Actively Cooled Airframe Structures for High-Speed Flight

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A preliminary assessment of forced convectively cooled aircraft structures is presented based on recent and ongoing studies. Particular emphasis is given to contractual efforts in which large panels of three different concepts are being designed and fabricated for cyclic thermal-structural tests at the Langley Research Center. Results of ambient temperature fatigue tests of small specimens of these concepts are reviewed. Aspects of conceptual and detail designs, material selection, fabrication, reliability, and heat-load/hydrogen fuel heat-sink matching are discussed. Results to date indicate that active cooling significantly impacts the structural design process, and, despite the use of conventional aluminum materials, advanced complex fabrication processes are required.

Nomenclature

D = tube diam, m (in.)
H = core height, m (in.)
N_x = in-plane loading, N/m (lbf/in.)
P = pressure, Pa (lbf/ft^2)
$\dot{q}$ = heat flux, W/m^2 (Btu/ft^2-sec)
S = space between tubes, m (in.)
T = temperature, K (°F)
ΔT = temperature difference, K (°F)
X = distance along cooling passage, m (ft)

Introduction

A VARIETY of structural concepts have been proposed for high-speed flight vehicles where aerodynamic heating is a critical concern. Many of these concepts employ heavy and costly high-temperature materials. One approach that avoids high-temperature materials, using instead conventional materials such as aluminum, is the forced convection actively cooled structure shown schematically in Fig. 1. This concept, which Ref. 1 indicates is the most attractive structure for hydrogen-fueled hypersonic cruise vehicles, uses a liquid coolant and a closed-circuit cooling loop to transmit aerodynamic heating from the structure to a heat exchanger, where it is transferred to the cryogenic hydrogen fuel flowing to the engine. This approach avoids many of the problems inherent with high-temperature structures, but introduces the complexity, fabrication difficulties, and reliability concerns peculiar to actively cooled systems.

Actively cooled structures have been investigated for several years. Most of the earlier work (e.g., Ref. 2) considered concepts with metallic heat shields, which radiated the majority of the incident heat to space, so that the heat flux to the cooled structure was low. The apparent problems and restrictions of metallic heat shields, as noted by Becker,[3] prompted the system studies of Refs. 1, 4, and 5, out of which concepts for unshielded, high heat-flux level active cooling systems evolved. However, the studies also showed that the hydrogen fuel-flow heat-sink was not sufficient to cool a completely bare aluminum hypersonic aircraft. Subsequent studies[6-16] have investigated various aspects of these actively cooled structures for high-speed aircraft. The possibilities of applying active cooling to augment thermal protection system concepts for the space shuttle were considered in Refs. 17-19. However, with the exception of some of the earlier work with shielded low heat-flux level systems, all of these efforts have been paper studies, and many of the practical, real-life problems associated with the design and fabrication of lightweight actively cooled structures were not explored. These problems are being addressed currently in a program in which three different actively cooled structural panels are being designed and fabricated for combined thermal structural testing at the Langley Research Center. In another current program, a fourth panel, which combines radiative and active cooling, is being designed to alleviate heat-load/heat-sink matching difficulties

The purpose of this paper is to provide a preliminary assessment of the status of actively cooled airframe structures based on the panel programs and other current studies of actively cooled structures. The paper will explore various aspects of such structures including concepts, design, material selection, fabrication, reliability, and heat-load/fuel flow heat-sink matching.

Design Considerations

Thermal factors play an important part in the design process involved in transforming the actively cooled structure shown schematically in Fig. 1 into a practical reality. In addition to the parameters normally considered in structural design, a variety of factors controlling the thermal performance of the cooling system – such as passage size, shape, and spacing; and coolant properties, flow rate, pressure, and temperature – must be factored into the structural design to obtain lightweight structures. Some significant effects of incorporating active cooling in structures are discussed in the following sections.

Heat Flux

Heat flux is a prime factor in sizing a cooling configuration. The influence of heat flux is illustrated in Fig. 2 by the results of a typical trade study to determine the optimum geometry and mass for an actively cooled skin with discrete half-round cooling tubes. The diameter and spacing shown are those required to minimize the unit mass of a glycol/water cooled aluminum configuration constrained to a maximum temperature of 422K (300°F) and a maximum temperature difference of 56K (100° F). These limits were selected to be

Presented at the AIAA/ASME/SAE 17th Structures, Structural Dynamics, and Materials Conference, King of Prussia, Pa., May 5-7, 1976 (in bound volume of Conference papers, no preprint number); submitted May 19, 1976; revision received Aug, 13, 1976.

Index categories: Aircraft Structural Design (including Loads); Structural Design, Optimal.

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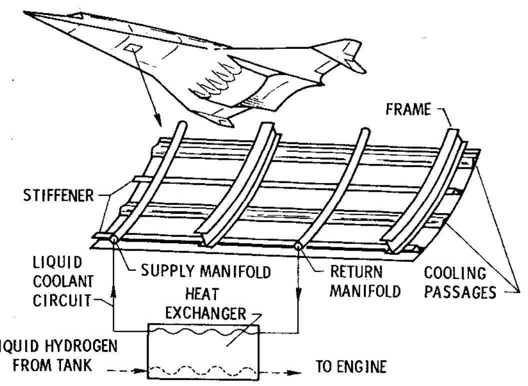


Fig. 1 Forced convection actively cooled structure.

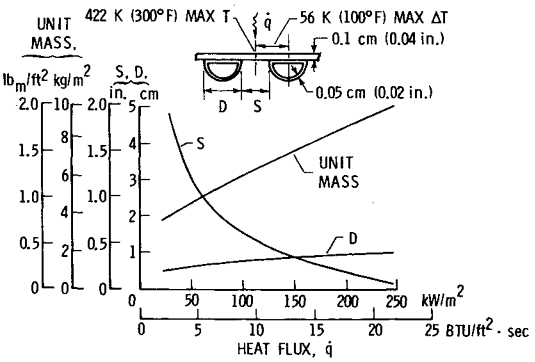


Fig. 2 Influence of heat flux on mass and design of an optimized configuration. Mass includes the metal, coolant inventory, and pumping penalty. [At 0.84×10^{-6} kg/J (5 lbm/hp-hr).]

within the usable temperature range for the metal and to avoid excessive thermal stresses. The unit mass includes the mass of the metal and the coolant in the tubes and a mass penalty to account for the energy required to pump the coolant through the tubes. [A pumping penalty of 0.84 $\times 10^{-6}$ kg/J (5 lbm/hp-hr) was used for this trade study and for the three panel concepts to be discussed later. Recent studies indicate 0.34×10^{-6} kg/J (2 lbm/hp-hr) is more realistic; however, this does not significantly alter the trends to be presented.] As shown, the tube diameters for the optimized configuration are small and relatively constant over a wide heat-flux range. The spacing between tubes decreases rapidly with increasing heat flux in the low heat flux range and approaches zero for high heat flux values although a more practical limit is that required to allow for fasteners or stiffeners. The unit mass increases rapidly with heat flux; however, the mass cannot be evaluated fully until the cooling and structural designs are integrated, since the coolant passages, if properly oriented, can serve as structural members, thereby offsetting some of the mass penalty.

Flow Transition

As shown in Fig. 3, large areas of transitional (laminar to turbulent) flow may occur in the coolant passages as a result of coolant temperature changes, which cause large Reynolds number changes along the passage length. (The viscosity of glycol/water is a strong function of temperature.) The presence of transitional flow adds complexity and uncertainty to the design process since in such areas the convective heat-transfer coefficient and, consequently, the metal temperatures are not well known. Furthermore, with changing flow regimes, the critical area from a structural standpoint may not be at the end of the panel, where the coolant temperature is a maximum. For the example illustrated, the critical area occurs at the end of the laminar flow region, where metal temperatures and temperature differences are the highest. The use

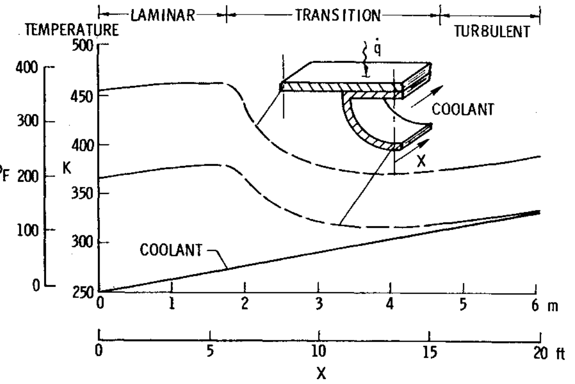


Fig. 3 Temperature distribution along panel—semicircular coolant passage.

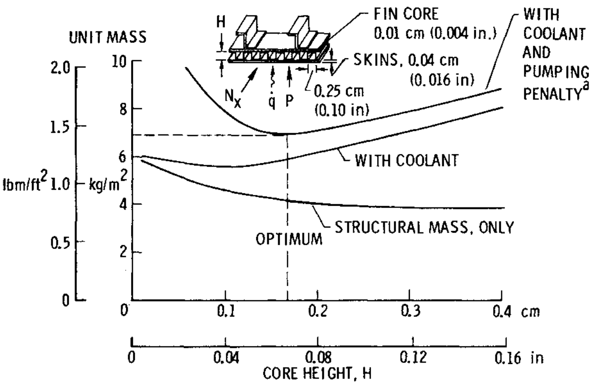


Fig. 4 Effect of coolant on mass trends for a stringer-stiffened, plate-fin structure. $N_x = 210$ kN/m (1200 lbf/in.); $\dot{q} = 136$ kW/m^2 (12 Btu/ft^2-sec); $P = \pm 6.89$ kPa ($\pm$ 1 psi). [At 0.84×10^{-6} kg/J (5 lbm/hp-hr).] [a]

of all turbulent flow has been considered, but increased pressure losses and resulting increases in configuration mass make this approach unattractive.

Thermal-Structural Interaction

The active cooling system has significant impacts on structural design trends. As indicated in Fig. 4, the presence of coolant in a stringer-stiffened plate-fin sandwich, in which the coolant passages are formed by the fin core and the face sheets of the sandwich, causes the mass of the sandwich required to carry a given load to increase with core height, instead of to decrease as it would for a conventional dry sandwich. However, as the core height is reduced, the increase in pumping penalty causes the mass of the structure to rise rapidly. Nevertheless, the net result is that minimum mass actively cooled sandwich structures tend to be thinner than conventional sandwich structures.

The effects of thermal and structural loading on panel mass are illustrated in Fig. 5. The figure shows the variation of mass (structure, coolant inventory, pumping penalty, and an allowance for manifolds) of stringer-stiffened plate-fin panels for a range of thermal and structural loadings. In these studies, structural design was based on general buckling determined by the procedure of Ref. 20. The strong dependence of panel mass on thermal as well as structural loading is readily apparent. Also apparent at zero heat flux is a discontinuity, which represents the minimum discrete mass increment required to include active cooling (coolant inventory, pumping penalty, and manifold allowance), and the structural mass increment that results from the changes in the design optimization trends as a consequence of active cooling.

All of the previously mentioned studies have been based on a uniformly heated panel. A current study (Contract NAS1-14140) is evaluating the effects of local hot spots, caused by inteference heating, on actively cooled panel design.

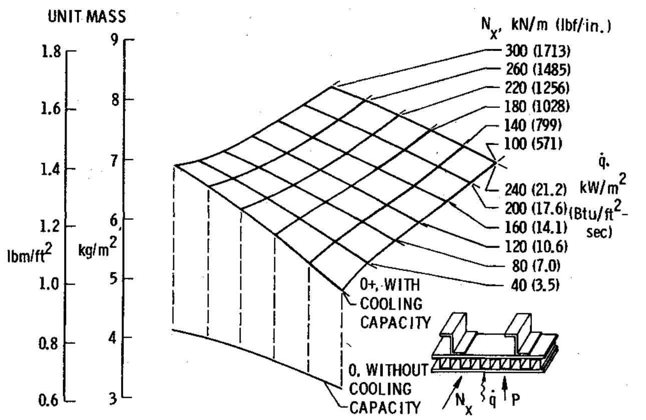


Fig. 5 Effect of structural and thermal loading on mass of a stringer-stiffened, plate-fin sandwich actively cooled panel. [Optimized for buckling only, nonoptima not considered; $P = \pm 6.89$ kPa (± 1 psi).]

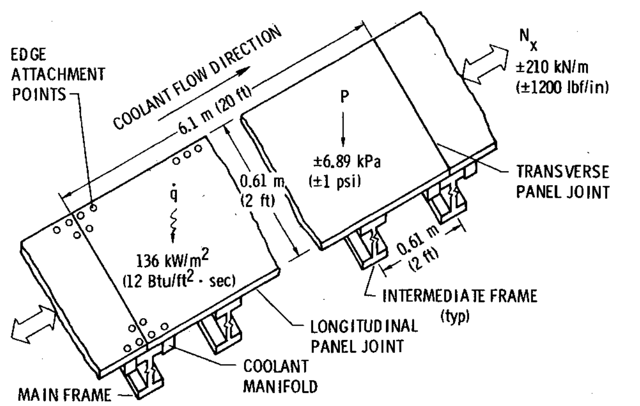


Fig. 6 Schematic of panel design requirements.

Coolant Distribution System

The design process used for major areas of an actively cooled structure generally appears adequate, although some improvements are desirable. In particular, provisions are needed for incorporating the effects of the coolant distribution system (pumps, controls, distribution lines, etc.) into the initial design optimization. Results from Refs. 10-13 indicated that overall actively cooled system mass can be lowered by operating at coolant pressures that are higher than those dictated by consideration of the cooled structural panel only, because of lower distribution line and coolant masses. A current study (Contract NAS1-13939) is including the distribution system mass in the panel design.

Panel Concepts

Design Conditions

Three distinctly different panel concepts have been developed to meet the requirements shown schematically in Fig. 6. Each full-scale panel is 0.61 by 6.1 m (2 by 20 ft) and is subjected to a uniform heat flux of 136 kW/m² (12 Btu/ft²-sec), a uniaxial limit load of 210 kN/m (1200 lbf/in.), and a uniform normal pressure of ± 6.89 kPa (± 1 psi). The design life requirements are 20,000 fully reversed fatigue cycles and 10,000 hr. These conditions represent a high thermal loading, but a moderate simplified structural loading to be experienced by hypersonic cruise aircraft in the Mach 6 to 8 speed range. The panel edges are designed to allow attachment and structural load transfer to identical panels. Frames, typical of aerospace construction, are spaced at 0.61-m (2-ft) intervals. Manifolds at both ends of the panel distribute and collect the coolant, which flows parallel to the longitudinal edge. The minimum coolant outlet pressure is 345 kPa (50 psi) to allow for pressure losses in the coolant return lines.

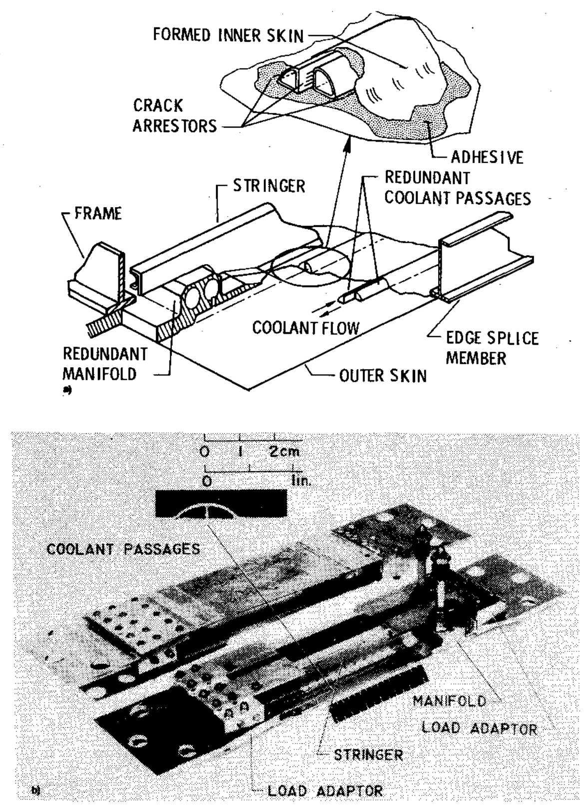


Fig. 7 Stiffened skin, redundantly cooled panel. a) Panel concept. b) Fatigue specimens.

Panel Descriptions

For each of the three concepts, small specimens of critical areas of the full scale designs have been fabricated for fatigue testing at ambient temperature with internal pressure. A 0.61-by 1.22-m (2- by 4-ft) test panel for each concept is to be fabricated for combined radiant heating/cyclic structural loading at the Langley Research Center.

The first panel (Contract NAS1-12806), shown in Fig. 7, features a skin-stringer structure with dual (redundant) counterflow cooling passages, and uses glycol/water as a coolant. Coolant passages of quarter ellipse tubes with wire crack arresters next to them are adhesively bonded between a flat outer skin and a formed inner skin. The tubes contain the coolant pressure and virtually eliminate peel stresses between the bonded skins. Each manifold assembly includes an inlet for one cooling system and an outlet for the other, resulting in counter-flow in adjacent passages. Both sets of cooling passages operate to maintain the panel at its design temperature during normal flight; should one-half of the dual system fail, either in the panel or in the distribution system, the panel has a life expectancy of ½ hr at normal operating conditions.

The second panel (Contract NAS1-12919), shown in Fig. 8, features a single pass nonredundant cooling passage system (half-circle tubes) embedded in a honeycomb sandwich, which is designed to contain any internal coolant leaks. The coolant tubes are brazed to a manifold, which uses double chambers to get full coolant flow at the transverse edge. The tube manifold assembly is then soldered to the outer skin. This concept uses methanol/water for the coolant.

The third panel (Contract NAS1-13382), shown in Fig. 9, uses a stringer-stiffened, brazed plate-fin sandwich with a plain 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. Inserts in the core are required to allow fastener penetration for attaching channel stringers at the frame locations. Stringers are adhesively bonded to the inner skin between frames. Glycol/water is used for the coolant. Ad-

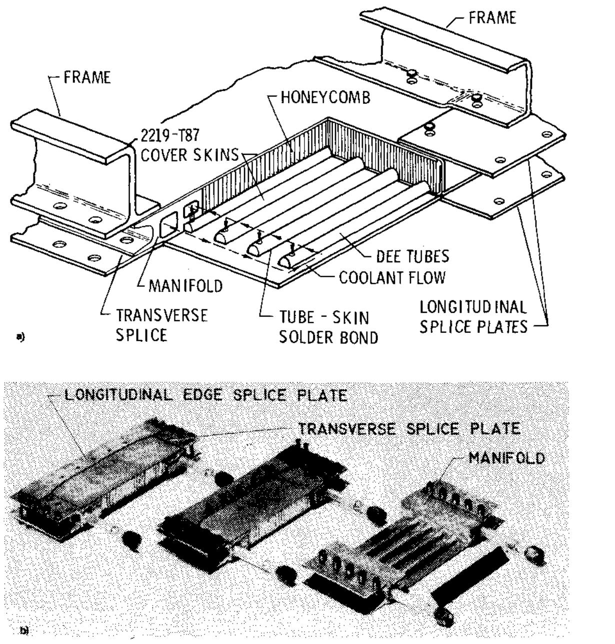


Fig. 8 Honeycomb sandwich panel. a) Panel concept. b) Fatigue specimens

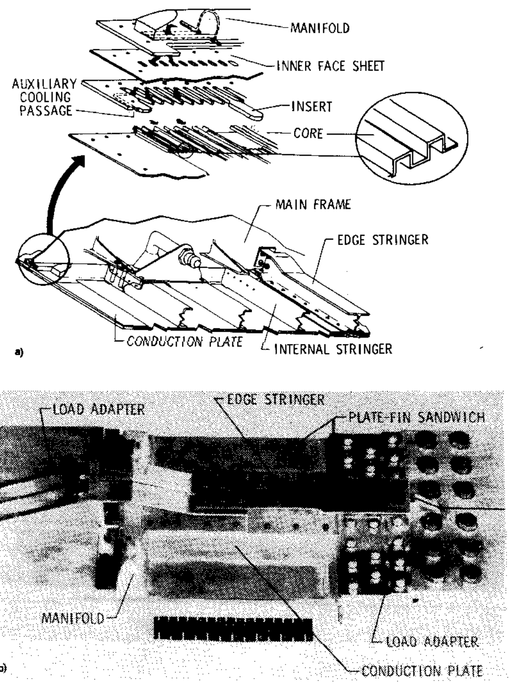


Fig. 9 Stiffened plate-fin sandwich panel. a) Panel concept. b) Fatigue specimen.

ditional features of each concept will be discussed in following sections.

Panel Closeouts

Thus far, the major design problems have been encountered at the panel closeouts (transverse and longitudinal joints, and manifolds). For example, all three of the panel designs feature a single row of fasteners at the manifold joint. The use of this poor design detail, shown by the fatigue specimen tests to be a problem, results from the need to keep the panel edges within the temperature limits of the material. As illustrated by the schematic shown in Fig. 10, the temperature increases rapidly in the fastener region. An increase of the flange width to add the needed second row of fasteners would result in temperatures well above the allowable. In order to reduce the

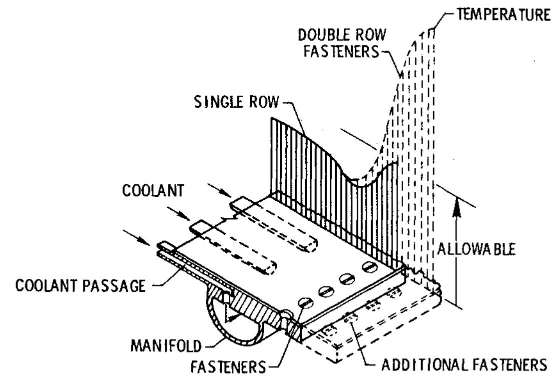


Fig. 10 Typical actively cooled panel joint.

excessive temperatures, innovative design effort is required to minimize the increase in mass and complexity of the flange area. One possible solution, which has not been examined in detail, is the use of heat pipes to increase the conductance in the flange area.

Unit Mass Breakdown

Table 1 gives the unit mass breakdown for each of the three concepts. Comparisons between the panels should be made with caution since they have not yet been tested to confirm their performance. As shown in Table 1, details such as manifolds, fasteners, reinforcements, and so forth, which are normally considered nonoptima, can account for as much as one-third of the final mass. Nonoptimum items probably do not vary significantly for a given concept and do not affect the optimization; however, they do vary between concepts, and thus may affect concept selection. For example, the large adhesive mass penalty (14%) is a distinct disadvantage for the honeycomb sandwich concept.

Material Selection

Structural Materials

Thermal conductivity appears to be the predominant factor in the selection of structural materials. Although previous studies[5,7] have postulated the use of titanium as well as aluminum, detail problems such as the edge cooling problem previously cited virtually exclude titanium because of its low conductivity. Aluminum with its high conductivity appears to be the clear-cut choice of the more conventional materials. However, the need for high fracture toughness, weldability, and brazability have, in some cases, dictated the use of less common aluminum alloys (2219 and 6061) for structural members. The use of adhesive bonding rather than welding or brazing permits a wider choice of structural alloys. Higher strength and higher temperature capabilities may favor the use of borsic/aluminum, Lockalloy, or berrylium as more extensive material data are obtained and better fabrication techniques are developed for these materials. However, these materials will require the use of higher temperature coolants than those presently used for aluminum if their full potential is to be realized.[7] Thermal conductivity strongly influences the choice of bonding material, as will be discussed in the section on fabrication.

Coolants

Aqueous solutions of glycol or methanol appear to be the most efficient coolants for actively cooled structures, and properly inhibited, they appear to be compatible with aluminum,[7] at least under static conditions. Compatibility under long-time flow conditions and with adhesives is not well known. Glycol/water poses a potential flammability hazard, should it come into contact with a bare or defectively in-

Table 1 Unit masses of three actively cooled panel concepts

Panel component	Concept unit mass, kg/m^2 (lbm/ft^2)					
	Stiffened skin, redundantly cooled		Honeycomb sandwich		Stiffened plate-fin sandwich	
Optimized mass						
Dry						
Skins	3.66	(0.75)	3.76	(0.77)	3.95	(0.81)
Cooling passages	0.93	(0.19)	2.73	(0.56)	0.64	(0.13)
Stiffening	3.91	(0.80)	1.32	(0.27)	1.71	(0.35)
Subtotal	8.50	(1.74)	7.81	(1.60)	6.30	(1.29)
Wet[a]						
Coolant inventory	1.46	(0.30)	1.86	(0.38)	2.49	(0.51)
Pumping penalty[b]	0.29	(0.06)	0.34	(0.07)	0.53	(0.11)
Subtotal	10.25	(2.10)	10.01	(2.05)	9.32	(1.91)
Nonoptimums						
Manifolds	0.53	(0.11)	0.64	(0.13)	0.44	(0.09)
Closeouts	0.93	(0.19)	1.76	(0.36)	1.71	(0.35)
Adhesives	0.10	(0.02)	2.10	(0.43)	0.29	(0.06)
Fasteners, etc.	0.34	(0.07	0.49	(0.10)	0.64	(0.13)
Total	12.15	(2.49)	15.00	(3.07)	12.40	(2.54)

[a]Glycol/water. [b]At 0.34×10^{-6} kg/J (2 lbm/hp-hr).

sulated silver-clad wire carrying direct current. However, Ref. 21 demonstrated that the reaction potential can be prevented by adding a silver chelating agent to the glycol/water.

Because the lower viscosity (thus lower pumping penalty) and density of methanol/water compared to glycol/water resulted in about a 5% unit mass savings, methanol/water was selected for the honeycomb sandwich concept. The contractor did not consider the potential flammability and toxicity of methanol/water to be serious problems for an actual aircraft. However, because of these potential problems and for simplicity, NASA decided to test all three actively cooled panels with glycol/water.

Fabrication

Despite the use of conventional materials (i.e., aluminum) for actively cooled structures, the need for pressure containment and high conductivity requires nonconventional fabrication techniques. The stiffened skin, redundantly cooled structural configuration (Fig. 7) features extensive adhesive bonding. This fabrication technique permits the use of high strength 2024-T81 aluminum at the expense of low bondline conductance. Difficulties have been encountered in fabricating leak tight joints at the interface between the coolant passages and the manifold shown in Fig. 11. As indicated in the sketch, there are several areas in which critical leak tight bonds are required. The fabrication process is complicated by: the need to seal curved surfaces, the additional parts required for the redundant cooling circuits, and the presence of wire crack arresters (not shown) embedded in the adhesive next to coolant passages. In order to simplify the fabrication process, the crack arresters will be omitted from the large test panel.

The honeycomb sandwich configuration (Fig. 8) incorporates a brazed tube manifold assembly of 6061 aluminum, which was to be bonded with a silver impregnated adhesive to a 2219-T87 face sheet. Difficulties with the adhesive (many voids and a measured conductivity much lower than expected), compounded by thermal distortions of the heat-treated tube assembly, which increases bondline thicknesses, led to the substitution of a soldering process to improve the conductance of the joint. Although a small fatigue specimen was successfully fabricated, as of the writing of this paper, the soldering process has not been successfully applied to the large test panel.

The importance of bondline conductance on maximum skin temperature is illustrated by Fig. 12. The honeycomb sandwich design was based on one-half the conductivity quoted by the vendor of the silver-filled adhesive. However, measurements indicated that the actual conductivity was more nearly one-fifth the quoted value. This low conductivity and random voids of up to 40%, which were encountered in fabrication attempts, produce unacceptable skin temperatures for the design coolant flow rate. With the higher conductivity afforded by solder, both the operating temperature and its sensitivity to void fractions or to uncertainties in conductance

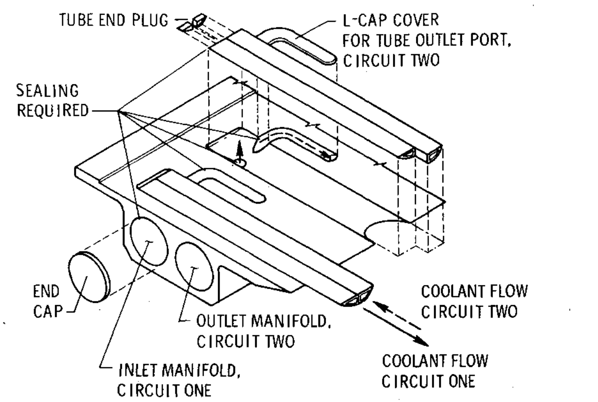


Fig. 11 Details of manifold assembly for stiffened skin, redundantly cooled concept.

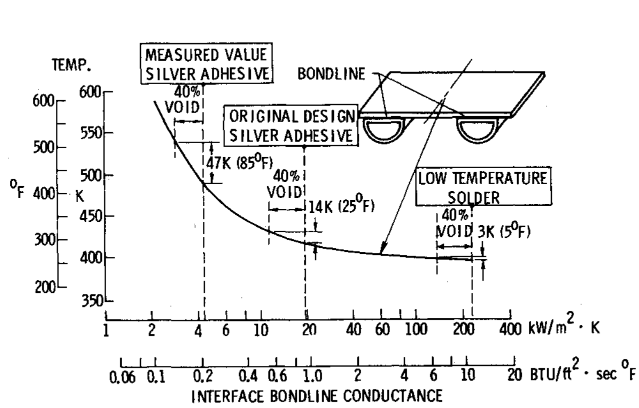


Fig.12 Effect of bondline conductance on metal temperature.

(conductivity/bondline thickness) are significantly reduced. As shown, with a 40% void fraction (or a corresponding conductance uncertainty) the maximum surface temperature with a soldered joint increases only 3K (5°F), from 396 to 399K (253° to 258°F), whereas the maximum temperature based on the measured conductivity for an adhesive joint increases 47 K (85°F), from 489 to 536 K (420° to 505°F).

The brazing process for the stiffened plate-fin sandwich configuration (Fig. 9) led to the use of the lower strength 6061 alloy for both skins. Thermal distortions incurred during heat treatment to improve the mechanical properties of this alloy could be a significant problem in the fabrication of full-scale panels. However, extensive process development resulted in distortion-free fatigue specimens, even without the use of fixtures during heat treating. The success attained with the fatigue specimens indicates the problem may be less severe than presupposed.

Reliability

Preliminary results of a limited number of ambient temperature tests of small pressurized fatigue specimens with alternating stress levels of approximately 124 MPa (18,000 psi) showed that: 1) even with surface flaws intentionally placed in the external skins, the design life of 20,000 cycles was exceeded before leakage occurred, and 2) failure was always progressive with leakage increasing slowly until final failure occurred. Even the stiffened plate-fin sandwich configuration (Fig. 9) which appears to be the most susceptible to crack propagation into the cooling passages, required more than 1400 additional cycles after initial leakage for a deliberately started flaw to propagate to structural failure. For the honeycomb sandwich concept (Fig. 8) a through crack deliberately started in the skin passed by a tube without propagating into the tube; furthermore, intentional leaks in a tube propagated into only about 10 cells through a full lifetime of cycling at the design pressure. Tests demonstrated that the crack arresters incorporated into the stiffened skin design (Fig. 7) slowed the crack growth rate significantly. Thus, it appears that through the proper selection of materials, design features, and stress levels, adequate fatigue life can be obtained. Furthermore, once leaks start, they do not progress rapidly; however, elevated temperature tests are required to confirm these findings.

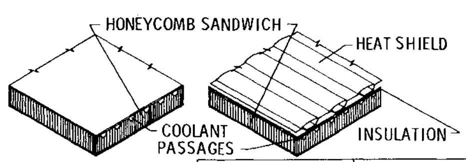
The reliability of the panels is not the only area of concern, since the results of Ref. 7 indicate that components of the distribution system, such as fluid connectors and mechanical equipment, are possibly far more critical items. Failure modes, failure detection, and corrective action have been the subject of the study of Refs. 14-16. Based on these studies, it appears that, in order to avoid overheating of the aircraft in the event of a failure in the active cooling system, a fail-safe abort concept is attractive throughout the Mach 3 to Mach 6 speed range. This concept consists of passive thermal protection and a low heat load abort descent maneuver from normal cruise speed. Additional research (Contract NAS1-13939) indicates that a dual active cooling distribution system is competitive on a mass basis with the fail-safe abort concept. Although these studies have indicated the critical problem areas and potential solutions, considerable additional effort, especially experimental, is required to provide reliable components and effective failure detection schemes.

The stiffened skin, redundantly cooled panel concept (Fig. 7) is the only concept that features dual coolant passages in the panel; however, the closeness of the dual coolant passages appears to be a disadvantage from the aspect of failure propagation into adjacent passages. Unfortunately, because of fabrication problems at the tube/manifold connection, it was not possible to determine from the small fatigue specimens the additional cycles required for a crack to propagate from one passage to the next.

Shielded Panels

Numerous studies[3-5, 7-9, 13, 15, 16] have indicated that, for hypersonic aircraft, the heat-sink capacity of the hydrogen fuel flowing to the engines during cruise and descent does not match the instantaneous heat absorbed by an aluminum structure. References 15 and 16 indicate that the heat load absorbed by bare aluminum aircraft exceeds the available fuel-flow heat-sinks by 23 to 67% over a Mach number range from 3 to 6. Furthermore, analytical results[3] indicated that the heat-load/fuel-matching problem will become progressively worse as the aircraft and engine performance is improved (lift-to-drag ratio and specific fuel consumption reduced). Thus, it appears that active cooling must be supplemented by radiative cooling (heat shields and/or skin coatings) over at least part of the aircraft surface. Alternatively, matching could be obtained through the use of higher temperature structural materials and coolants; however, such alternatives do not appear particularly attractive.[7]

The combined use of radiation and active cooling has been explored in the fail-safe abort studies of Refs. 15 and 16. The thermal/structural design of radiative/actively cooled structures for the same operating conditions as the three bare panels previously discussed is being investigated (Contract NAS1-13939). To date, several candidate radiative surface configurations, representing a broad spectrum of concepts, from Shuttle reusable surface insulation to metallic heat shields, have been screened. The most attractive candidate is a René 41, corrugation stiffened, beaded skin heat shield plus insulation shown schematically in Fig. 13. This radiative concept reduces the absorbed heat load by over an order of magnitude, and reduces the total mass of the structure, including the distribution system mass, by about 10%. The fact that the total mass of the configuration is reduced, although the mass of the shielded structure alone is 37% higher than the bare panel, emphasizes the need for including distribution system mass in the panel optimization. The performance of the radiative/actively cooled concept is to be evaluated through tests of a large panel in the Langley 8-ft high-temperature structures tunnel.



	BARE		SHIELDED	
HEAT FLUX, kW/m² (Btu/sec-ft²)	136.2	(12.0)	9.1	(0.8)
UNIT MASS, kg/m² (lbm/ft²)				
PANEL	12.8	(2.62)	12.0	(2.46)
FLUID PENALTY	2.2	(0.45)	1.0	(0.20)
SUB-TOTAL	15.0	(3.07)	13.0	(2.66)
RADIATION SYSTEM	---	---	7.3	(1.49)
SUB-TOTAL	15.0	(3.07)	20.3	(4.15)
DISTRIBUTION SYSTEM	8.6	(1.77)	1.2	(0.25)
TOTAL	23.6	(4.84)	21.5	(4.40)

Fig. 13 Comparison of bare and shielded actively cooled panels.

Concluding Remarks

Results from recent and ongoing studies have been used to provide a preliminary assessment of the status of actively cooled airframe structures for high-speed cruise flight. Various facets of such structural panels, including concepts, design, material selection, fabrication, reliability, and heat-load/fuel heat-sink matching, have been examined.

Results of investigations to date indicate that active cooling significantly impacts the design and optimization of structural panels because of the addition of numerous variables, the added complexity of panel details, and the requirements of interfacing a distribution system. It has been shown that the optimum configuration is a strong function of thermal as well as structural loading. For the most part, state-of-the-art design techniques appear adequate for the major areas; however, inclusion of distribution system factors in the optimization process appears desirable. Closeouts (transverse and longitudinal joints, and manifolds) have proved to be troublesome design areas, which are complicated by active cooling requirements; additional innovative effort is required in this area.

Thermal considerations and coolant pressure containment have strong influence on the selection of materials and fabrication techniques. The high conductivity of aluminum strongly favors this conventional material; however, the need for pressure containment dictates the use of less conventional joining techniques (welding, brazing, and bonding), and the use of the less common and weaker, albeit tougher, alloys. The use of adhesives permits the choice of higher strength aluminum alloys, but introduces problems because of low bondline thermal conductance and unknown compatibility with coolants.

Results of ambient temperature tests of small pressurized fatigue specimens showed that, even with surface flaws intentionally placed in the external skins, the design life was met before leakage occurred and failure was always progressive rather than catastrophic, with leakage increasing slowly until final failure occurred.

Studies have indicated that matching heat load to fuel-flow heat-sink is a problem for bare aluminum actively cooled aircraft even at cruise Mach numbers as low as 3. Through the addition of a radiative exterior surface, the cooling requirements of a panel can be reduced by an order of magnitude, and the mass of the configuration, with distribution system penalties included, reduced by about 10%.

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