplified as the lateral expansion of only one module need be accommodated. In addition, module cowls are independent and allowed to slip relative to one another. The leading- and trailing-edge sections of the sidewall remain integral between adjoining scramjet modules; however, since these sections are near ambient temperature, the thermal stresses are acceptable[4,9]. The design features expansion joints and seals at the top and bottom of the sidewall and a sliding seal between the cowls. This overall freedom to expand precludes any thermal stress due to the absolute temperature change from ambient; however, thermal stresses caused by the nonlinear temperature profiles can be relieved only by minimizing the thermal gradients.

Primary Structure. Three basic engine shell concepts were investigated: two frame-stiffened honeycomb-core sandwich panels and a deep-core honeycomb sandwich panel. One of the stiffened concepts had sidewall frames swept 48 degrees (parallel to isotherms to minimize thermal stresses) and the other had vertical sidewall frames (parallel to isobars to minimize unstart pressure stress); the latter is shown in figure 4. Both stiffened configurations use a 10-mm-thick honeycomb-core sandwich and seven frames; the deep-core honeycomb concept has a core thickness which varies from 6 to 50 mm and has two vertical frames. Analytical results[9] indicate relative displacements between adjoining components are generally small for all three configurations at steady state conditions. The small relative displacements, which are a direct result of matching temperature distributions at the component interfaces (fig. 6), permit the panel corners to be rigidly joined allowing the use of a simple static seal or even a welded corner. All three concepts have approximately the same mass per unit capture area of 1260 kg/m^2. As a comparison, the HRE with a mass per unit capture area of 1500 kg/m^2 was heavier in spite of the more structurally efficient circular shell construction. The deep-core honeycomb concept was selected as the baseline design primarily because it exhibits the least deflection in the sidewall and nozzle areas and is the least complex structure.

Preliminary results[9] indicate that the basic shell concepts have a significant temperature gradient through the thickness during thermal transients (e.g., maneuvers, combustion shutdown) which may significantly impact the final design of both the seals and basic shell structure.

Fuel-Injection Struts

The fuel-injection struts (see figs. 2, 4, and 8) presented the most formidable cooling and structural problems. The struts must simultaneously support a large side load, contain high-pressure hydrogen at two temperature extremes, and withstand the high thermal stresses resulting from complex aerodynamic heating as well as convective heating from the hot hydrogen in the internal manifolds. To compound these problems, the cross-sectional area and contour cannot be altered without significantly changing the engine propulsion performance.

The struts, shown in figure 8, have a maximum thickness of 2.5 cm and chords of 25 cm (center strut) and 38 cm (side struts), span 46 cm, and are swept back 48°. As shown in figure 9, each strut is subdivided internally into four longitudinal compartments. The fore and aft compartments serve as coolant inlet and outlet manifolds respectively and the central compartments serve as fuel manifolds for the strut trailing edge (parallel to airflow) and wall (perpendicular to airflow) fuel injectors. Coolant in the inlet manifold is injected through a slot, impinges on the leading edge, and splits (unequally) to flow along each wall to the trailing edge, where it is collected in the outlet manifold. This quadrilateral manifold configuration was selected over a more structurally efficient (high pressure containment) tubular configuration because the former has a greater volumetric efficiency which results in larger fuel and coolant flow areas and thus lower pressure losses.

Thermal Loading. Overall thermal expansions of the strut are accommodated by the mounting system. The strut top wall and cowl mounts are basically at midchord. At the top the strut has rotational freedom about the transverse axis and translational freedom in longitudinal and transverse directions. At the cowl the strut has rotational freedom about all axes and translational freedom along the 48° sweep line.

Analytical results[4] revealed temperature differences of up to 470 K through the primary structure wall and attendant thermal stresses up to 80 percent of the allowable stress. These large temperature differences and stresses were caused by internal convective heating from the hot hydrogen in the manifolds. The internal heating, which is normally negligible compared to the aerodynamic heating, is increased significantly by the higher velocities caused by the restricted flow area. Attempts to reduce these stresses by rearranging the fuel and cooling manifolds as well as the coolant circuitry proved fruitless. However, the addition of a metallic plate-fin thermal buffer (fig. 10a) in the hot manifolds reduced primary structure thermal stresses by approximately 64 percent, as indicated in figure 10b. The thermal buffer fins are oriented transverse to the fuel flow direction to restrict flow and provide essentially stagnant hydrogen in the passages between the shield and the strut wall, thereby eliminating direct convective heating to the strut wall.

External Pressure Loading. The maximum external pressure loading occurs at the Mach 5.2 thermal choke condition when the aerodynamic flow in the passage between the sidewall and a side strut unstarts and the flow in the other three passages remains started. The net side loading due to pressure on the strut is approximately 0.7 MPa.

Analytical results[4,9] indicate that the combined thermal and pressure stresses exceed the allowable stress (σ_a). The thermal stress (0.8 σ_a) is caused by the nonlinear chordwise temperature gradient and wall in-depth temperature gradient shown in figure 11a for a coolant outlet temperature equivalent to the superalloy temperature limit of 890 K. The temperature gradients are significantly reduced, as shown in figure 11a, by increasing the coolant flow to obtain an outlet temperature equal to the fuel temperature (430 K). Attendant thermal stresses are reduced to 0.3 σ_a and the combined stresses are reduced approximately 50 percent to acceptable levels as shown in figure 11b. This technique adds no complexity to design or fabrication and even though the strut coolant flow rate is doubled, the overall cooling requirement is increased only 5 percent. As discussed later, excess coolant is available at this flight condition. An alternate technique, identified in reference 4, ties the three struts together at midspan; however, the tie greatly complicates cooling design and fabrication.

Vibration analysis of the strut indicates a first mode (bending) frequency of 170 Hz. This frequency is within the range of engine time varying loads (e.g., combustion, shocks, transient unstart). A cursory look at the flutter potential indicated a factor of safety of nine on dynamic pressure. However, the dynamic response of the strut to the time varying pressure loads may be critical, consequently a detailed analysis is planned.

Low-Cycle Fatigue Life

A program is in progress to develop and experimentally validate the fabrication and material technology required to obtain reasonable thermal fatigue life for the cooling jacket. The goal for the airframe-integrated scramjet is 1000 hours and 10 000 cycles of hot operation 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 presented in figure 12. The life goal appears attainable through a number of factors such as engine design, fabrication, and material selection. The improvements attributable to these factors are graphically illustrated in the figure. The bottom curve indicates the anticipated life of the Hastelloy X coolant jacket for the HRE. 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 photochemically 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 present in the HRE configuration. (The braze joint to the cooler primary structure remains, however.) The two candidate configurations fabricated by this process are shown in the figure. Finally, another increment in life is attained through the selection of a material with high thermal conductivity, which decreases the temperature difference, and with high ductility, which increases the fatigue life directly. To date Nickel 201 and Inconel 617 appear to be the most attractive materials. However, since these materials are not suited for primary structure application because of low strength, a new problem arises because high strength materials required for the primary structure generally have different coefficients of thermal expansion than the Nickel 201 and Inconel 617. Thus residual stresses may occur at ambient conditions because of thermal growth during the braze cycle. This problem is currently being investigated.

Cooling Requirements

The fraction of the stoichiometric fuel flow required to cool the scramjet engine at two dynamic pressures is shown in figure 13 as a function of Mach number. (A value of 1.0 indicates that all of the fuel flowing to the engine is required for cooling). Preliminary, and somewhat more optimistic, estimates of the cooling requirements have been presented in other papers [2,3,11]; however, the present results are based on more detailed analyses and are more realistic. The results are presented inversely to the normal manner - with cooling requirements increasing from top to bottom - to highlight the impact of hydrogen temperature indicated by the secondary scale on the right. The curves are based on a hydrogen supply temperature of 56 K and the assumption that all cooling routes are balanced so that the hydrogen exits from each at a temperature of 890 K, a limit set by the superalloy material used in the primary structure. Any reduction in the average exit temperature, such as proposed for the struts, would increase the coolant flow required for cooling the engine. The fuel provides an adequate heat sink for cooling the engine at Mach numbers up to approximately 9 at a dynamic pressure of 24 kPa and to even higher Mach numbers at a dynamic pressure of 72 kPa. The cooling requirements are less severe at the higher dynamic pressure because the heat load increases as the 0.8 power of the dynamic pressure while the fuel requirement increases linearly. At lower Mach numbers there is surplus hydrogen fuel heat sink for airframe and/or additional engine cooling.

The curves presented in the figure can also be interpreted as a good approximation of the maximum hydrogen coolant supply temperature that the engine could tolerate without exceeding the prescribed outlet temperature if all of the fuel passed through the engine cooling circuits. When viewed from this perspective, it is more readily apparent that all of the surplus fuel heat sink is not available for airframe cooling. For example, at Mach 6 and a dynamic pressure of 24 kPa the engines require approximately 50 percent of the fuel heat sink for cooling and the coolant supply temperature could be approximately 450 K. However, that is too hot for cooling an aluminum airframe and, although 50 percent of the fuel heat sink is not required for engine cooling, only about 32 percent is available for airframe cooling. The other 18 percent would most likely be used to reduce the engine operating temperature levels and thereby increase the material strength and life, provided the reduced operating temperature is not detrimental to the engine propulsion performance. As shown by the figure, the engine requirements begin to reduce the fraction of heat sink available for airframe cooling above a Mach number of approximately 7.5.

Airframe Structures

Since Becker proposed the use of convectively cooled airframe structures of conventional low temperature materials (e.g., aluminum) at the 7th ICAS Congress,[3] a major portion of structures research for high-speed cruise flight sponsored by the Langley Research Center has involved such structures. The basic concept, suggested by Becker, (fig. 14) uses a closed-loop secondary cooling circuit with liquid coolant flowing through passages in the surface structure to transport the absorbed aerodynamic heating to a heat exchanger where the heat is rejected to the cryogenic hydrogen fuel flowing to the engine. The concept which uses a high-level cooling system (i.e., one that absorbs virtually all of the incident heat load) with the fuel as the ultimate heat sink evoked visions of largely unshielded hypersonic cruise vehicles with long-life, low-mass structures of conventional low-temperature materials.

Although early studies 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(12-17) and hardware studies(5,18,19), following the lead of Becker, concentrated on bare cooled structures with high-level cooling. Recent studies(20-22) have yielded a better understanding of the significance of heat sink matching and the mass penalties associated with high-level cooling. From these studies a coherent and consistent definition of the most attractive convectively cooled structural approach is emerging, an approach that combines both passive and active thermal protection.

Recommended Application Regions

Recommended application regions for airframe concepts that combine passive and convective cooling are indicated in figure 15. The limits shown are approximate, and precise definition depends on the intended application. At the lower incident heat fluxes an overcoated convectively cooled structure is the favored concept. The overcoat, which is a moderate-temperature elastomeric material applied to the outer surface of the structure, is an outgrowth of the fail-safe abort studies by Jones(23). At higher heat fluxes the overcoat is replaced by high temperature insulation and metallic heat shields. This approach represents a marriage of convective active cooling with the mature radiative heat shield technology developed for entry vehicles(24). Only at the highest heat flux levels where heat shields reach excessive temperatures would bare convectively cooled structures be used. Fortunately, high heat flux areas represent only a small fraction of the surface of vehicles operating at Mach numbers up to approximately 10. As discussed in subsequent sections the use of hot surface thermal protection (overcoats or heat shields) with convectively cooled structures reduces total mass and provides other benefits including improved heat-load/heat-sink compatibility, increased safety and reliability, tolerance to off-design conditions, and ease of fabrication.

Hot-Surface Thermal Protection

Before discussing the benefits of integrating passive and convective cooling it is appropriate to review the status of hot surface thermal protection (heat shields and overcoats).

Heat Shields. Various radiative metallic heat shields have been considered for use with convectively cooled structures (22). The corrugation-stiffened shield shown in figure 15 has been extensively investigated analytically and experimentally as part of the NASA space transportation system effort(24). Corrugated superalloy heat shields have been shown to be suitable for reentry applications up to 1260 K which corresponds to a heat flux that is approximately 40 kW/m^2 higher than the upper use limit suggested in figure 15, TD nickel chrome shields to 1480 K which corresponds to an incident heat flux in excess of 400 kW/m^2, and refractory alloys to even more severe conditions. As concluded in reference 24, the basic technology for metallic heat shields is "in hand." Increasing service life of heat shields from the hundreds of mission cycles required for space transportation systems to the thousands required for hypersonic aircraft remains a significant but hardly insurmountable task since the heating environment for aircraft is less severe.

Overcoats. The low-density silicone, elastomeric material recommended as an overcoat is representative of a class of materials that also has been extensively investigated as part of the space effort - originally as an ablator(25) and more recently as a surface insulator.(26) When maintained at temperatures below about 600 K, as in the intended application, the material provides a resiliant insulation surface; if inadvertently overheated the material becomes a tenacious charring ablator providing an additional margin of safety. The overcoat concept in contrast to metallic shields is not limited by minimum gage restraints and can be sized to provide the optimum insulation thickness. Typically the thickness, which would vary with heat flux and overcoat material properties, would be less than 1.0 cm. The life and durability of overcoats have not been directly addressed and therefore remain unproven. However, a coating of silicone rubber (a probable base material for overcoats) applied to an area on the bottom of a high speed research aircraft (YF-12) to prevent impingement damage from jettisoned covers for a heat-transfer experiment showed no evidence of damage after over two years of service. During the two years, the material was exposed to temperatures up to 560 K and foreign object damage from the experiment and debris from landings including one on a dry lake bed.

Safety and Reliability

Safety and reliability are critical concerns for convectively cooled structures because such structures depend on mechanical equipment and contain liquid coolant under pressure. These concerns have prompted studies of means of permitting hypersonic aircraft to decelerate to a less hostile flight environment without exceeding the temperature limitations of the structure if the cooling system malfunctions(20,23). These studies involved methods of detecting malfunctions, configuration modifications to extend or augment the heat sink capacity of the structure, and minimum total heat-load flight maneuvers. The most recent of these "fail-safe abort" studies(20) presents highly convincing evidence that fail-safe abort systems are completely feasible throughout the Mach 3-6 speed range (the limits of the study). Additionally, results of the study indicate that hypersonic cruise aircraft capable of safely aborting flight from the cruise condition can be lighter than a bare convectively cooled configuration without abort capability! Table I, which contains information extracted from reference 20, summarizes the structural mass and cooling characteristics of three pairs of convectively cooled aircraft designed for 200 passengers and a range of 9.26 Mm at Mach numbers of 3.0, 4.5, and 6.0. At each Mach number one of the two aircraft is a bare configuration with no abort capability, the other is the configuration with the best abort performance, as defined by the study, for that Mach number. At Mach 3.0 the total mass of the structural system for the configuration with abort capability is only 57 percent of the mass for the bare configuration; at Mach 4.5, 84 percent; and at Mach 6.0, 66 percent. The key to the abort capability and lower mass is the hot surface insulation (overcoat or heat shield). Insulation provides a thermal response delay that enables the aircraft to decelerate to a less hostile flight environment if the system fails. Insulation also reduces the instantaneous heat load to the cooling system during normal flight to or below the heat sink capability of the hydrogen fuel flow thereby eliminating the need for extra hydrogen solely for cooling.

The results of table I highlight the importance of matching heat load with available heat sink. The penalty for not matching the heat sink, as indicated by the additional hydrogen required for cooling, is most pronounced at the lowest Mach number. The severity of the penalty is the consequence of the higher lift-to-drag ratio and lower specific fuel consumption postulated for the Mach 3 vehicle and the duct burning turbo fan engine. The trend is consistent with early analytical work[3] which indicated increased heat sink matching difficulty with higher aircraft and engine performance.

Durability of the coolant passages is also an important consideration; however, preliminary ambient temperature fatigue tests of convectively cooled surface structural elements[5,18] indicate that coolant passages can be designed and fabricated with adequate life and noncatastrophic failure characteristics. Test results showed that even with surface flaws intentionally placed in the external skins of the structure a design life of 20 000 fully reversed cycles at limit load was exceeded before leakage occurred, and failure was always gradual rather than catastrophic with leakage increasing slowly until final failure occurred. In fact, tests of a honeycomb configuration with discrete cooling tubes[18] indicated that cracks in the structural skin would propagate past the tubes without penetrating them; furthermore the tubes retarded crack growth at tube-skin intersections.

Off Design

In a study[21] which assumed an adequate fuel heat sink was always available, shielded convectively cooled structures were recommended for uniform heat fluxes greater than about 85 kW/m^2 and nonuniform heat fluxes as low as 35 kW/m^2. This recommendation was based on a merit parameter which included mass, fabricability, inspectability, and reliability. The study recommended bare configurations with either plain tubes or tubes with internal fins at low heating rates; however, overcoated configurations were not considered.

Unit masses for bare and shielded panels from reference 21 and recently calculated unit masses for overcoated panels are presented in figure 16 for two different heating distributions. The results are shown as a function of the uniform heat flux that would be absorbed by a bare cooled structure with a surface temperature of 394 K. For the nonuniformly 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. Both the bare and overcoated configurations employed coolant passages with internal fins since experimental heat transfer data upon which the study was based indicated that at Prandtl numbers encountered with convective cooling systems, fins augment heat transfer without significantly increasing pressure losses and thus yield the lowest mass configurations. Unit masses for the overcoated configuration were calculated by the authors using structure and system masses from reference 21 and overcoat material properties from reference 27. The overcoat had a maximum thickness of about 1.0 cm at a heat flux of about 10 kW/m^2. At higher fluxes the thickness was reduced to avoid exceeding the material maximum use temperature and at lower fluxes the thickness was reduced to decrease mass. As shown in figure 16, overcoated configurations exhibit a clear mass advantage over bare configurations for both uniform and nonuniform heating. Figure 16 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 from uniform to nonuniform heating which increases the average heat flux by a factor of 1.4, increases shielded panel mass by less than 8 percent and bare configuration mass by 16 to 50 percent.

Besides facilitating accommodation of heating nonuniformities, insulation (both overcoats and heat shields) decreases the sensitivity of convectively cooled structures to transients as indicated by figure 17. The figure 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 136 kW/m^2 to a 422 K surface. For the factor of two step increase in aerodynamic heat transfer coefficient the temperature of the structure protected by the shield slowly increases by an insignificant 10 K and the shield temperature increases about 149 K to 1232 K. (A temperature within the use range of superalloy shields). In contrast, the bare structure responds rapidly and increases about 57 K to 479 K which is unacceptable for aluminum. The lower sensitivity of shielded structures will certainly simplify cooling system controls and may make it possible to size insulated convectively cooled structures for steady-state heat loads, whereas bare configurations must be sized for the most severe maneuver heat load.

Fabrication

Reference 5, which surveys several design and fabrication studies, indicates the feasibility of designing, optimizing, and fabricating bare convectively cooled structures for a heat flux of 136 kW/m^2. However, the report cites several problems that were encountered during the fabrication of small fatigue specimens and larger (0.61 by 1.22 m) convectively cooled structural panels for experimental verification and performance testing. These problems are more tractable for shielded configurations.

For example, 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 18 which presents maximum skin temperatures for bare and shielded convectively cooled configurations. Both configurations were designed for the same aerodynamic heating environment and employed similar construction with discrete cooling tubes spaced 2.54 cm. As shown, skin temperatures for the bare structure are excessive at conductances representative of available adhesives. Thus, bond-line conductance was the controlling factor which dictated 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[19]. At the lower heat flux adhesive bonding yields acceptable temperatures and was used successfully to attach cooling tubes to the structure of a shielded configuration[22].

Another problem that was more difficult for bare than shielded structures was the bolted joints at the end of a structural panel. As shown in figure 19, for a bare panel (heat flux = 136.2 kW/m^2) 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[5,18] and was redesigned for the shielded structure[22] (heat flux = 9.1 kW/m^2). 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.

System Trades

Collectively, previous studies have indicated the inadequacies of bare convectively cooled aluminum structures for hypersonic cruise aircraft and identified the numerous benefits attainable by combining passive thermal protection with convective cooling. Once it is accepted that some type of hot surface insulation is inevitable, and in fact desirable, it is possible to consider trades to establish the optimal use of convectively cooled structures and the potential use of mixed thermal/structural concepts.

Lowest total unit mass, which has been the primary criterion for selecting a concept in the preceding discussion, may not be the proper criterion in an overall trade study. The composition of the masses and perhaps more importantly the cooling requirements of different configurations vary radically even when the unit masses are the same because surface temperatures and hence absorbed heat fluxes vary widely. For example, at a uniform heat flux of 131 kW/m^2 both the overcoated and heat-shielded configurations (previously presented in figure 16) have a unit mass of 18.5 kW/m^2; however, as shown in figure 20, the cooling system comprises approximately 43 percent of the mass of the overcoated configuration and less than 13 percent of the mass of the shielded configuration. Furthermore, the cooling requirement of the shielded configuration, which absorbs only 7 percent of the incident heat flux, is less than 10 percent of the requirement of the overcoated configuration. For comparison, a bare configuration, which must absorb the total incident heat load, can accommodate less than three-fourths the heat load (91 vs 131 kW/m^2) of protected configuration with the same total mass. In fact, if cooling capacity is critical, it may be advantageous even at low heat fluxes to select shielded configurations, despite attendant mass penalties (fig. 16), because of greatly reduced cooling requirements.

There may be areas for which convectively cooled structures are not desirable. For example, a study of actively cooled structures[17] which used overall vehicle performance as a merit parameter and assumed an unlimited fuel heat sink concluded that improved performance could be obtained by replacing the cooled engine nacelle structure with a hot structure because the reduction in cooling system mass more than offset the mass increase of the hot structure. In fact, the fuselage tankage area, which was the focal point of the study, may not be a desirable application for convectively cooled structures. Preliminary calculations by the authors based on the insulation system of reference 28, heat shields of reference 20, and structure of the fuselage/tankage study[17] indicate a simple insulated and shielded configuration is lighter than a convectively cooled configuration. Results of these calculations, summarized in figure 21, indicate that in addition to being 21 percent lighter, the insulated configuration is 30 percent thinner thereby increasing the volumetric efficiency; even though the insulation was actually sized for a Mach 8 airframe whereas the cooled configuration was designed for Mach 6. The shielded and insulated configuration is less complex and avoids the ironic situation of requiring thermal protection to prevent freezing of the coolant in the feeder lines[29].

Finally, it appears desirable to consider cooled structure temperature from a total system standpoint. Generally, in system studies, the temperature has been arbitrarily set near the limit for the structural material to conserve the limited heat sink. With the increased design flexibility provided by insulated convectively cooled structures it may be desirable to operate the structure in some areas, such as the passenger compartment, at temperatures nearer the desired interior environment. Additionally, thermal/structural optimization studies of insulated structures[30,31] have shown that minimum mass designs do not necessarily coincide with the maximum use temperature for the structural material. In fact, reference 30 states that the structural operating temperature should be included as a design variable.

Experimental Program

To complement the system studies a series of design and fabrication studies has produced three 0.61 m by 1.22 m structural panels for thermal structural testing. The test structures, shown in figure 22, include a shielded panel and two bare panels of different construction. All panels were designed for the same environment: a uniaxial inplane limit load of ± 210 kN/m, a uniform normal pressure of ± 6.89 kPa, and a thermal environment that would produce a uniform heat flux of 136 kW/m^2 to a 0.61 by 6.1 m full scale panel with a surface temperature of 422 K. Additionally, each panel was designed for a life of 10 000 hours and 20 000 fully reversed limit load cycles. The panels differed in both structural and cooling concepts but each used aluminum as the structural material and a 60/40 glycol-water mixture as a coolant. The heat-shielded configuration features a corrugation stiffened René 41 heat shield and an adhesively bonded honeycomb sandwich structure with half round coolant tubes. One of the bare configurations uses an adhesively bonded stiffened-skin structure with redundant, counter-flow, quarter-ellipse coolant tubes; the other uses a brazed plate-fin sandwich with adhesively bonded stiffeners for both the structure and cooling passages. Additional characteristics and features of the concepts are presented in reference 5 and complete details of the shielded panel design and fabrication are presented in reference 22.

A breakdown of the unit masses and absorbed heat fluxes (i.e. cooling requirements) for the three test panels and a fourth bare honeycomb concept that was abandoned because of fabrication difficulties[19] are presented in table II. As indicated the cooling requirement (absorbed heat flux) for the shielded configuration is over an order of magnitude less than that for the bare configurations. As a result, the mass of the ancillary active-cooling system (pumps, heat exchangers, distribution system, etc.) is reduced sufficiently so that the total configuration mass for the shielded configuration is 7 percent lighter than the corresponding bare configuration even though the mass of the shielded structure alone is approximately 35 percent higher than the mass of the bare panel. The bare stiffened sandwich and stiffened-skin structures are lighter than the honeycomb sandwich; therefore, since the mass savings afforded by shielding is primarily in the cooling system mass, it is apparent that shielding could be applied to the other structural concepts in table II to obtain configurations that are even lighter.

To date the design and fabrication studies have provided insight into some of the practical problems of designing and fabricating low mass convectively cooled structures[5,19,22] and a preliminary appraisal of the fatigue characteristics using small ambient temperature specimens[5,18]. Currently, the large (0.61 by 1.22 m) specimens are being tested at the Langley Research Center. All three of the convectively cooled panels will be tested in a special test apparatus shown in figure 23. The structure will be simultaneously heated with the radiant lamp array, cooled with a chilled glycol-water solution, and cyclically loaded by the servo-controlled testing machine. The shielded configuration will also be tested at a Mach number of 7 in the Langley 8-foot high-temperature structures tunnel to detect possible aerothermal problems and investigate possible hot gas ingress problems which would seriously degrade overall performance. In addition, durability and thermal cycle tests of hot surface insulations are planned. Data from the experimental program will permit a quantitative assessment of the thermal and structural performance and structural integrity of both shielded and bare convectively cooled structures.

Concluding Remarks

Closely coordinated research over the past decade has identified critical thermal/structural design problems and has produced viable design concepts for a second generation experimental scramjet. The design concepts for the hydrogen-fuel-cooled engine structure involve a variety of innovative features to accommodate the harsh aerothermal environment encountered within the engine. The baseline concept that has evolved has reasonable mass characteristics, and cooling requirements that permit engine operation to Mach numbers of 9-10 without additional hydrogen for engine cooling. At lower Mach numbers significant excess heat sink capacity is available for airframe cooling or reduced engine structural temperatures. Studies have identified fabrication techniques and coolant passage configurations that increase fatigue life of the structure an order of magnitude over previous configurations. Future research will involve experimental verification of the selected concepts.

Extensive studies of hypersonic airframe structures provide a coherent and consistent definition of the most attractive convectively cooled structural approach. The studies indicate that at the lower incident heat fluxes (lower Mach numbers) an overcoated convectively cooled structure is the favored concept. (The overcoat is a moderate temperature elastomeric insulation applied to the exterior surface of the structure.). At higher heat fluxes the overcoat is replaced by high temperature insulation and metallic heat shields, and only at the highest heat fluxes in areas where the heat shield temperatures are excessive would bare convectively cooled structures be used. Overcoats or heat shields provide numerous benefits including: improved heat-load/heat-sink compatibility, increased safety and reliability, tolerance to off-design conditions, lower mass, and ease of fabrication. An experimental program is presently underway to verify the performance and life of bare and shielded convectively cooled airframe structures in a realistic heating, loading, and cooling environment. The program includes heating and loading in a special test apparatus and aerothermal testing at a Mach 7 in the Langley 8-foot high-temperature structures tunnel.

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TABLE I. FAIL-SAFE ABORT ACTIVELY COOLED AIRCRAFT
[200 PASSENGER, 9.26-Mm RANGE (REF. 20)]

MACH NUMBER		3.0		4.5		6.0	
ENGINE		DUCT BURNING TURBO FAN		TURBO RAMJET		TURBO RAMJET	
FAIL SAFE ABORT		NO	YES	NO	YES	NO	YES
THERMAL PROTECTION	UPPER SURFACE	BARE	SILICONE OVERCOAT	BARE	SILICONE OVERCOAT	BARE	SILICONE OVERCOAT
	LOWER SURFACE	BARE	SILICONE OVERCOAT	BARE	TITANIUM HEAT SHIELD	BARE	RENÉ 41 HEAT SHIELD
MASS SUMMARY, Mg							
Actively Cooled Structure		38.2	37.7	38.7	37.7	38.9	37.7
Thermal Protection System		0	1.5	0	5.2	0	8.4
Active Cooling System		3.3	2.3	5.6	2.6	7.7	3.2
Failure Detection System		0	0.5	0	0.5	0	0.6
SUBTOTAL		41.5	42.0	44.3	46.0	46.6	49.9
Additional Hydrogen for Cooling		32.1	0	10.7	0	29.4	0
TOTAL		73.6	42.0	55.0	46.0	76.0	49.9
HEAT LOAD TO HEAT SINK RATIO							
		1.62	1.0	1.23	0.41	1.67	0.46

TABLE II. UNIT MASSES OF FOUR CONVECTIVELY COOLED STRUCTURAL CONCEPTS

THERMAL CONCEPT	SHIELDED DISCRETE TUBES	UNSHIELDED DISCRETE TUBES	UNSHIELDED PLATE-FIN SAND.	UNSHIELDED REDUNDANT TUBES
STRUCTURAL CONCEPT	HONEYCOMB SANDWICH	HONEYCOMB SANDWICH	STIFFENED SANDWICH	STIFFENED SKIN
*ABSORBED HEAT FLUX, kW/m^2	9.1	136.2		
COMPONENT	UNIT MASS, kg/m^2			
Optimized Mass				
Dry				
Skins	5.86	3.76	3.95	3.66
Cooling Passages	0.78	2.73	0.64	0.93
Stiffening	1.42	1.32	1.71	3.91
SUBTOTAL	8.06	7.81	6.30	8.50
Wet				
Cooling Inventory	0.59	1.86	2.49	1.46
Pumping Penalty	0.01	0.34	0.53	0.29
SUBTOTAL	0.60	2.20	3.02	1.75
Non Optimums				
Manifolds	0.78	0.64	0.44	0.53
Closeouts	0.63	1.76	1.71	0.93
Adhesives	1.95	2.10	0.29	0.10
Fasteners, etc.	1.02	0.49	0.64	0.34
SUBTOTAL	4.38	4.99	3.08	1.90
Radiation System	7.27	-	-	-
Total Panel Mass	20.31	15.00	12.40	12.15
Distribution System	1.76	** 8.64	** 9.40	** 8.6
Total Concept Mass	22.07	23.64	21.80	20.75

* All concepts designed for an incident heat flux of 136.2 kW/m^2
** Approximate values based on results from reference 22; distribution system mass was not included in the original design of these concepts.

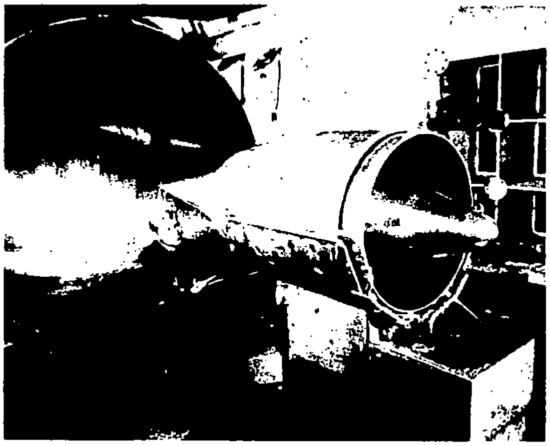

Figure 1. Hypersonic Research Engine (rear view) installed in the Langley 8-foot high-temperature structures tunnel.

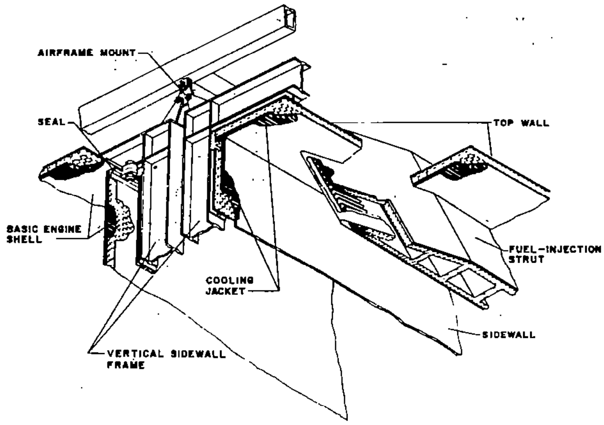

Figure 4. Typical construction of engine shell and fuel-injection strut.

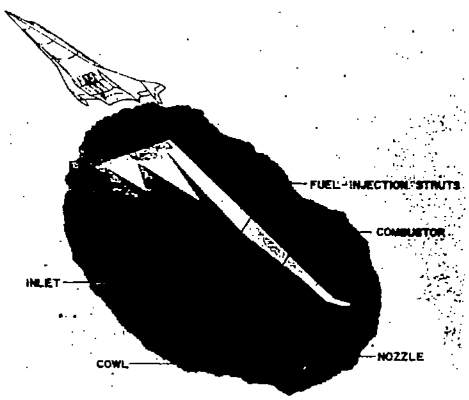

Figure 2. Airframe-integrated supersonic combustion ramjet.

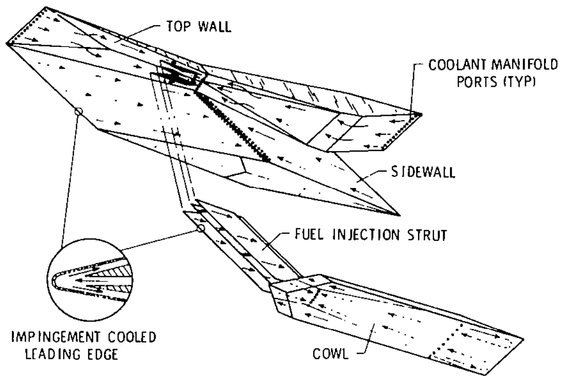

Figure 5. Hydrogen coolant routing scheme (One sidewall removed).

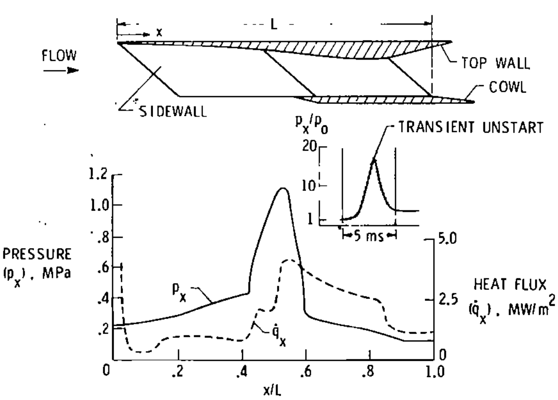

Figure 3. Typical design loads - sidewall.

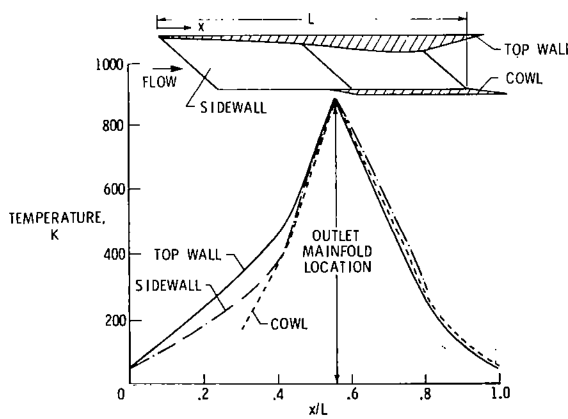

Figure 6. Engine component temperature distributions.

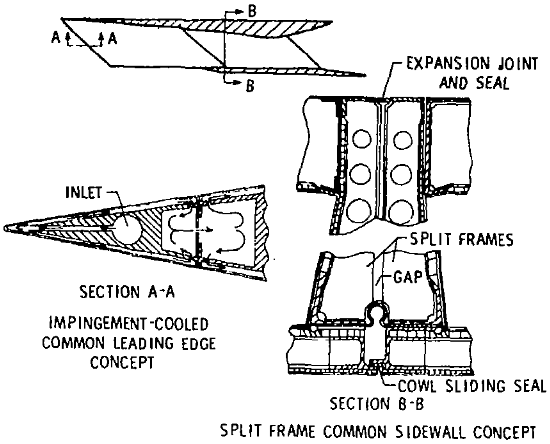

Figure 7. Leading edge and sidewall concept.

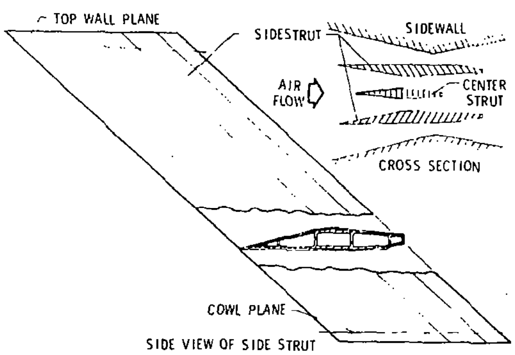

Figure 8. Fuel-injection struts.

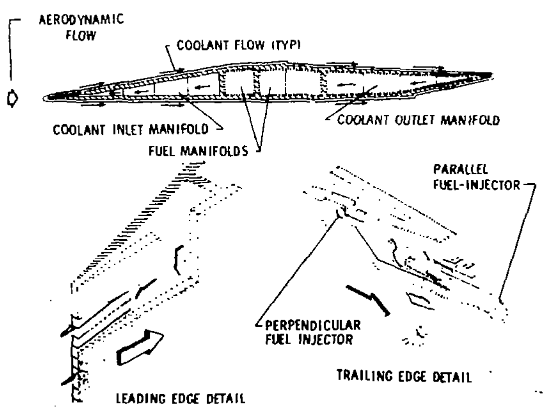

Figure 9. Fuel-injection strut detail.

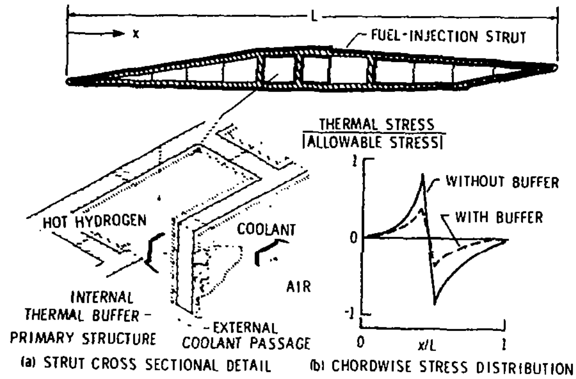

Figure 10. Internal thermal-buffer concept.

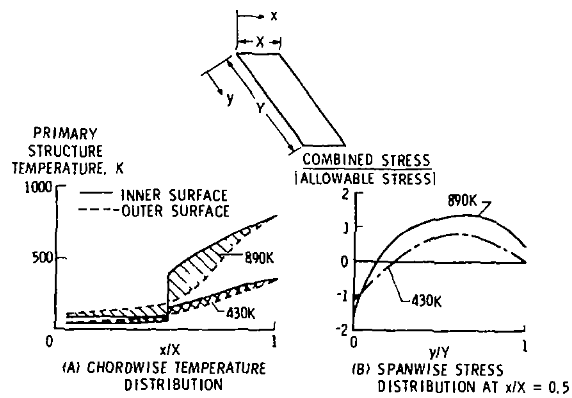

Figure 11. Strut temperature and stress distributions for coolant outlet temperatures of 430 K and 890 K.

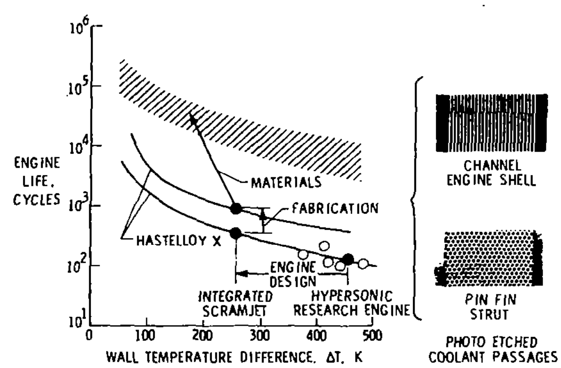

Figure 12. Factors improving thermal fatigue life.

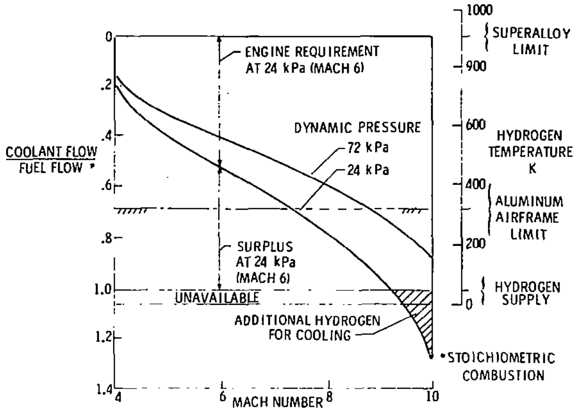

Figure 13. Engine cooling requirements.

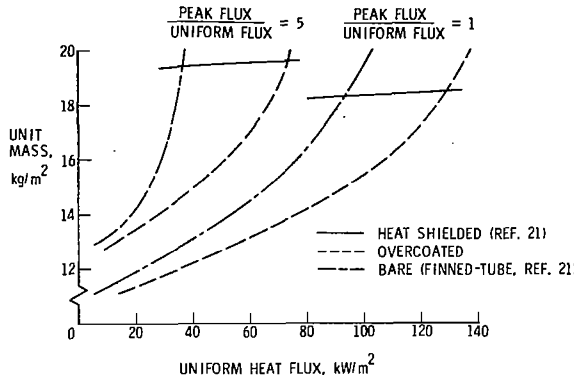

Figure 16. Convectively cooled panel masses.

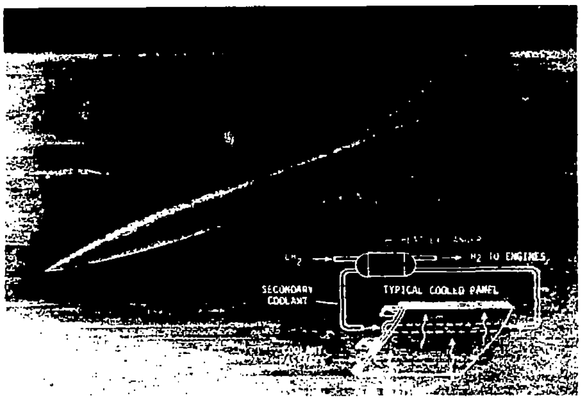

Figure 14. Convective cooling system for hypersonic aircraft.

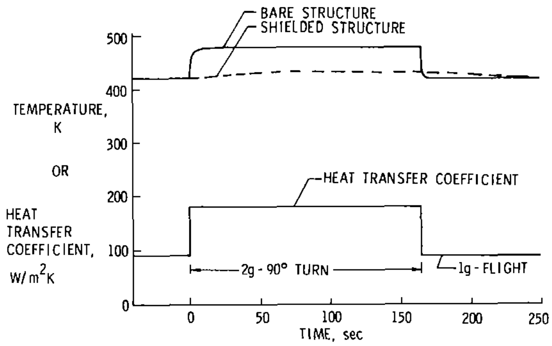

Figure 17. Sensitivity of convectively cooled structures to transient heat loads.

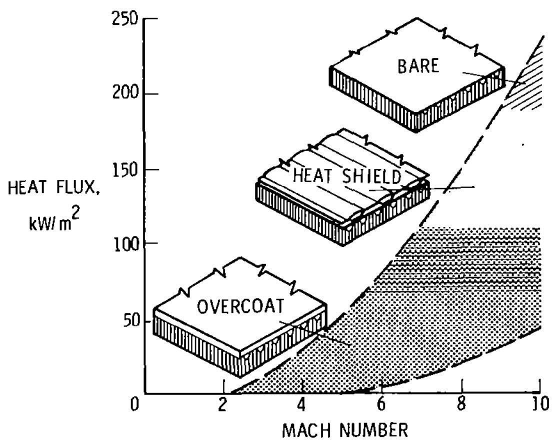

Figure 15. Recommended application regions for convectively cooled airframe structures.

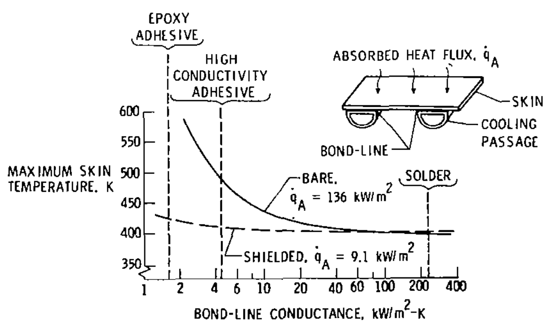

Figure 18. Effect of bond-line conductance on maximum skin temperature for bare and shielded configurations.

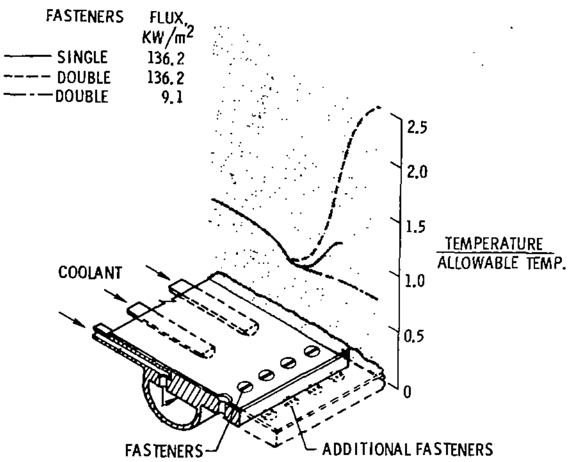

Figure 19. Effect of absorbed heat flux on joint design.

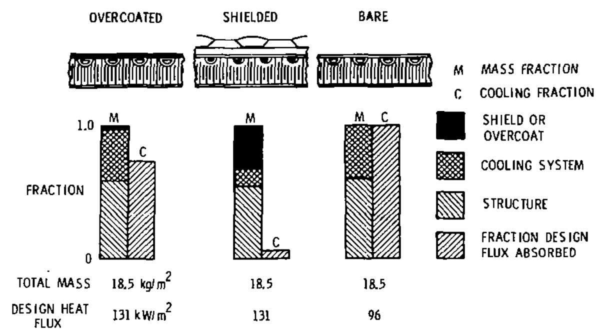

Figure 20. Mass and cooling characteristics of convectively cooled structures.

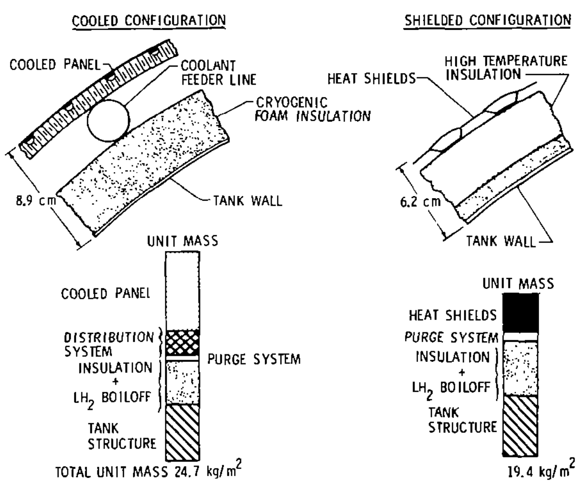

Figure 21. Comparison of convectively cooled and shielded tank structures.

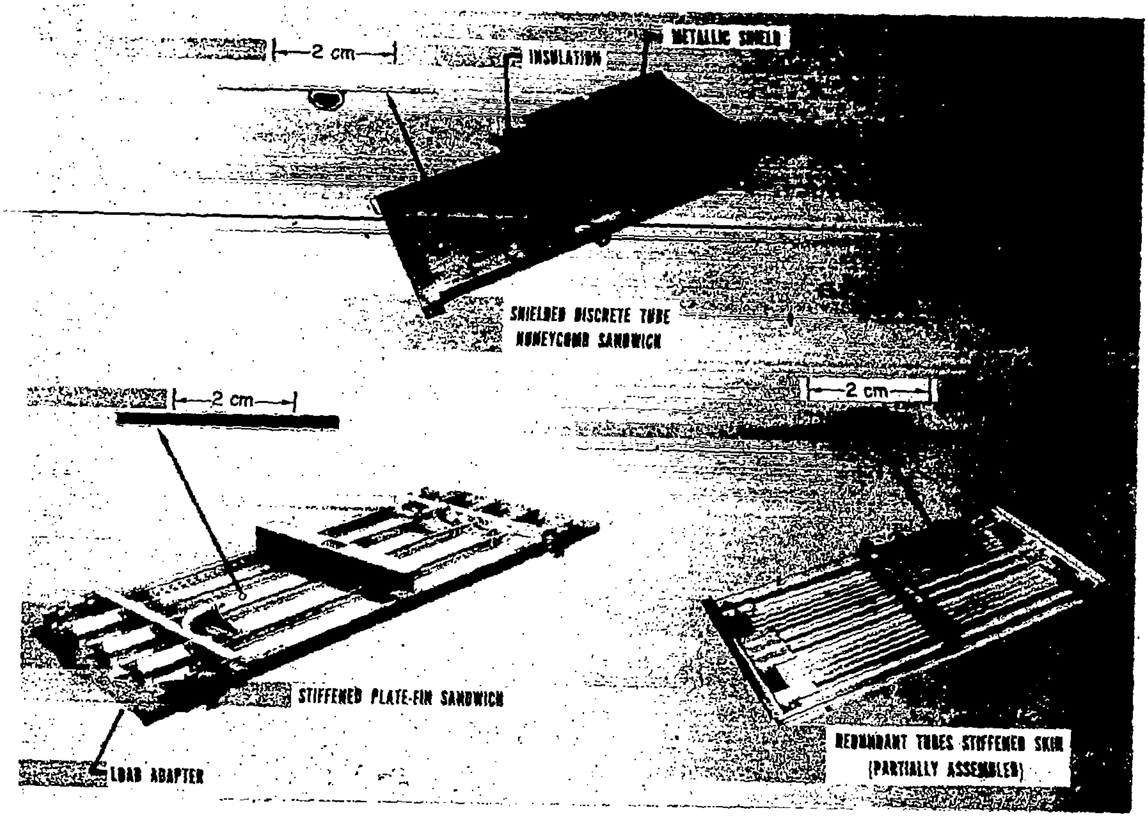

Figure 22. Large (0.61 by 1.22 m) convectively cooled test panels with cooling passage details.

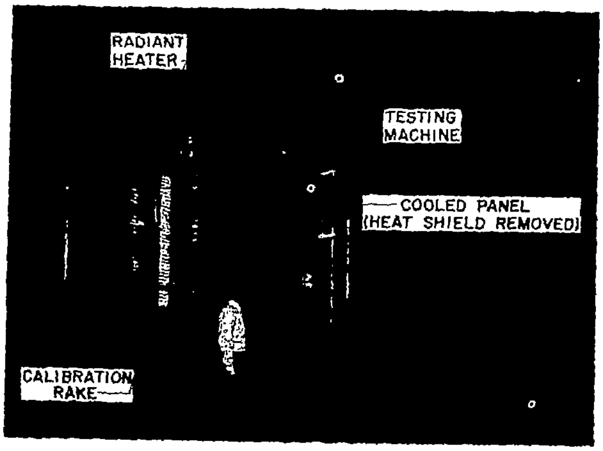

Figure 23. Test apparatus for convectively cooled structures.