DESIGN AND ANALYSIS OF A SCRAMJET ENGINE*

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INTRODUCTION

A preliminary design of a hydrogen-fueled, regeneratively cooled, airframe-integrated Scramjet was accomplished at NASA Langley Research Center. The three-dimensional, fixed-geometry Scramjet concept is designed to operate over a flight Mach number range of 4 to 10. The concept was found to be viable from the standpoints of both engine structural mass and coolant requirements. The overall objectives of this program were to extend these studies and to define a practical engine concept.

The work falls into four broad areas: (1) to develop and evaluate a design concept for the cooled-structures assembly of the engine; (2) to develop concepts for engine subsystems in sufficient detail to show feasibility and to estimate mass, volume, and operating requirements; (3) to establish design concepts for the aircraft/engine interface; and (4) to identify problem areas requiring further R&D.

Conclusions from study are that: (1) excess-fuel heat sink is available at all flight conditions; (2) a service life of 1000 cycles and 100 hr is feasible at steady state temperatures and with temperature differences; (3) structure and thermal protection system (TPS) masses are reasonable; (4) a modularized concept can provide accessibility and replaceability of components; and (5) thermal transients during ascent and descent along typical mission trajectories will govern design and operating procedures for the TPS and the engine. The resulting cooled-structure design is feasible and can utilize current materials and manufacturing technology.

The presentation will show the design configurations evolved during the study and the results of various analyses performed in support of the design. The discussion emphasizes the engine structure and TPS, including the fuel injection struts. These represent the main study areas during the program and the main issues with respect to feasibility.

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PROGRAM OBJECTIVES

The program objectives were to define a cooled-structures assembly given the engine geometry and engine operating conditions. Consideration was also given to engine subsystems, in particular, the fuel subsystem associated with the operating engine. The engine mounting and the interfacing with the airplane were evaluated, and conceptual designs were defined. This presentation, however, emphasizes the cooled-structures assembly. Most of the work was done in this area, and the basic technology issues are in this area.

SCRAMJET CONCEPT

(Figure 1)

The concept of the three-dimensional Scramjet is a modular one. It uses a rectangular configuration. Several of these modules are mounted to the compression surface of the airplane. The reference configuration for the study used six modules for design purposes. Installation and removal of the engines are based on an assembly of modules rather than single modules.

This shows the main components of the engine. The inlet is defined by the sidewalls and has a 48 deg sweep. It has fixed geometry. The three struts are mechanically inserted and mounted between the topwall and the cowl. The combustion area and nozzle are defined by the topwall, sidewalls, and cowl. All surfaces exposed to the engine internal and external gas flows are regeneratively cooled using the hydrogen fuel.

SCRAMJET CONCEPT

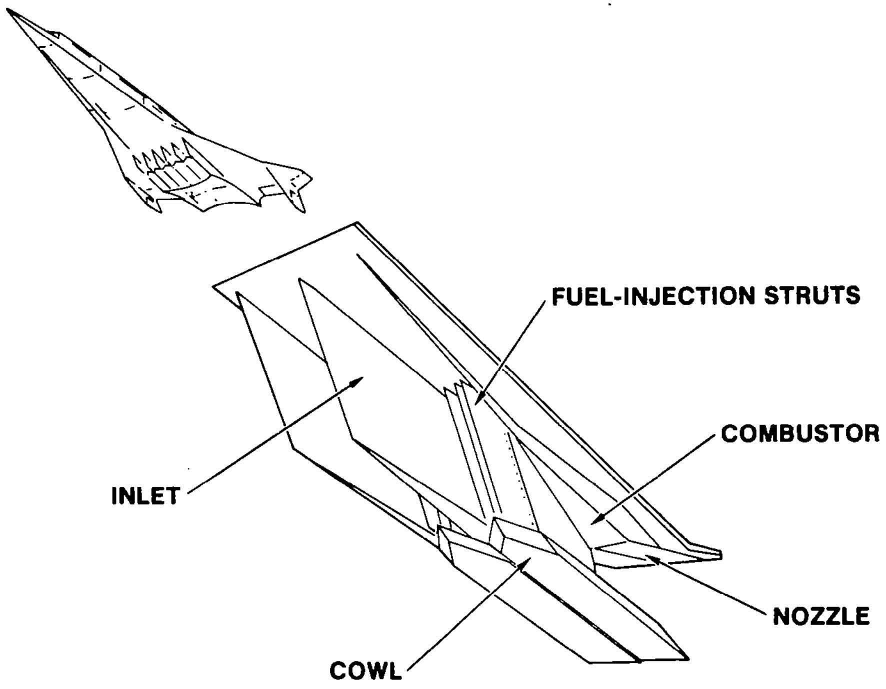


Figure 1

COOLED SCRAMJET STRUCTURE

(Figure 2)

The selected configuration consists of the thermal protection system (TPS), which is a regeneratively cooled hydrogen heat exchanger, mounted to the primary support structure. The primary support structure is all honeycomb. Beam-stiffened configurations were studied and honeycomb was selected as the most desirable. Results of the analysis leading to this selection will be shown.

Beams are used in two locations, at the forward and aft mounts, to distribute the loads. The assembly of the panels is by a bolted connection. Brazed or welded assemblies were also considered. Bolted assembly, although heavier and potentially with more design and manufacturing difficulty, is the only practical one if disassembly and reassembly of components is a design requirement. The outside of the cowl is removable to permit access for engine assembly and installation.

The fuel injection struts represent one of the most critical design areas of the engine. Design of the load carrying structure, the TPS, the fuel and coolant manifolding, and the mounting in the topwall and cowl are all constrained by the envelope imposed by aerodynamic requirements.

COOLED SCRAMJET STRUCTURE

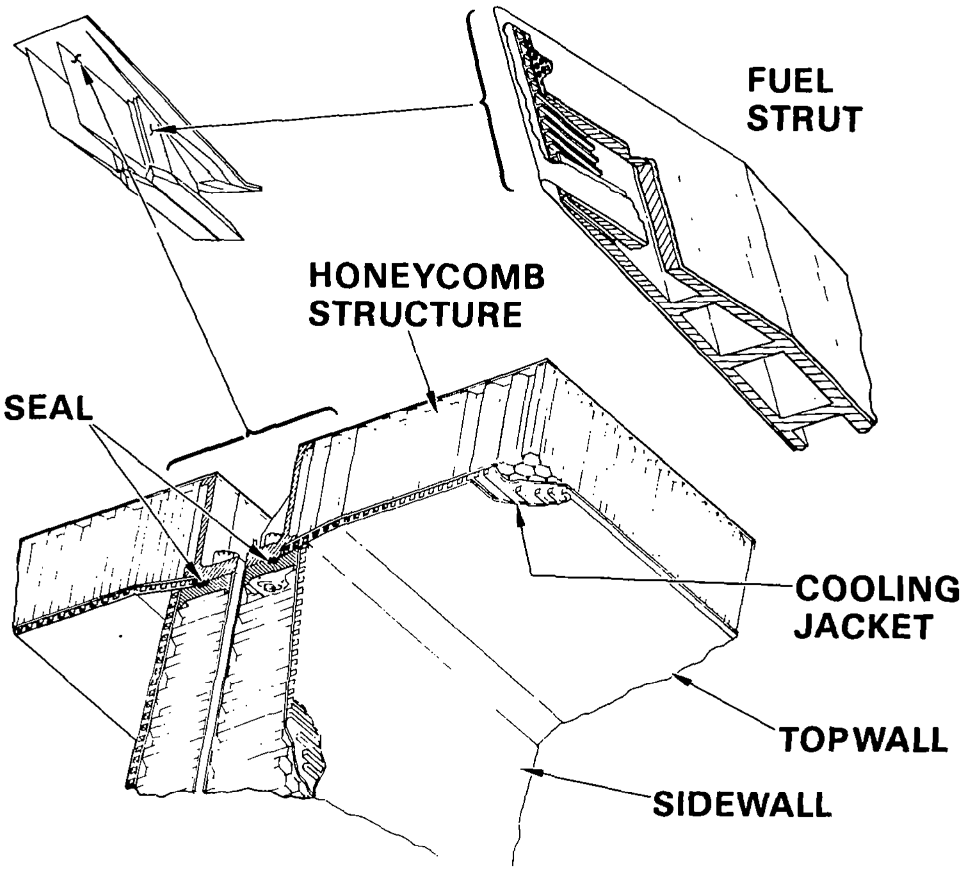


Figure 2

DESIGN CONDITIONS

(Figure 3)

The most important constraint on design is the need to achieve a 100-hour life with 1,000 cycles of operation for any operating condition. The design approach was to evaluate and define the structure and the materials combinations at steady state conditions, that is, at ΔT's corresponding to steady state. The resulting design was then evaluated under conditions of transient thermal and pressure loads.

The metal temperature limit for the TPS was set at 1140 K (1600°F). This was deemed the maximum practicable temperature for the nickel-base superalloys which are available for use in the engine. Specifically, Hastelloy X and Nickel 200 are the TPS face sheet materials.

The hydrogen outlet pressure was set at 5.3 MPa (750 psia), which is the fuel injection pressure; the inlet pressure is consistent with hydrogen pump technology. The 890 K (1600°R) maximum coolant temperature was selected to avoid creep in the primary structure. Coolant equivalence ratio was to be less than one in all cases to avoid dumping of hydrogen. In addition, the desirability of having hydrogen cooling capacity available for aircraft cooling provides further incentive for limiting coolant equivalence ratio.

DESIGN CONDITIONS

LIFE	100 HRS AND 1000 CYCLES
DEFLECTIONS	$<$5% AREA AND 0.4 DEGREES
METAL TEMP	$<$1140 K (1600°F)
HYDROGEN	
INLET	6.9 MPa, 55 K (1000 PSIA, 100°R)
OUTLET	5.3 MPa, 890 K (750 PSIA, 1600°R)
COOLANT ϕ	$<$1.0

Figure 3

CANDIDATE CONFIGURATIONS

(Figure 4)

The candidate configurations for the TPS heat exchangers are summarized here. A plate-fin configuration was used on the hypersonic research engine (HRE). In this application, it will not have the required cycle life and creep life. The reason it does not is the braze joints next to the hot face sheet. These result in stress concentrations and degraded material at the hottest point in the heat exchanger.

All of the machined configurations shown have the braze joint at the cold side of the heat exchanger. They also provide an opportunity to reduce the stress concentration at the hot face sheet by appropriate contouring, with a minimum obtained for the circular configuration. In fact, when a photochemically milled channel is used, the geometry tends to a full radius at the hot face sheet.

The pin-fin configuration has high heat transfer coefficients and high pressure drop. It is used in localized areas which require high heat transfer for short flow lengths.

Of these, the plate-fin configuration has the best heat transfer performance. As noted, it will not satisfy the structural criteria. The pin fins are used in the struts to get the necessary heat transfer coefficients. The pressure drop is available to use there, since the flow lengths are short. In all other areas, plain channel configurations are used.

CANDIDATE CONFIGURATIONS

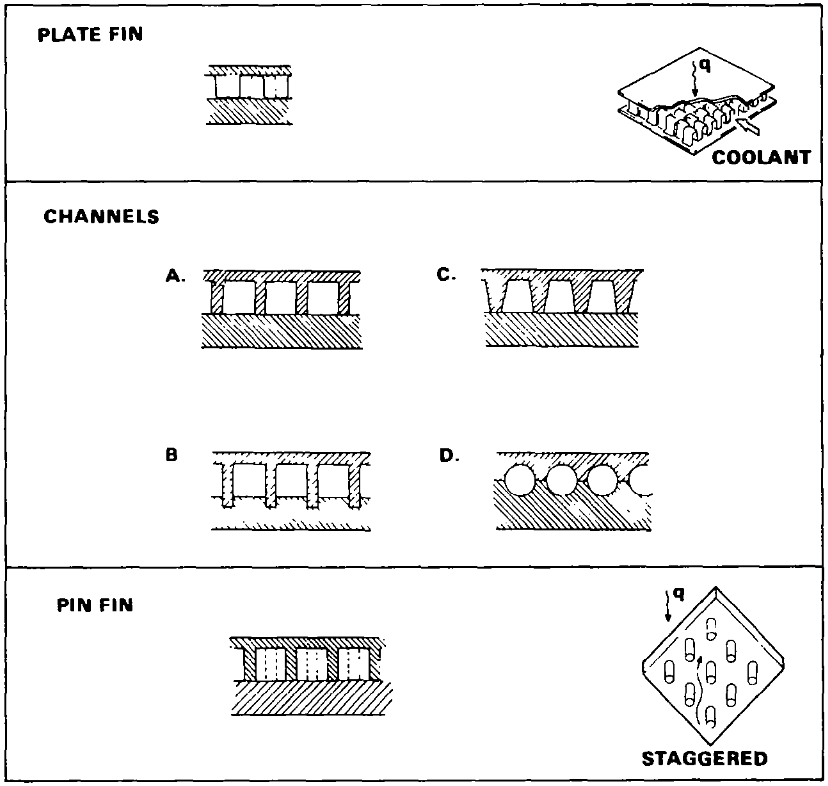


Figure 4

TPS PASSAGE SELECTION

(Figure 5)

The height of the channels is indicated. It ranges from 0.63 to 1.27 mm (0.025 to 0.050 in.). At the leading edges of the sidewalls and cowl, pure nickel is used - Nickel 200 or Nickel 201. Pure nickel is also used as the hot face sheet of the strut TPS. All other areas in the engine use Hastelloy X as the face sheet material.

TPS PASSAGE SELECTION

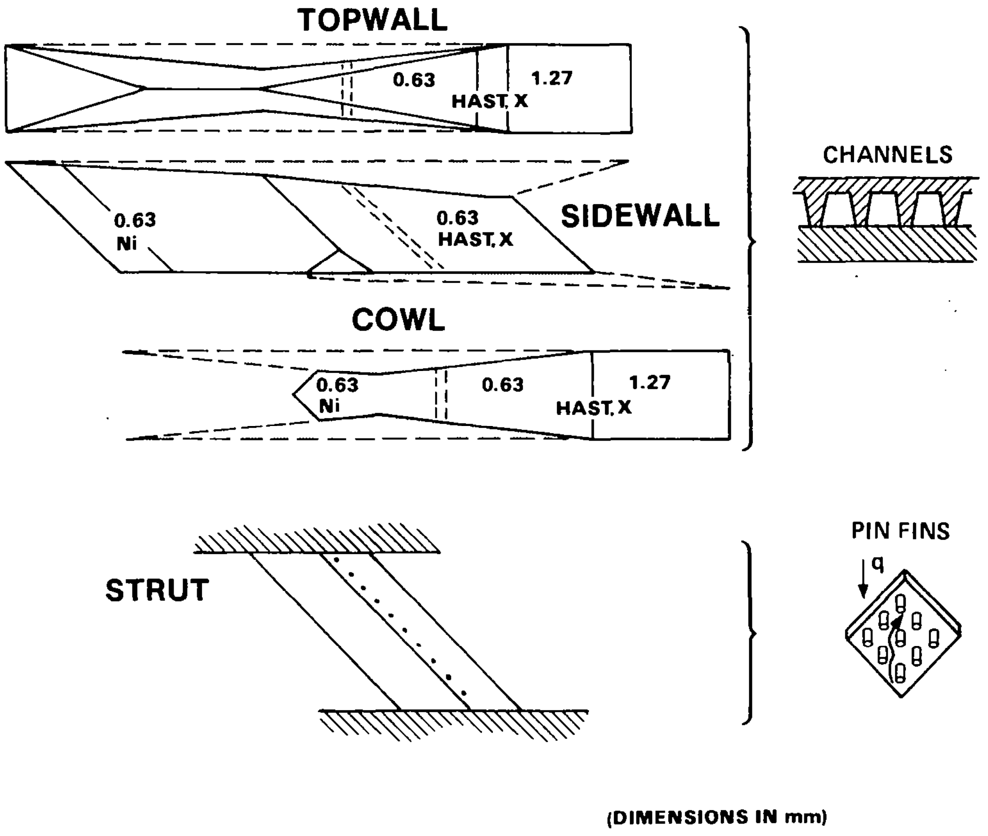


Figure 5

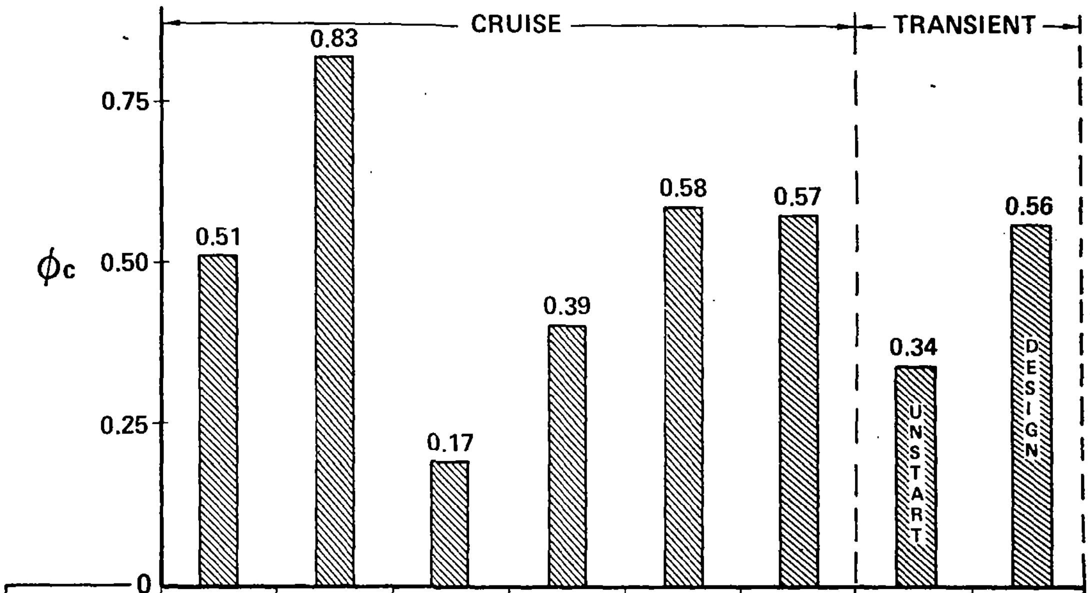
ENGINE COOLING PERFORMANCE

(Figure 6)

Using the selected heat exchangers, the engine cooling performance was derived in terms of the coolant equivalence ratio for each of the operating conditions. (Coolant equivalence ratio is the ratio of the required coolant flow to engine fuel flow.) In all cases, the ratio is below the design limit of 1.0.

The design condition has a high fuel equivalence ratio. Consequently, the coolant equivalence ratio appears to be low. The adverse effect here is that a high coolant flow must be accommodated within the allowable pressure drop limits. This represents an area for trade-off with respect to other operating conditions. Generally, the high fuel equivalence ratios are associated with off-design operation and, as such, need not govern the design.

ENGINE COOLING PERFORMANCE



CONDITION	A	B	C	D	E	F	G	H
MACH NO.	6	10	4	6	8	10	5.1	10
ϕ_f	1.0	1.5	1.0	1.0	1.0	1.5	1.0	1.5

Figure 6

TPS CYCLE LIFE--STEADY STATE

(Figure 7)

Published data for parent metals (Hastelloy X for the panels and nickel for the struts) was used to assess the cycle life at ΔT's corresponding to steady state operation. Maximum steady state ΔT is about 220 K (400°F) for any of the operating conditions, including design condition H. Results for both the forward and aft flow routes of the cowl and sidewall are shown; the top panel has a single flow route; the center struts were individually considered. Based on the published data, the 1,000-cycle design requirement is achievable for all components at steady state conditions. The design is, therefore, governed by engine transient operations, as shown subsequently.

TPS CYCLE LIFE – STEADY STATE

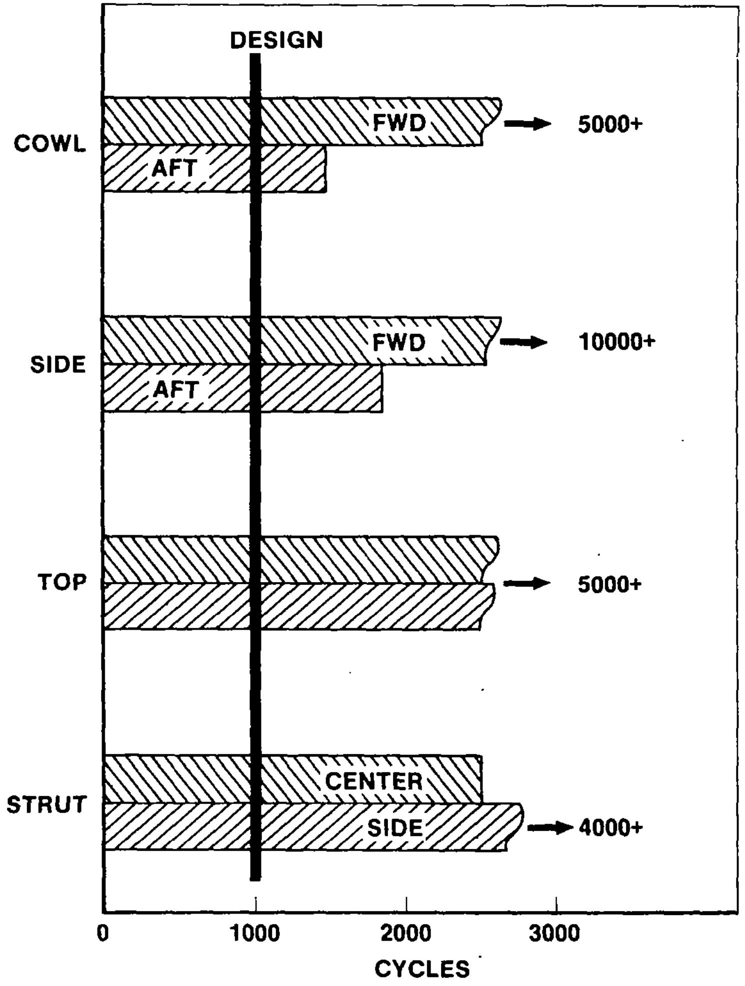


Figure 7

LEADING EDGE CYCLE LIFE

(Figure 8)

Leading edge cycle life was separately considered. In each case, the leading edges are nickel. Hastelloy X meets the requirements of the sidewall, but offers no particular advantage. Nickel is required to achieve a 1,000-cycle life in all other locations.

The strut and panel leading edges use direct impingement cooling. The cowl apex is a hemispherical point on the cowl and is also cooled by impingement. Its heat flux is the highest of any of the leading edge areas, 4600 W/cm^2 (4040 Btu/sec-ft^2) vs 2030 W/cm^2 (1790 Btu/sec-ft^2) for the center strut and 1060 W/cm^2 (935 Btu/sec-ft^2) for the sidewall. A leading edge radius of 1.27 mm is used in all areas.

LEADING EDGE CYCLE LIFE

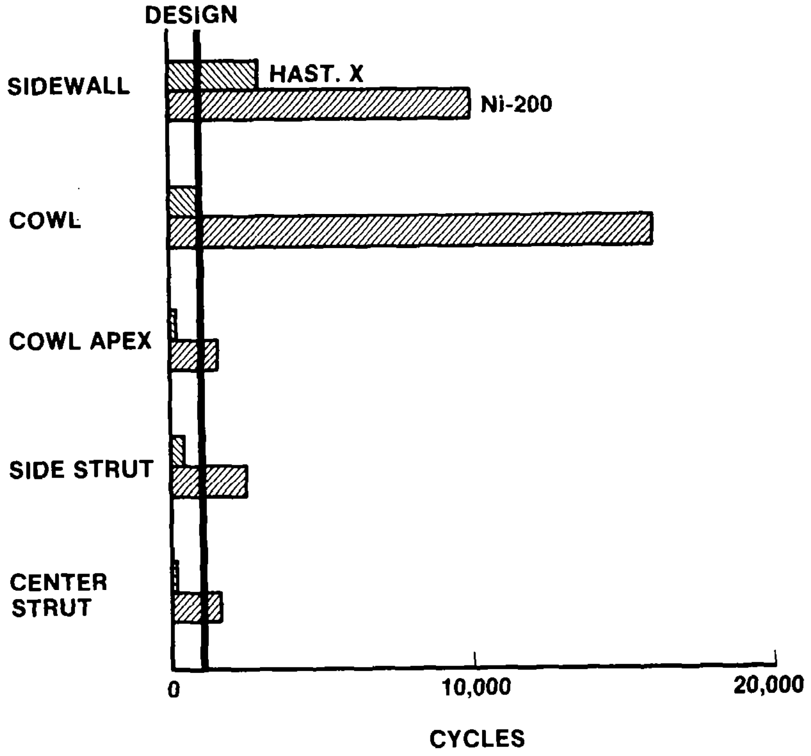


Figure 8

FINITE ELEMENT MODELS

(Figure 9)

Three basic engine structural concepts were studied: swept frame, in which a set of 7 beams was used to support a relativley shallow-depth, honeycomb panel structure; vertical frame, which used the same 7 beams, but ran these beams normal to the engine axis; and all honeycomb, in which only 2 beams were used at the mount points. The models were symmetrical about the centerline and were evaluated using the ANSYS computer program.

FINITE ELEMENT MODELS

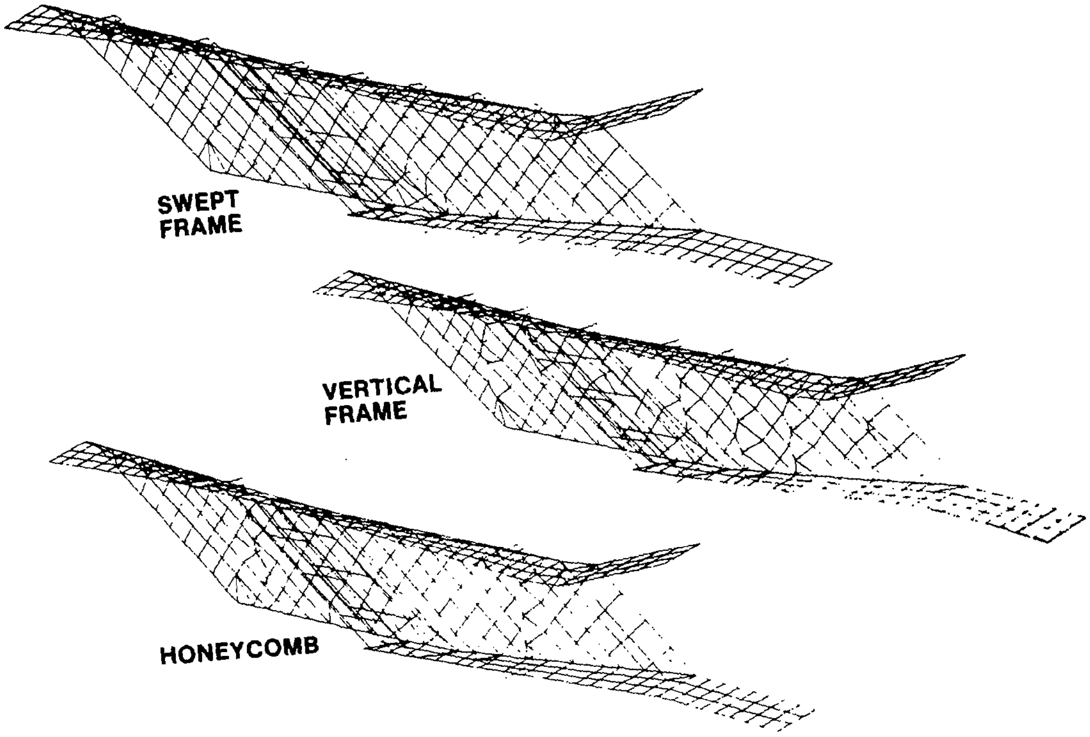


Figure 9

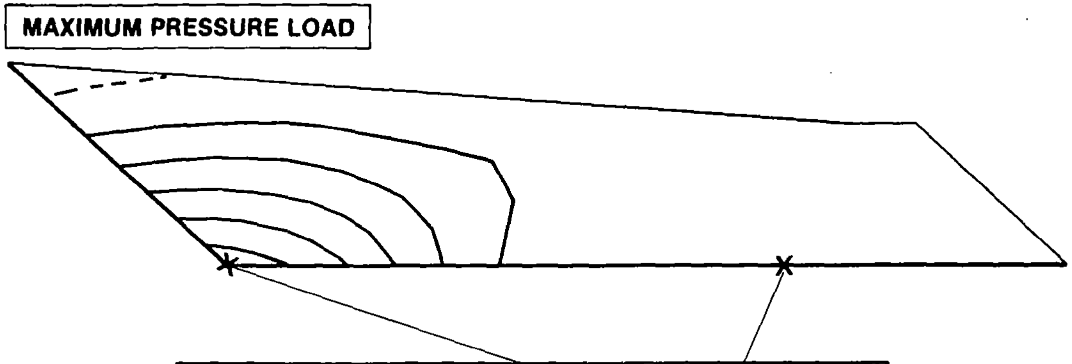
SIDEWALL DISPLACEMENTS

(Figure 10)

This shows the performance of the sidewall as obtained from the finite element models for each of the configurations. Its design is critical at the maximum pressure load, which occurs during the Mach 5.1 unstart condition. Maximum displacement occurs at the bottom corner of the leading edge. The maximum stress for all of the structures occurs in an area near the nozzle, in the relative position shown here. The honeycomb shows both the lowest displacement and lowest comparative stress. These comparative stresses are not absolute values. A separate analysis of the topwall was run to assess the quantitative validity of these stress. The conclusion drawn was that they do permit a general evaluation of structural performance. Since these results are for a transient, nonoperating condition, limitation of stress is the primary concern.

The results shown here were the main reasons for selecting the all-honeycomb configuration as the most desirable. Other components similarly favored the all-honeycomb structure, although not as strongly as in the case of the sidewall.

SIDEWALL DISPLACEMENTS



STRUCTURE	DISPLACEMENT, cm (IN.)	COMPARATIVE STRESS, MPa (KSI)
SWEPT BEAM	5.81 (2.29)	469 (68)
VERTICAL BEAM	2.74 (1.08)	594 (86)
HONEYCOMB (SHOWN)	0.58 (0.23)	400 (58)

Figure 10

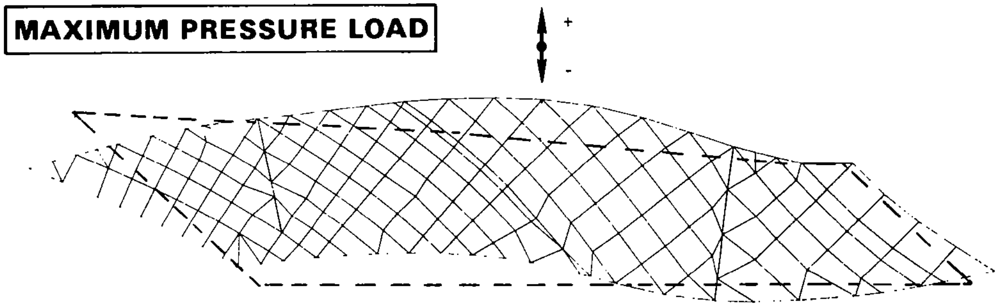
SIDEWALL DISTORTED GEOMETRY

(Figure 11)

The vertical displacement of the sidewall, plus and minus, is shown for each of the three configurations. The honeycomb shows the maximum displacement at the top of the leading edge of the sidewall. In other areas, it is equivalent to or better than any of the other configurations.

The distorted geometry shown here is indicative of conditions at the panel corner joints. Initial engine design concepts used sliding seals at all of the corners. These are difficult to achieve in the thermal environment of a Scramjet. The distortion results obtained suggested the use of rigid connections at the corners. Results from finite element models showed that the stresses associated with rigid connections are acceptable.

SIDEWALL DISTORTED GEOMETRY



STRUCTURE	VERTICAL DISPLACEMENT, mm					
	LE TOP	LE BOTTOM	MID TOPWALL	MID COWL	TE TOP	TE BOTTOM
SWEPT BEAM	+ 0.127	+ 7.61	+ 2.79	0	- 2.34	- 2.74
VERTICAL BEAM	- 3.91	+ 3.70	+ 3.81	+ 4.16	0	+ 0.127
HONEYCOMB (SHOWN)	- 4.36	+1.29	+ 3.21	+ 2.31	0	+ 0.913

Figure 11

STRUT LOADS-kN (LB)

(Figure 12)

The Mach 5.1 unstart condition that is critical for design of the engine panels is also the most severe loading condition for the struts. The most severe assumption that can be made is that it is possible for the engine to remain started on one side of a strut and be unstarted on the other side. There is not sufficient experimental data to say whether or not this is in fact possible.

These are the net loads that go with the conditions shown. They are quite substantial in relation to the strut geometry, which is that of a long, slender body. Both the deformations and stresses produced by these loads make strut structural design one of the most critical areas of the engine.

STRUT LOADS-kN (LB)

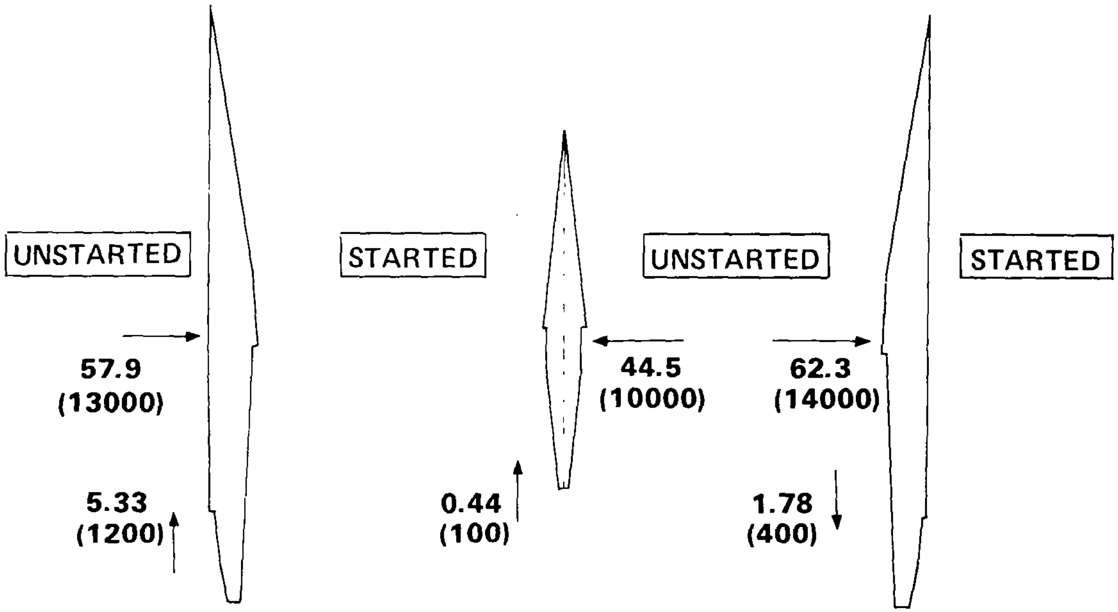


Figure 12

STRUT STRUCTURAL DESIGN

(Figure 13)

The materials used in the strut are Inconel 718 for the primary structure and Nickel-200 for the face sheet of the TPS. A 3-D model was used at the Mach 5.1 unstart condition to evaluate stress and deformation. The design that evolved used 2.03-mm (0.080-in.) walls with 3.17-mm (0.125-in.) ribs and webs. The goal was to keep all the stresses elastic. In fact, localized stresses, for the model used, exceed the elastic limit and deformations exceed 3.81 mm (0.150 in.). These result from the assumptions made with respect to mounting the strut in the top panel. Imposition of constraints representative of the actual design is expected to reduce both stresses and deformations to the desired levels.

STRUT STRUCTURAL DESIGN

- METHOD:
  - 3-D MODEL
- DESIGN:
  - 2.03mm (0.080-IN) WALLS
  - 3.17mm (0.125-IN.) RIBS AND WEBS
- GOALS:
  - STRESSES ELASTIC
  - 3.81mm (0.15-IN.) DEFORMATION
- MATERIALS:
  - INCONEL 718
  - NICKEL-200 TPS

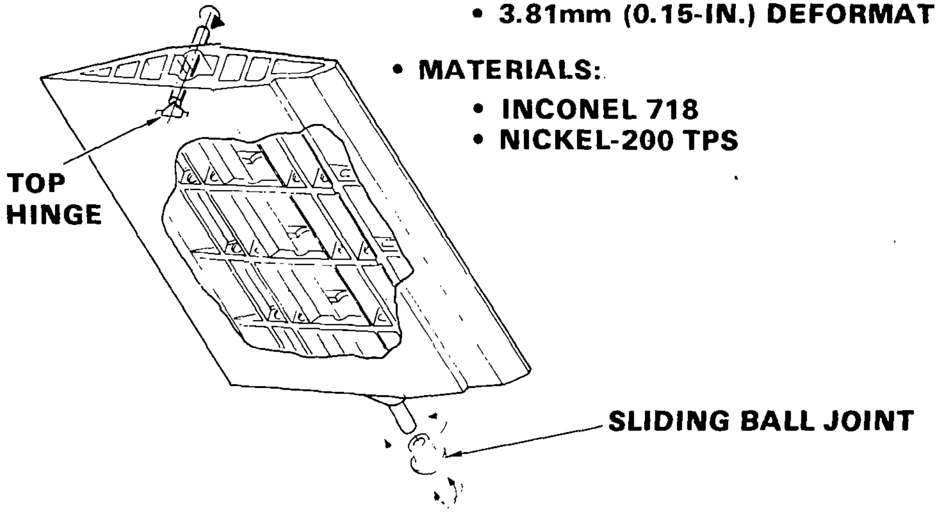


Figure 13

STRUT DISPLACEMENTS

(Figure 14)

The calculated displacements range to 7.6 mm (0.3 in.), twice the value set as a goal. The stresses near the top center of the strut, in the shaded region, exceed the elastic limit. The model used, however, allows for no constraint by the strut mounts in the topwall. In fact, these mounts restrict the motion of the strut to essentially zero. As a result, deflections are expected to decrease by 50 percent. Stresses would be similarly reduced. Preparation of an extensive new model will be required for a more precise, quantitative assessment of the mount effects. Based on qualitative estimates, successful operation of the strut without a midspan support tie appears feasible.

STRUT DISPLACEMENTS

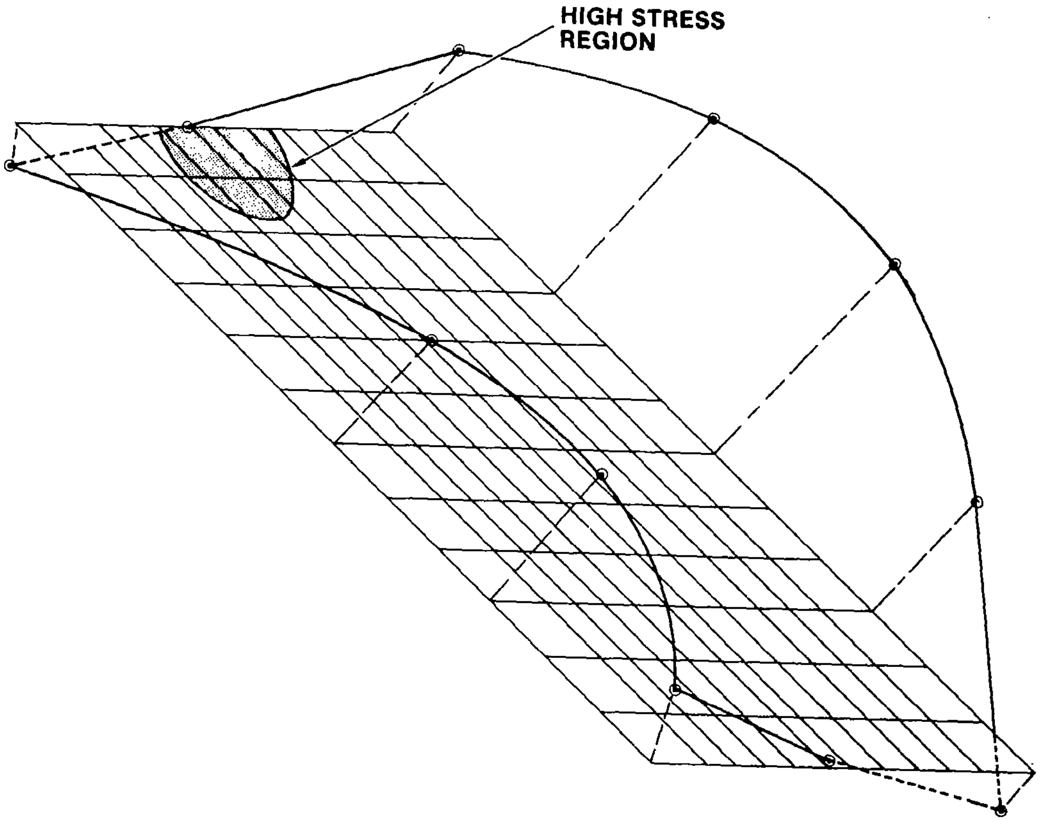


Figure 14

SIDE STRUT

(Figure 15)

This is a wet-wall strut. Configurations in which the coolant flowed in separate tubes were also studied. There is not enough cross-sectional area in the strut to use this type of configuration within the pressure drop design limits.

The main features of the strut thermal design appear in the enlarged view. The strut manifolds incorporate a plate-fin heat shield around the wall. This heat shield isolates the strut structure during transients and limits the temperature differences to acceptable values. The thermal protection system heat exchanger is a pin-fin configuration throughout. Pin fins can be used in the strut because the flow lengths are relatively short and the relatively high pressure drops become acceptable. The high heat transfer performance of pin fins is required, in turn, because of the high heat flux loadings on the strut.

SIDE STRUT

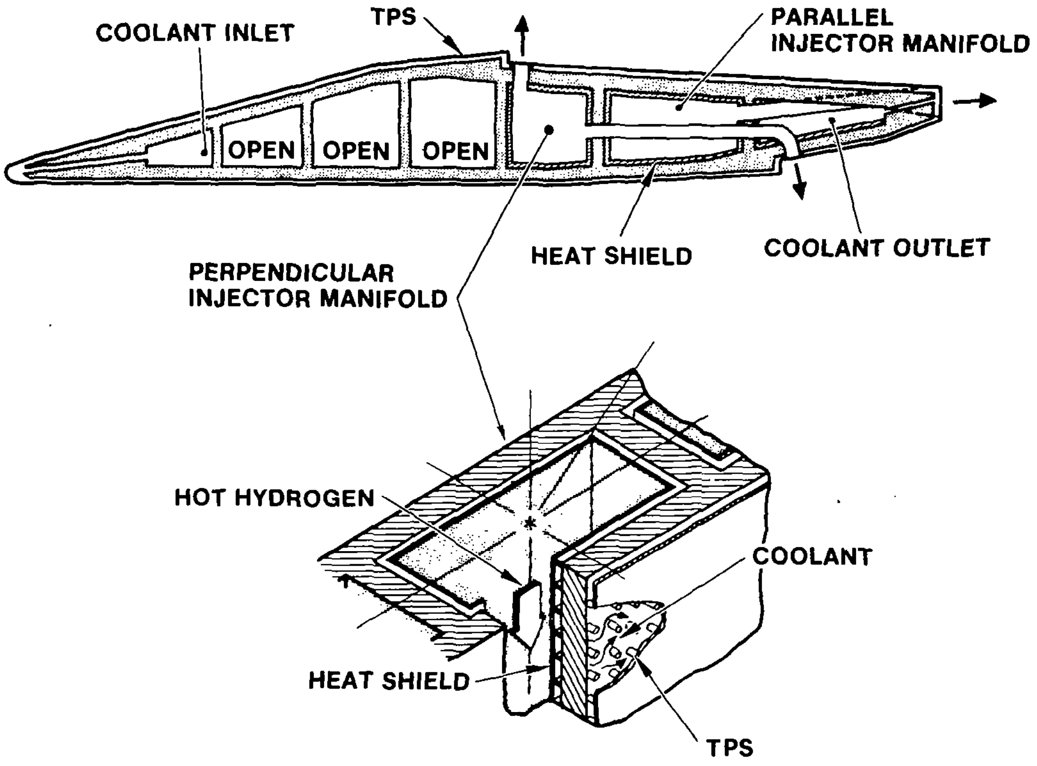


Figure 15

STRUT COOLANT MANIFOLDS

(Figure 16)

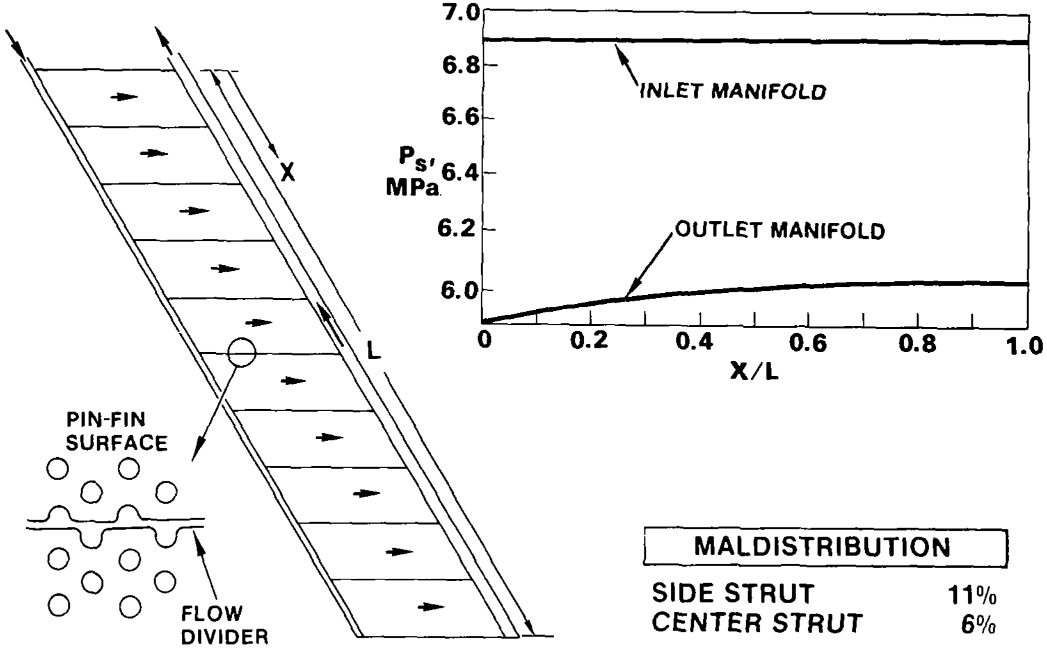
Coolant inlet and outlet occurs from the same (top) end of the strut. This results in a relatively long manifold flow length. Because of the relatively limited space available in the struts, Mach numbers are also fairly high. Flow distribution in the coolant manifolds was therefore investigated. The conclusions, however, were the same for all of the manfiolds, i.e. that acceptable design solutions are available within the existing constraints.

The chart shows the static pressure distribution in the inlet and outlet coolant manifolds. The coolant temperature in the inlet manifold is 55 K (100°R) and the Mach number fairly low. As a result, the pressure in the inlet manifold is essentially constant.

The temperature in the outlet manifold is about 550 K (1,000°R), the density is much reduced, and the Mach number considerably higher. Nevertheless, the static pressure variation in the manifold is fairly small. The resulting maldistribution, therefore, was smaller than anticipated, ranging from 11 percent in a side strut to 6 percent in the center strut. These values are associated with condition H (Mach 10, 2g turn, fuel equivalence ratio 1.5). Since this is an off-design operating point, these maldistributions appear acceptable. At other conditions, the flow maldistributions would be even less.

Because of the pressure gradient in the outlet manifold, there is a tendency for the flow in the strut sides to skew. To control this skewing and assure controlled flow in the strut sides, flow dividers are incorporated in the pin-fin surface.

STRUT COOLANT MANIFOLDS



MALDISTRIBUTION	
SIDE STRUT	11%
CENTER STRUT	6%

Figure 16

HONEYCOMB TRANSIENT ANALYSIS CASES

(Figure 17)

After the various steady state analyses and designs were completed, the selected all-honeycomb structure was modeled on a thermal analyzer program. Sections of the structure that were analyzed are identified by the numbered paths. Since the corner of a module was expected to be critical, all cross-sections analyzed were taken in this area.

HONEYCOMB
TRANSIENT ANALYSIS CASES

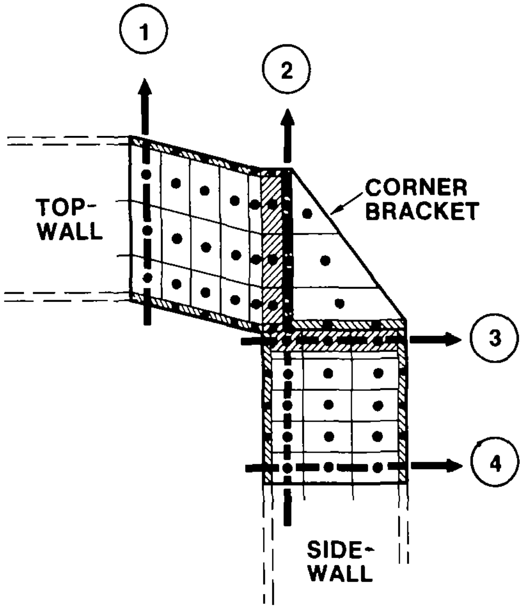


Figure 17

COOLANT OUTLET TRANSIENT

(Figure 18)

The coolant transient response was evaluated in the area of the outlet manifold for a trajectory that combines acceleration by rocket (typical of a research airplane) with extended cruise at Mach 6. In addition, it was assumed that fuel and coolant flow control was on a step basis. This is an unusually severe combination and represents an extreme condition.

The first 80 seconds involve acceleration to Mach 3. At Mach 3, the coolant is turned on, on a step basis. Acceleration continues to Mach 6, at which point the fuel is turned on and combustion starts. Following deceleration to Mach 3, coolant is turned off, again on a step basis. Alternative coolant and fuel scheduling is certainly possible and even likely, but was not analyzed. Most trajectories considered for cruise applications have used slow acceleration (0.2g), with durations of around fifteen minutes to attain Mach 6.

COOLANT OUTLET TRANSIENT

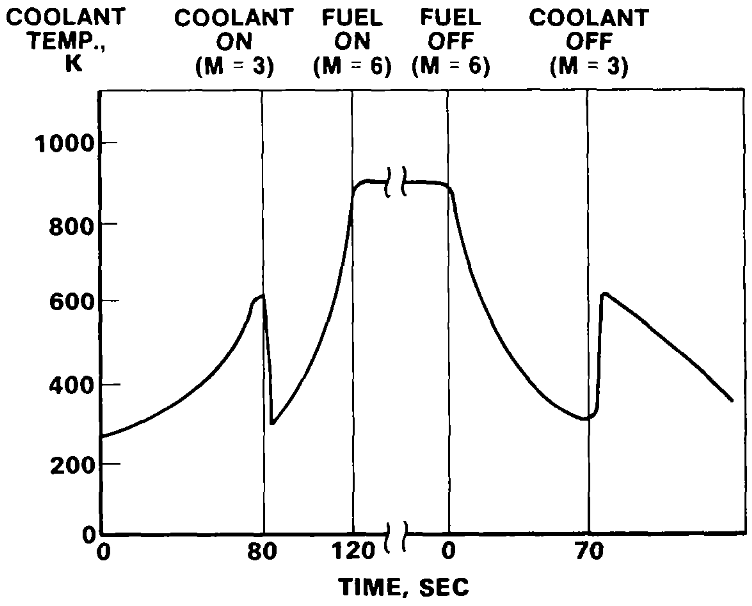


Figure 18

TPS/HONEYCOMB TEMPERATURE HISTORY ④

(Figure 19)

This temperature history goes with the trajectory, fuel schedule assumptions, and coolant response discussed above. It was obtained with the thermal analyzer model. The 'front' is the hot face sheet of the TPS; the 'back' is the unheated face sheet of the honeycomb, as much as 5 cm (2 in.) from the hot face sheet. Hastelloy X and nickel were investigated for the honeycomb core. For the face sheet, whether the core be nickel or Hastelloy, the response is extremely fast. At the startup, the front sheet very quickly goes to 890 K (1600°R) resulting in a ΔT of 670 K (1200°R). The resulting low-cycle fatigue life is too short. At shutdown, the temperature relationships of the front of the TPS and the back of the honeycomb are reversed. The ΔT developed is somewhat less than at startup, on the order of 550 K (1,000°R), but still higher than desired.

These results point up the need to find a way to limit ΔT. It cannot be done with change of materials. A combination of a material change combined with changes in the mission trajectory and with coolant and fuel scheduling, however, can reduce temperature differences to acceptable values. Design solutions that produce such reduced ΔT's are also available, but add complexity to the engine.

TPS/HONEYCOMB
TEMPERATURE HISTORY ④

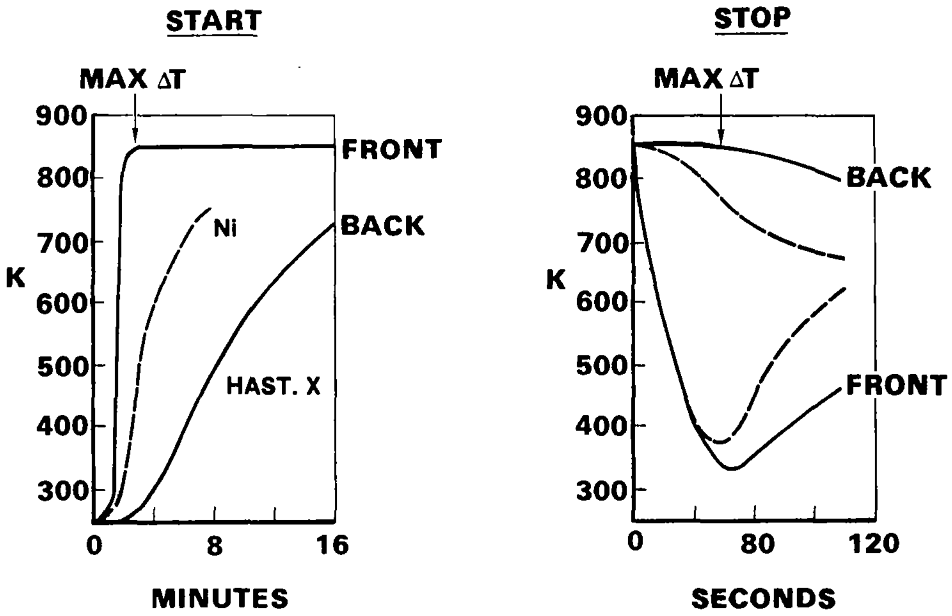


Figure 19

TRANSIENT STRESS ANALYSIS MODEL

(Figure 20)

A short axial section of the engine was structurally modeled to permit evaluation of the transient stresses at selected times along the trajectory. This shows how the various elements of the structure were modeled and what elements were modeled. The temperatures used in the analysis were obtained from the thermal analyzer program.

TRANSIENT STRESS ANALYSIS MODEL

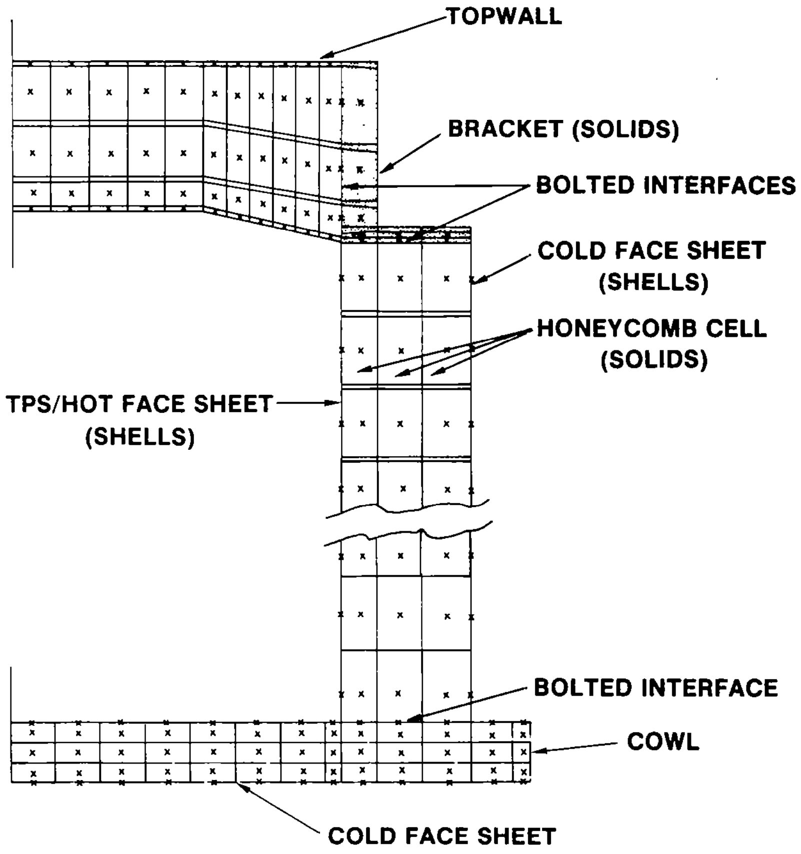


Figure 20

PEAK THERMAL STRESSES (ELASTIC)

(Figure 21)

These are the peak thermal stresses that result from the transient ΔT's discussed above. They were calculated as elastic stresses and are of magnitudes that will result in plastic flow of the material. At start-up, 1520 MPa (220 KSI), the yield for the material, 900 MPa (130 KSI), is greatly exceeded. At shutdown, the calculated stress is lower because of the somewhat reduced ΔT, but still well above the yield. As indicated previously, these high stresses must be reduced (to about half the values shown) by reduction of the ΔT's, by changes in engine operation, mission trajectory, or by TPS design.

PEAK THERMAL STRESSES
(ELASTIC)

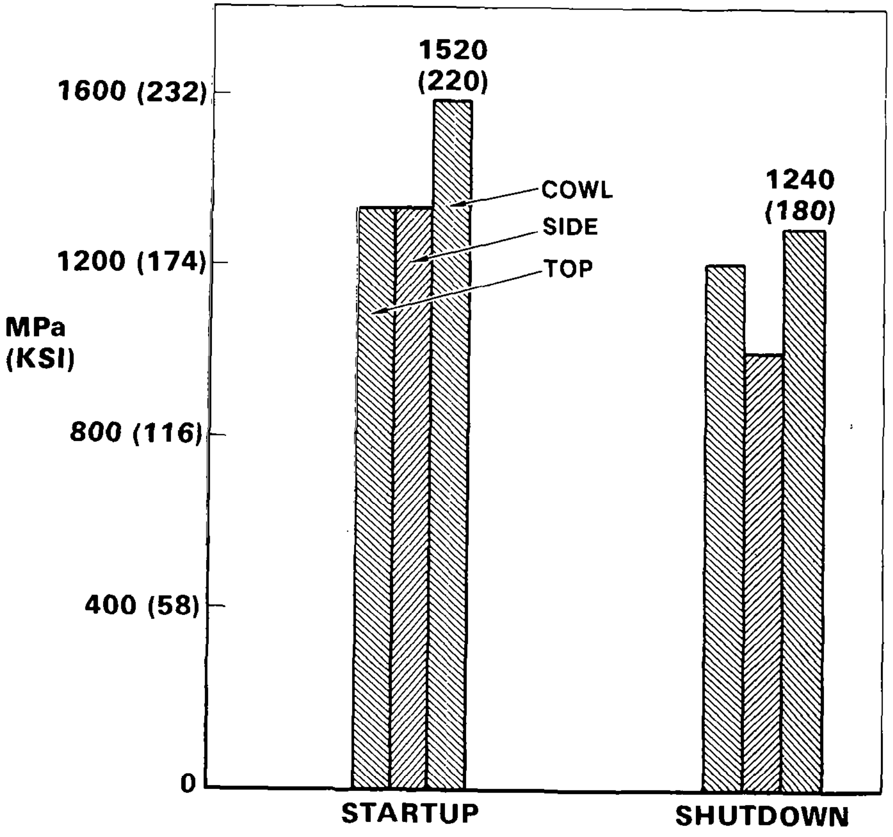


Figure 21

TYPICAL HONEYCOMB TEMPERATURES

(Figure 22)

This chart considers the structural transient response along the engine axis. (The assumptions were slightly different than those used for the previous analysis, resulting in somewhat different values.) At 125 sec into startup, the ΔT is 500 K (900°F). It falls off fairly sharply with distance from the outlet manifold. At about 46 cm (18 in.) from the outlet manifold, ΔT's are at steady state values and acceptable. Design solutions aimed at reducing ΔT are only required over an approximately one meter length. The rest of the engine will be controlled by steady state ΔT's, which have been found compatible with the design goals.

TYPICAL HONEYCOMB TEMPERATURES

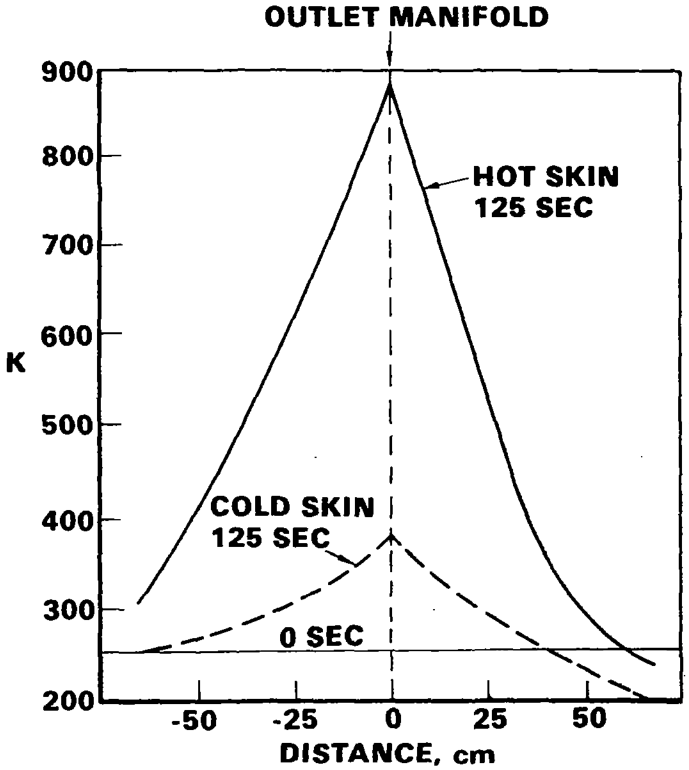


Figure 22

ENGINE WEIGHT--6 MODULES @ 37 X 46 cm

(Figure 23)

Looking at the swept-beam, vertical-beam, and all-honeycomb structures, the conclusion is that there is really not much to choose between them. Other considerations than weight will select the configuration. Some of these considerations have been discussed. Deflection, ease of fabrication, and ease of assembly favor the all-honeycomb configuration. The transient ΔT's and the associated problems would have to be accommodated in each one of the designs. In addition, the beams in the beam-supported configurations have a very slow thermal response. So in those configurations, means are needed to accommodate the ΔT between the beams and the panels, an additional complexity. Given the transient problem, the honeycomb therefore remains the favored configuration. The core of the honeycomb used here has a quarter-inch cell size.

The weight for the mounting is based on an Inconel 718 mounting frame accommodating the six modules. The weight of a fuel system was estimated based on controlling two groups of three modules each. Plumbing and instrumentation weight were based on a typical Scramjet installation.

ENGINE WEIGHT
6 MODULES @ 37 x 46 cm

ITEM	N (LB)		
	SWEPT BEAM	VERT BEAM	HONEY-COMB
STRUCTURE	13570(3050)	13430(3020)	13080 (2940)
TPS & MANIFOLDS	6230(1400)	6230(1400)	6230 (1400)
HONEYCOMB	2850 (640)	2850 (640)	3700 (830)
BEAMS & CLIPS	1690 (380)	1510 (340)	310 (70)
L.E.,T.E.,STRUTS	2850 (640)	2850 (640)	2850 (640)
MOUNTING		620 (140)	
FUEL SYSTEM		2410 (540)	
PLUMBING **INSTRUMENTATION**		1330 (300)	
		4360 (980)	
TOTAL	17930 (4030)	17800 (4000)	17440 (3920)

Figure 23

SUMMARY—THERMAL-STRUCTURAL DESIGN

(Figure 24)

A thermal-structural design has been defined in terms of the required flow routing. That flow routing is based on minimizing temperature discontinuities in the axial direction. Specific configurations have been defined both as regards the heat exchanger passage geometry and the layout of the heat exchanger, and material selections have been made. Hastelloy X, nickel, and Inconel 718 are the three materials used in the engine. Fabrication of the TPS/structure is considered to be within current technology.

In case of the structure, beam-supported and all-honeycomb configurations were considered, the latter using beams at the mounts only. The all-honeycomb configuration has been selected because of its good deflection and stress performance and its favorable manufacturing aspects.

In the case of the strut, various structural and manifolding arrangements were considered. The configuration that has been evolved is believed to satisfy deflection and stress limits. Verification of this will require additional, fairly extensive computer remodeling. The manifold design has been analytically verified for the wet-wall configuration, with the pressure loads carried by the strut structural shell.

SUMMARY
THERMAL-STRUCTURAL DESIGN

- TPS
    - FLOW ROUTING
    - CONFIGURATION
    - MATERIALS
- STRUCTURE
    - BEAMS
    - ALL-HONEYCOMB
- STRUTS
    - STRUCTURE
    - MANIFOLDS

Figure 24

DESIGN DATA REQUIREMENTS

(Figure 25)

Design of the engine will benefit from additional data in critical areas. Better definition of the engine unstart pressures is of particular interest because of their effect on the structure and controls requirements. The unstart loads that are being used are generally considered unrealistically severe. The vertical and horizontal pressure distributions are unknown. The possibility of an unsymmetrical unstart within a module (strut to strut) was assumed, but needs evaluation.

No data exists on aerodynamic interaction of one module with the next module. Is a single module unstart equivalent to unstarting the whole group of six modules? How does the unstart propagate, if at all. The dynamics associated with propagation of the unstart through a module and from module to module are similarly unknown, as is the possible existence of a buzz problem with the inlet. These data will be needed to support a final detailed design for the engine.

In the case of the thermal-structural design, a better definition of the distribution of heat flux in the combustor is needed. The shock pattern needs to be defined. Corner heating is a problem peculiar to a 3-D engine. The data used predict no problem in the corners from the heating point of view. That needs to be verified, because test configurations from which the data were derived were not the same as the 3-D Scramjet configurations.

The basic aerodynamic data used in the study assumed sharp leading edges. Instead, blunting to 1.27 mm (0.05 in.) was required for pressure drop, heat transfer, and structural reasons. The aerodynamic interaction of the aircraft and the engine is clearly important to thermal-structural design of the engine itself and of the interfaces with an airplane.

DESIGN DATA REQUIREMENTS

- ENGINE UNSTART
  - PRESSURES
    VERTICAL
    HORIZONTAL
    SYMMETRY
  - MODULE-MODULE
    INTERACTION
    PROPAGATION
  - DYNAMICS
    PROPAGATION
    BUZZ

- HEAT FLUX DISTRIBUTION
  - COMBUSTION
  - SHOCKS
  - CORNERS
  - BLUNTING
  - AIRCRAFT INTEGRATION

Figure 25

CONCLUSIONS

(Figure 26)

The transient performance of the TPS/structure during engine start-up and shutdown governs the design. For the most severe assumptions concerning mission trajectory and engine operating procedures, ΔT's can range to 670 K (1200°R). Reduction of ΔT's to acceptable levels is possible by changes in operating procedures and, if required, in design of the TPS.

Specific structural design solutions have been identified for the engine. These have been incorporated in layout drawings of the engine. Analyses have verified that there are no basic structural problems once the transient operation is accommodated.

The design objectives for the engine, given control of the temperatures during transients, are feasible: 1000 cycles and 100 hours of engine operation. TPS temperatures are being limited to 1140 K (1600°F) on the surface and 890 K (1600°R) at the prime structure. Deflections during normal engine operation can be limited to the specified values and remain acceptable during the severe loadings assumed for engine unstart.

CONCLUSIONS

- TRANSIENTS GOVERN DESIGN
- DESIGN SOLUTIONS IDENTIFIED
- DESIGN OBJECTIVES FEASIBLE

Figure 26