Review of the
Design and Development
Orbiter
Structure and Thermal Protection System (TPS)

Tom Moser

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Credits and Recognition

The successful design of the Structure and TPS is in large part because of

- **The leadership, support, and commitment of**
  - **John F. Yardley – NASA Associate Administrator for Spaceflight**
  - **Chris C. Kraft, Jr. – Director of NASA Johnson Space Center**
  - **Max Faget – Director of Engineering, NASA JSC**
  - **Robert F. Thompson – Manager, Space Shuttle Program**
  - **Aaron Cohen – Manager, Orbiter Project**

- **The many dedicated engineers and authors of the technical papers (provided)**
  - **"*Orbiter Structural Design and Verification*", P.C. Glynn and T.L. Moser**
  - **"*Strength Integrity of the Space Shuttle Orbiter Tiles*", T.L. Moser and W.C. Schneider**
  - **"*Reliability Engineering of the Space Shuttle: Lessons Learned*", T.L. Moser**
  - ***"Structural Load Challenges During Space Shuttle Development",* A.C. Mackey and R.E. Gatto**
  - **"*Shuttle Structural Dynamics Characteristics",* C.T. Modlin and G.A. Zupp**

The Systems Engineering (SE) Process

- A thorough and in-depth Systems Engineering effort is critical to the success of any complex development program, especially where technology advancement is required.

- The Space Shuttle Program is an excellent case study

- In the SE process, structural engineering is an important element, and is the SE element for which this lecture focuses.

The Systems Engineering Process (con't)

- Structural engineering parameters assessed during each phase of the Shuttle design and operations process
  - Concept Studies – weight, cost, producibility
  - Concept Definition – weight, cost, producibility
  - Preliminary Design – detail design trades- configuration, weight, cost, producibility and operations
  - Critical Design – same as PD but emphasis on weight, cost, and flight certification plans.
  - Production – weight management, anomaly resolution consistent with design requirements
  - Certification – design and/or operations modifications
  - Operations – determining operations flexibility within the capabilities of the structure

Orbiter Structure

Concept Studies
(1968-1972)

(Conceiving and characterizing (qualitatively and quantitatively) the concepts that would serve as a Space Transportation System)

Study Variables

- Earth-to-Orbit Transportation System
- Multi-year budgets
- Development and ops costs
- Payload mass and size (delivery and return)
- Operational orbits
- Fully or partially reusable flight systems
- Turn-around time
- Entry cross-range

Shuttle Study Parameters Significant to Structural and Thermal Engineering

- Initial Performance requirements that were structural and TPS drivers:
  - Reusable Space Flight System
  - Payload size for delivery and return
  - Cross-range for landing
  - Low development and recurring costs, and peak annual costs
- Structural evaluation parameters
  - Load path efficiency
  - Weight
  - Payload size
  - Aerodynamic surface loading
  - Peak temperatures
  - Heat rate and load
  - Technology readiness
  - Producibility and operability
  - Reliability
  - Cost

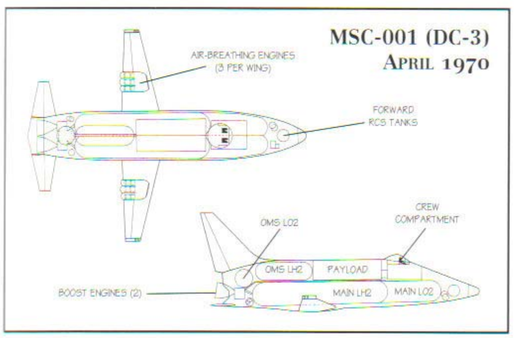
Early Shuttle Configurations

NASA JSC (formerly MSC) conceptually designed 53 Orbiters in a “skunk works” from ’70 to ’72

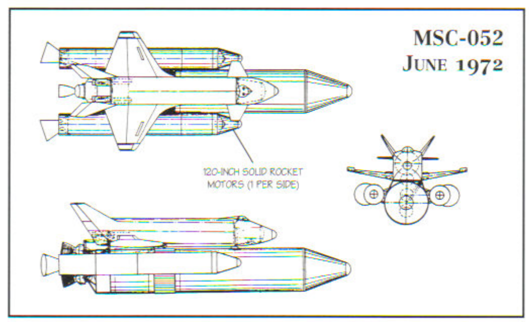
- Payloads: 15K to 40K lbs.; 8’ to 15’ dia.; 30’ to 75’ long
- Orbiter wings: Straight to 60 deg. Delta; Double Delta
- Landing weights: 70K to 215K lbs.
- Boosters: Fully reusable; Partially reusable: Expendable
- Propulsion System: LH2 and LOX; Air Breathers; Pump fed and Pressure fed;
- Propulsion Tanks: Internal to Orbiter, External to Orbiter, Expendable

For each configuration, the Structural Parameters on the previous page were quantified for assessment.

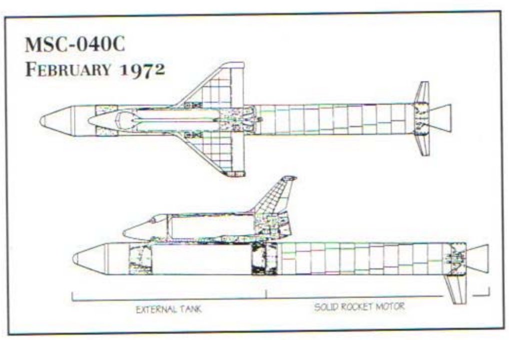
Selected MSC Configurations



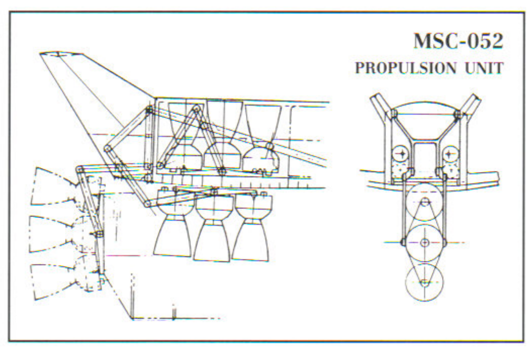
The MSC-001, also known as the DC-3, was the first serious in-house look MSC engineers took at developing an orbiter. This design is discussed in further detail on page 102.



Part of the continuing research to find an method of handling the engines, this design again attempted to retract the engines into the orbiter when the ET was jettisoned.



Other boosters were considered by NASA for the MSC-040C orbiter, such as this single large solid rocket motor attached to the aft end of the external tank.



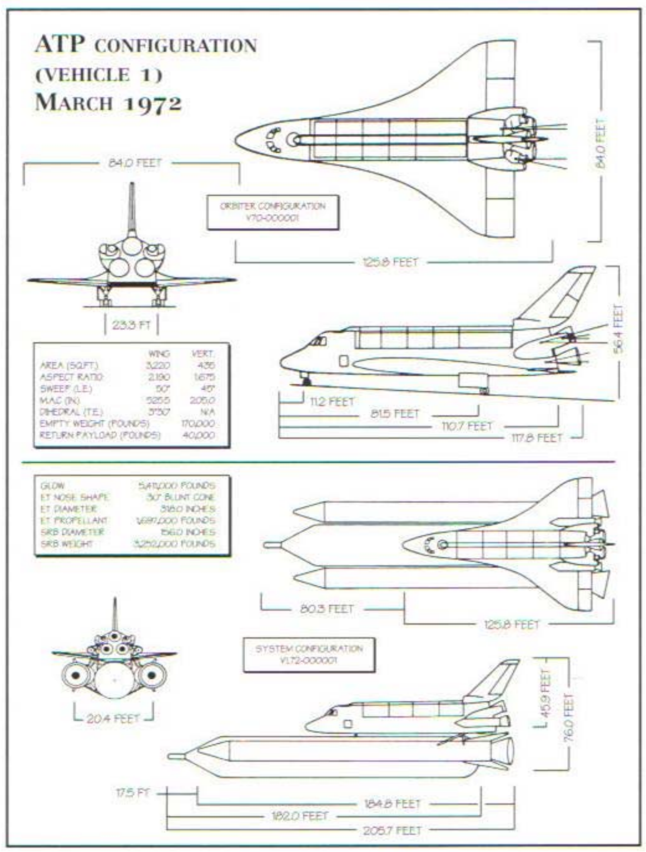
Final Concept

- Two and one half stage launch vehicle
- Reusable Orbiter
  - Delta wing
  - 100 mission life
  - Ascent - 3g max acceleration and max. q = 650psf
  - Atmospheric flight – +2.5g/1.0g
  - Crew of four for one week
  - Payload
    - 65,000 lbs. delivery, 40,000 lbs. return
    - 15’Dia x 60’ Length
    - Up to 5 Payloads /mission
    - Deployable
  - 1265 mile cross range during entry
  - TPS material not defined

Concept Definition

(Ready to proceed to Preliminary Design
July 1972)

Space Shuttle Configuration



Beginning Design, Development, Test and Evaluation (DDT&E)

- Four years of NASA in-house and contracted studies resulted in the configuration and top level requirements that were structure drivers, e.g.
  - Orbiter Life - 100 missions
  - Payload – 65K lbs., 15'dia.x 60'lg, 1 to 10
  - 1265 mile cross range (entry to landing)
  - Max. aero dynamic pressure, q=650 psf
  - Max. ascent acceleration, 3 g's
  - Re-entry maneuvers, 2.5 g/-1.0g limit
  - Rationale loss of one SSME during ascent
- The challenge was to not over specify the structural requirements in order to enable flexibility and authority for the contracted DDT&E

Challenges for the Definition Phase

- Detailed Design criteria
- Airframe material
- Structural design
  - Integral or floating cabin
  - Accounting for Thermal Stress
  - Compartment venting
  - Major Structural Concepts Trades
- Design Loads

Orbiter Structural Design Criteria

- Ultimate Factor of Safety = 1.4 for limit load (maximum expected loads)
- Yield F.S. – not specified (no detrimental deformation allowed for limit loads)
- Thermal and mechanical stresses to be additive except when thermal stress is relieving
- Life -100 missions with a scatter factor or 4, all parts considered for fracture mechanics
- Ultimate F.S.=1.25 at the end of life
- Material allowables
  - 95 percentile and 95 percent confidence for single load paths
  - 90 percentile and 95 percent confidence for redundant load paths

Combined Stress Criteria

- An unprecedented criterion was established for combining stresses to
  - Assure determining a realistic maximum expected stress
  - Avoid reducing stress because of thermal gradients
  - Incorporate classical tank pressure induced stress

Combined Stress Criteria

3.2.2.2.6 ULTIMATE COMBINED LOADS. THE MECHANICAL EXTERNAL, THERMALLY INDUCED, AND INTERNAL PRESSURE LOADS SHOULD BE COMBINED IN A RATIONAL MANNER ACCORDING TO THE EQUATION GIVEN BELOW TO DETERMINE THE DESIGN LOADS. ANY OTHER LOADS INDUCED IN THE STRUCTURE, E.G., DURING MANUFACTURING, SHALL BE COMBINED IN A RATIONAL MANNER. IN NO CASE SHALL THE RATIO OF THE ALLOWABLE LOAD TO THE COMBINED LIMIT LOADS BE LESS THAN 1.40

K_1L EXTERNAL + K_1L THERMAL + K_2L PRESSURE, $\geq 1.40\ \Sigma$ L

K_1 = 1.4 WHEN THE TERM IS ADDITIVE TO THE ALGEBRAIC SUM, Σ L

K_2 = 1.5 FOR TANKAGE WHEN THE TERM IS ADDITIVE TO THE ALGEBRAIC SUM, Σ L

K_1, K_2 = 1.0 WHEN THE TERM IS SUBTRACTIVE TO THE ALGEBRAIC SUM, Σ L

FIGURE 4.- COMBINED LOADS CRITERIA.

Airframe Material

- Systems studies showed that the weight of structure plus TPS was approximately the same (p.20)
  – Based on allowable max. temp., heat sink, and unit weights
- Aluminum was selected based
  – Producibility and material properties data base
  – SR-71 (Titanium – "Black Bird") experience
  – Beryllium manufacturing difficulty.

Structure and TPS Weights and Costs

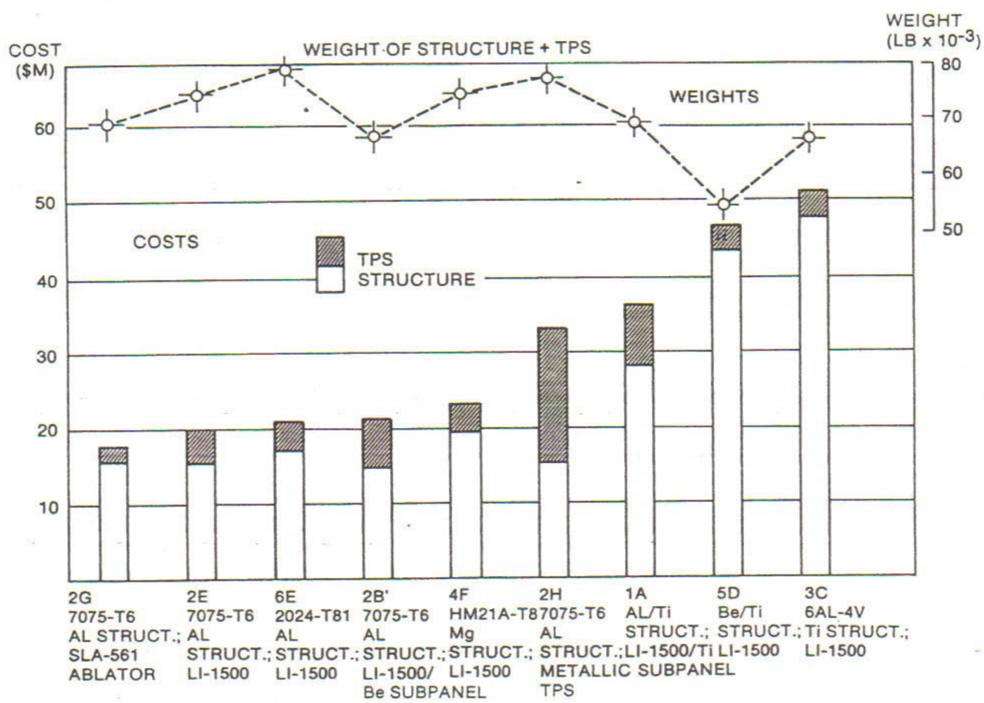


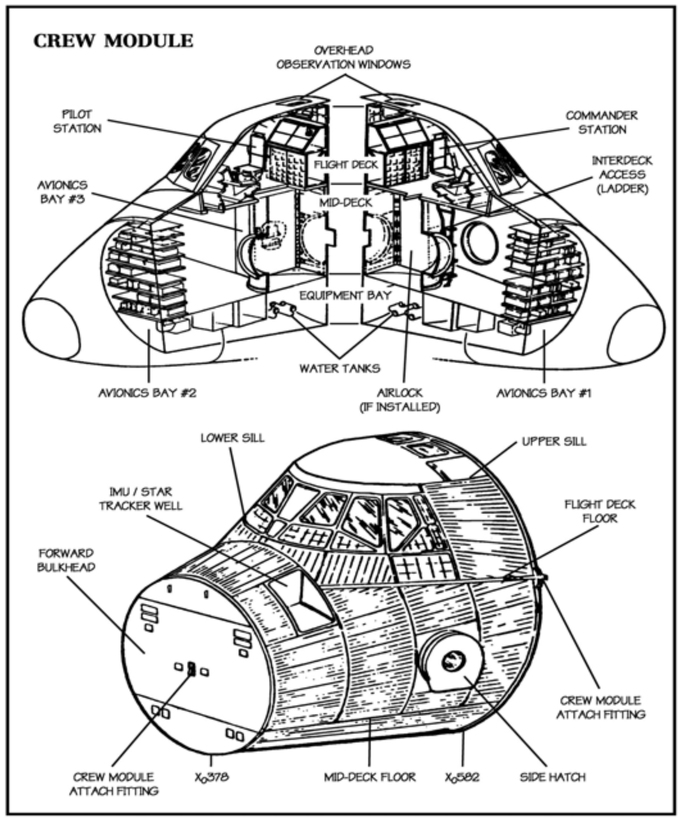
FIGURE 3.- ORBITER STRUCTURE/TPS FIRST UNIT COST COMPARISON

Crew Module (Cabin) Design

- Pressure integrity of the Cabin was critical for crew safety and had to be verified prior to each flight.
- A “floating” design (p.22) isolated the Cabin from the fuselage loads, simplified the design and increased reliability.
- The Cabin design weight was 30K lbs. based on Apollo densities and growth.

Crew Module Concept

- Pressure vessel design
- Four discrete attachment points with the forward fuselage
- Minimum heat transfer to Crew Module
- Fracture mechanics – leak before rupture



Accounting for Thermal Stress

Issue:

- Desensitizing the structural design for thermal stress was not practical (based on SR-71 and Concorde experience).
- Areas effected by thermal gradients
  - between skin-stringer panels and frames or ribs
  - between upper and lower wing covers
  - circumferentially around frames
  - between lower surface and side skin panels
  - between the wing and fuselage and tail and fuselage
  - Within skin-stringer panels
- Not possible to represent the entire structure with a 3-D finite element model for temperature and loads

Accounting for Thermal Stress (con’t)

Approach:

- Determined the temperatures on the vehicle for eight initial conditions for entry and at several times during entry
- Analyzed 100+ models for various regions of the vehicle and extrapolated to the entire structural model (p.25)
- The operational planners had to ensure that the operational envelope stayed within the budget.

Accounting for Thermal Stress (con’t)

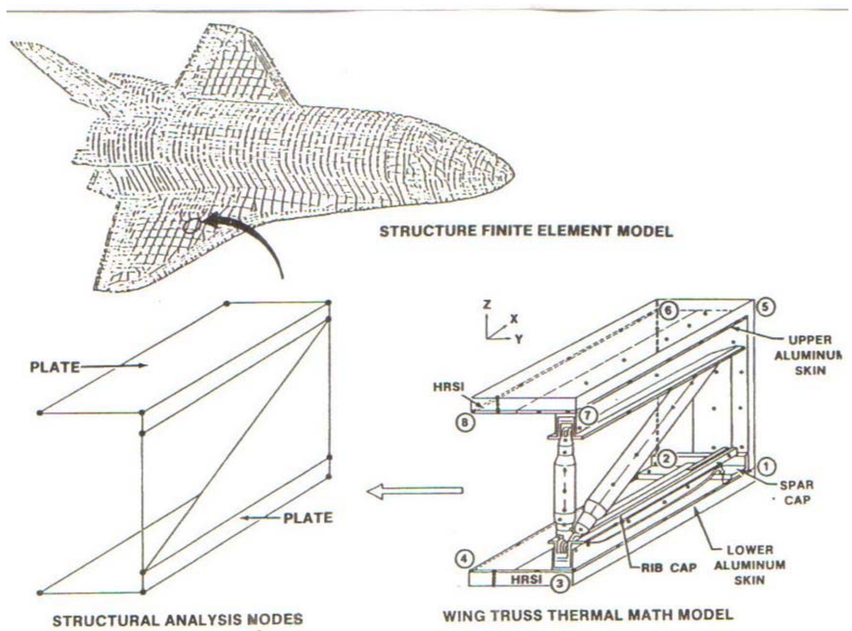


Figure 6.- Orbiter thermal stress analysis modeling.

5. STRUCTURAL FLIGHT CERTIFICATION

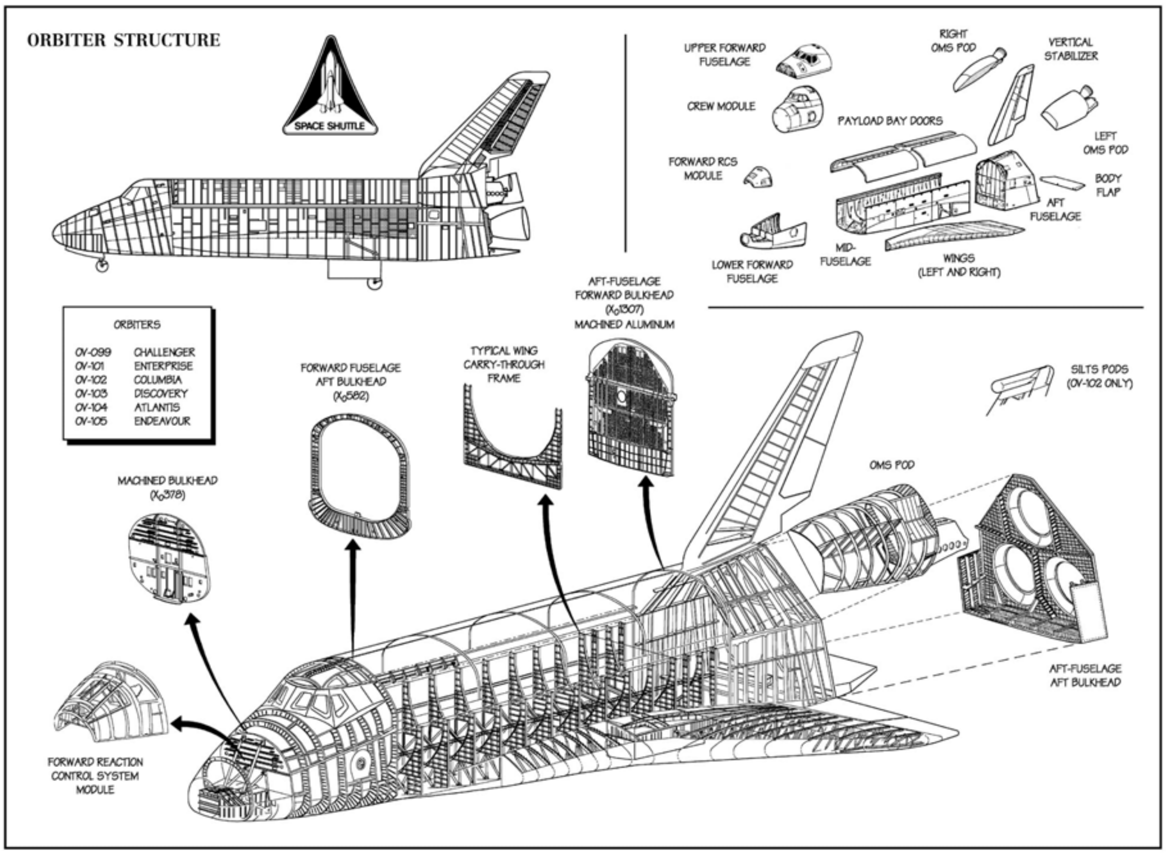
Compartment Venting

- Previous spacecraft design would have connected the entire volume and vented it through base vent areas.
- The Orbiter design precluded this approach because of contamination and cleanliness of the payload bay and the potential hazards of hydrogen concentration.
- Extensive analyses were required because of the pressure coefficients at the vents, pressure differential across bulkheads, and to define critical combinations of venting parameters.

Major Structural Concept Trades

- SSME Thrust Structure: Space frame vs. plate girder saved 1730 lbs. of weight
- Aft Wing Spar carry-through: Integrating with the aft (1307) bulkhead vs. a floating carry through saved 450 lbs. of weight
- Payload bay doors: Designed for torsion and pressure loads only (not body bending) to enable doors to be flexible and “zipped” closed prior to re-entry, or maximum reliability for opening and closing in space.
- Payload attachments: Designed to be statically determinate so as to preclude load sharing based on the relative stiffness of Orbiter and payload(s).

Structure Configuration



Design Loads

Nominal Shuttle Mission

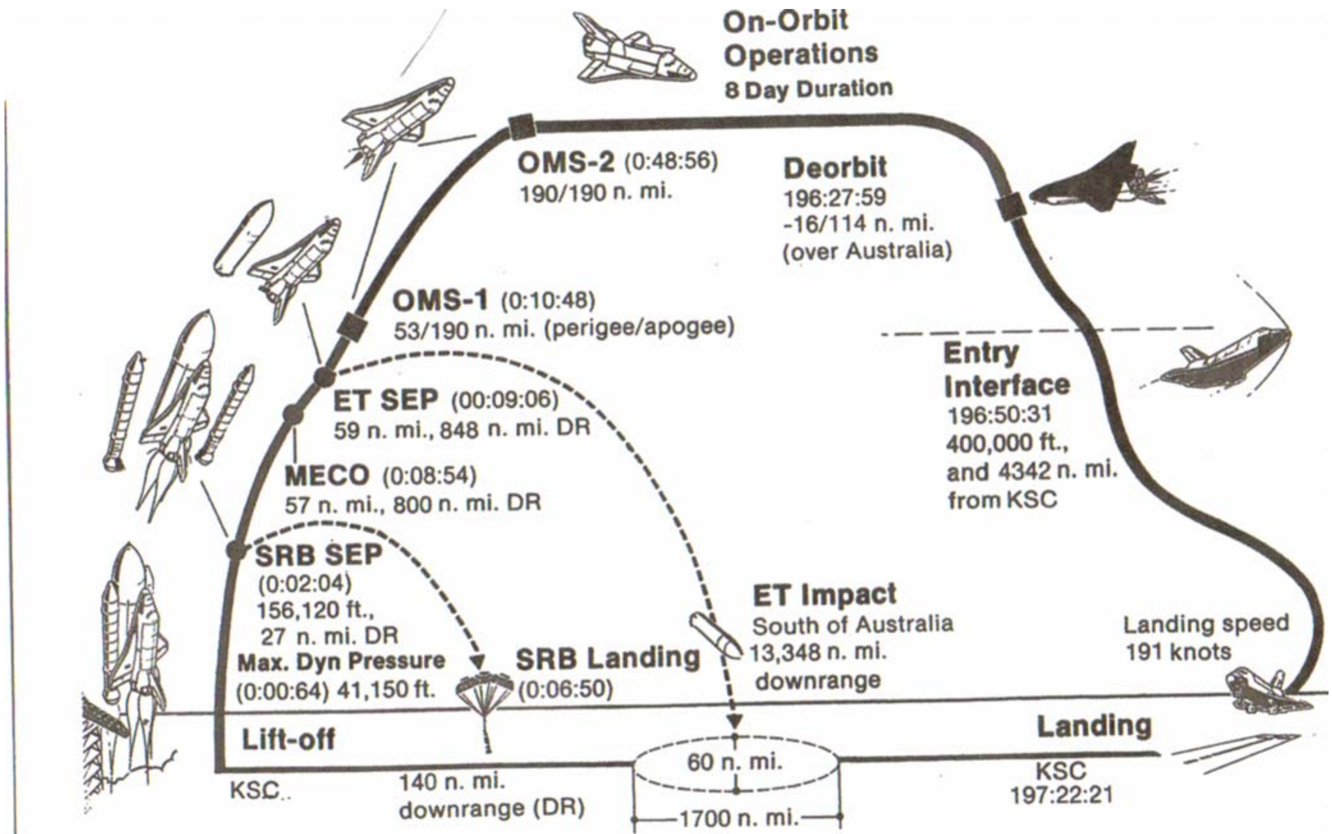
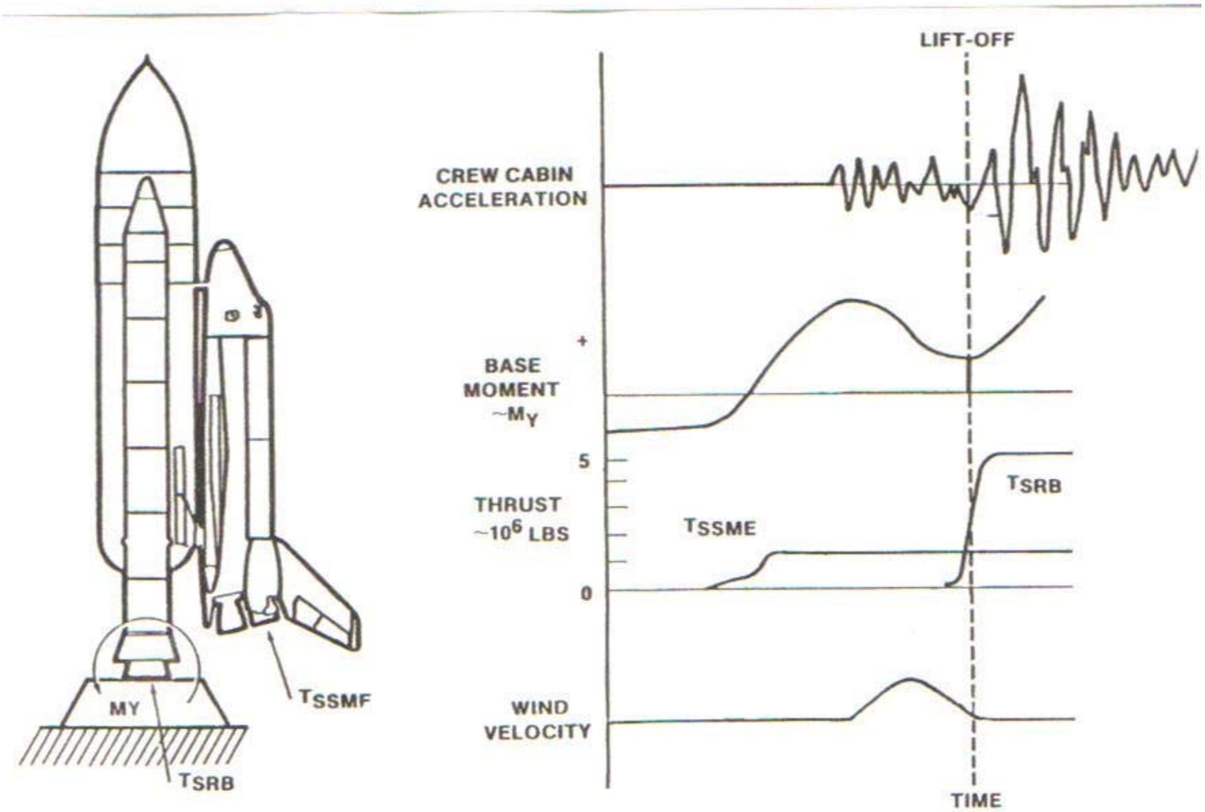


Figure 1.- Space shuttle nominal mission.

Lift-Off Loads

- Determined by a statistical combination of:
  - Rocket engines
    - Start Sequence
    - Thrust vector misalignment
    - Ignition overpressure
  - Ground winds and gusts
  - Vortex shedding
  - Proximity to nearby structures
  - Pressurization
  - Shrinkage of structure because of cryo temps.

Lift Off Loads



Ascent

Ascent Loads

- Surveying the entire flight envelope to determine critical conditions for hardware design was cumbersome and not practical
- Innovative approach:
  - Developed synthetic wind profiles using recorded data and guidelines
  - Determined angle of attack and sideslip by analytically flying the vehicle (with control system) through the synthetic winds profiles
  - Added system dispersions (3 sigma) such as SRB thrust mismatch, aerodynamics, thrust variations, flight control system variations
  - Generated an envelope of side slip and angle of attack was generated (similar to an aircraft V-n diagram)
  - Generated design loads at any point around the “squatcheloid” envelope (p. 35).

Ascent Loads Envelope (Squatchaloids)

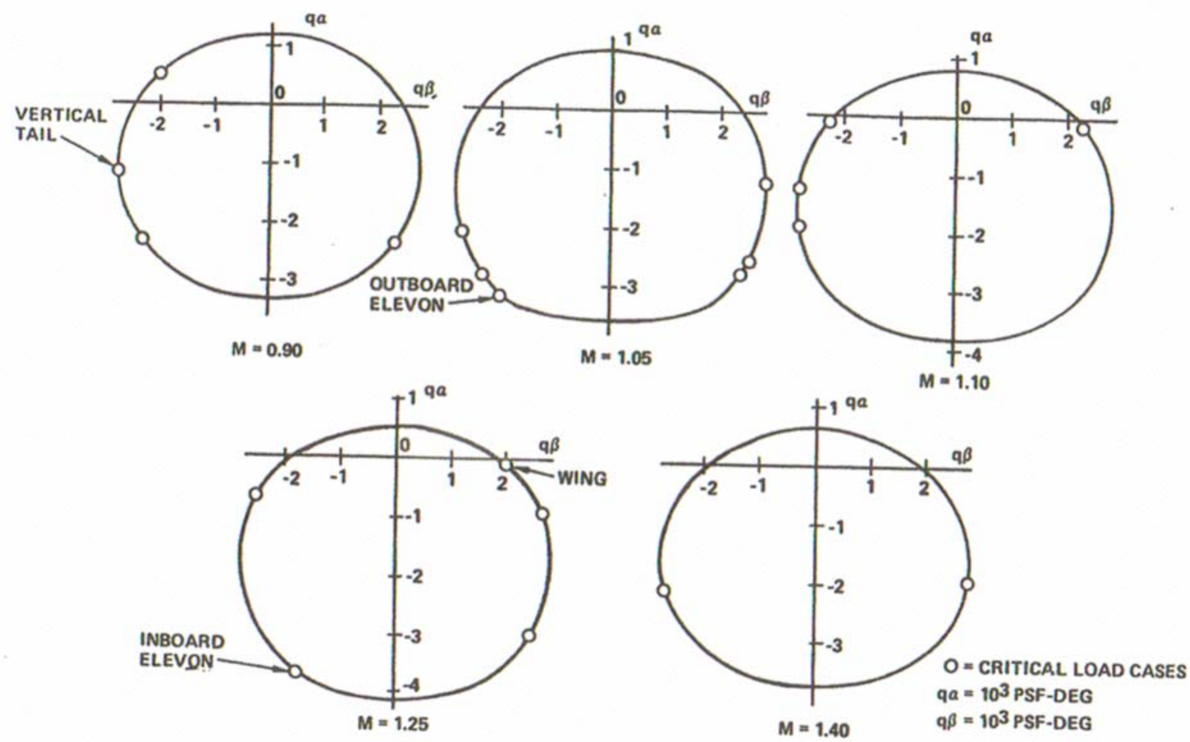


Figure 3.- Squatcheloids with critical load cases.

Benefits of the Squatcheloid Approach

- Load indicators were established for hundreds of conditions within the envelope that could be used for trajectory analyses
- SSME thrust structure were designed for realistic conditions rather than a worst case
- Allowed the performance, flight control, and structures disciplines to work in parallel.

Descent Loads

- Entry simulations using ballistic trajectories did not require any significant maneuvers and therefore no meaningful “design to” envelopes.
- Structural design was based on Mach number dependent V-n diagrams (p.38)
- Max. speed, equivalent to 375 psf, was derived from upsetting the nominal trajectory and recovering within the entry control limits.
- The criterion came under serious challenge because the deterministic flight conditions could not justify the many descent cases.
- The criterion was found to be logical and set a precedent for deviating from deterministic ballistic load definition.

Descent Loads Criterion

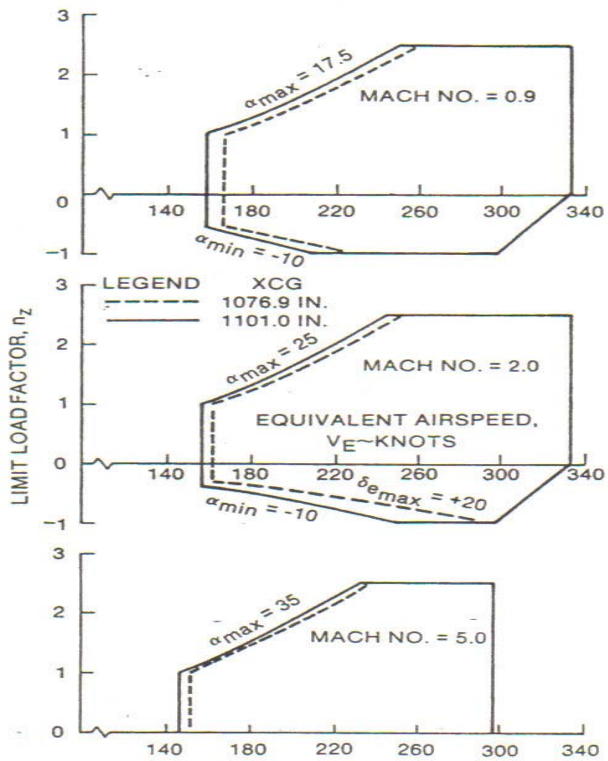


FIGURE 2.- DESCENT V-n CRITERIA.

Detailed Design

(Completing the design and establishing flight certification plans)

Challenges for Detailed Design

- Weight reduction
- Ground Certification for first flight

Weight Reduction

- As with any aircraft or spacecraft, weight control/management is a major effort and requires a weight reduction effort – no different for the Orbiter.
- Weight reductions:
  - Payload bay doors – 900 lbs. - Changing from Aluminum to Graphite/Epoxy (limited knowledge)
  - Thrust Structure – 1200 lbs.(?) – Titanium stiffened with Boron/Epoxy for increased compression modulus
  - Other use of composite materials (p.41)

Structure Materials

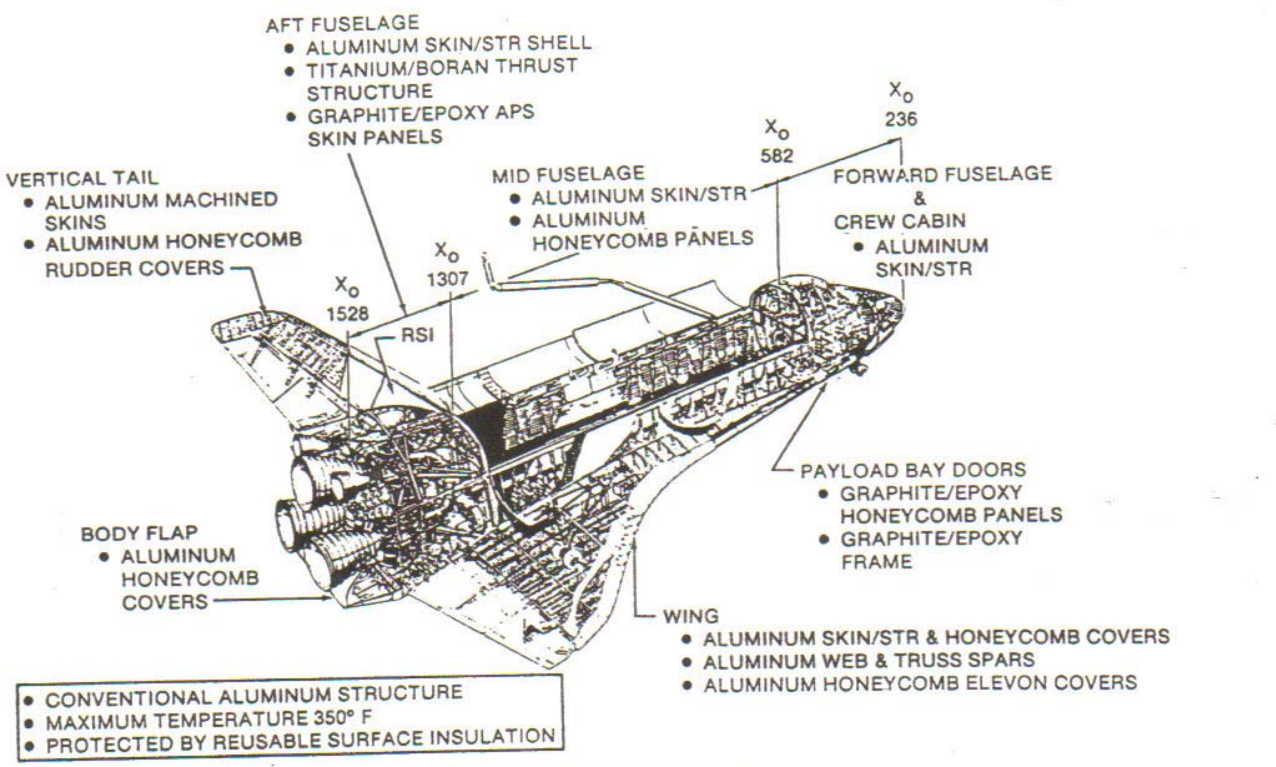


FIGURE 5 — ORBITER STRUCTURE

Structural Certification

(Deviating from the “norm” and Innovation)

Ultimate Strength Integrity

- Consistent with classical airframe certification, the Orbiter Project planned for a dedicated Static Test Article.
- Situation:
  - Most of the primary structure had significant thermal stress components. Attempts to factor mechanical loads to induce equivalent thermal stress resulted in inconsistent stress distribution.
  - Combining mechanical loads and thermal environment (ala Concorde testing) was not practical
  - The Project had a $100 million funding short-fall
- Solution:
  - Apply 110% of limit mechanical loads to an airframe
  - Predict the strain response to verify the structural analyses
  - Extrapolate to 140% of mechanical load and add thermal stress to demonstrate ultimate load capability
  - Refurbish the airframe as a flight vehicle (Challenger) to save $100 M.
  - The approach passed an independent review of "wide body aircraft" experts.

Static Test Article- *Challenger*

Fatigue Life Integrity

- Consistent with classical airframe certification, the Orbiter Project planned for a dedicated Fatigue Test Article.
- Situation
  - A short life of 100 missions did not indicate low- cycle, high-stress being critical for integrity
  - High acoustic levels (p. 47) did indicate that high-cycle, low-stress was critical for integrity
  - How to certify a large, complex, multi-material, multi-configuration structure with multi-combinations of mechanical and thermal loads at high acoustic levels.
- Solution
  - Test representative structure (p.47) acoustically to failure to determine the acoustic fatigue damage allowable
  - Size the test articles so only one third of the specimen was the test region – two thirds was compromised for boundary conditions.
  - Adjust the determined allowable for the effect of flight loads and elevated temperature.

Acoustic Fatigue Tests

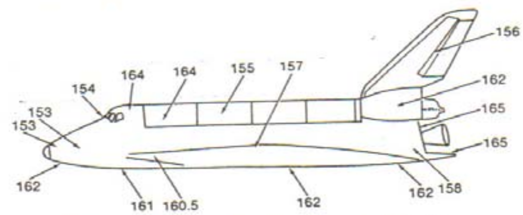


FIGURE 7.- ORBITER AERODYNAMIC-ACOUSTIC NOISE LEVELS.

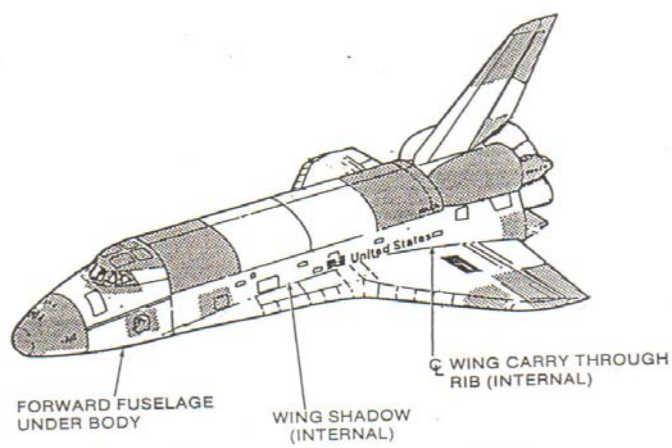


FIGURE 8.- ORBITER ACOUSTIC FATIGUE TEST ARTICLES.

Thermal Protection System

Concept Definition

(Ready to proceed to Preliminary Design
July 1972)

Requirements

- Protect the structure from maximum temperatures of 2800 deg. F
- Reusable for 100 missions
- Light weight
- Cost effective

TPS Options

- The US had re-entry vehicle experience with
  - ablative TPS (Mercury, Gemini, and Apollo) – *not reusable*
  - "hot structure" designs (up to 800 deg. F) – *complex design*
  - metallic TPS (up to 2800 deg. F) – *oxidation*
- NASA and contractor Lockheed developed a fibrous silica material with 2500 deg. F capability – *fragile and low strength*

Structure and TPS Weights and Costs

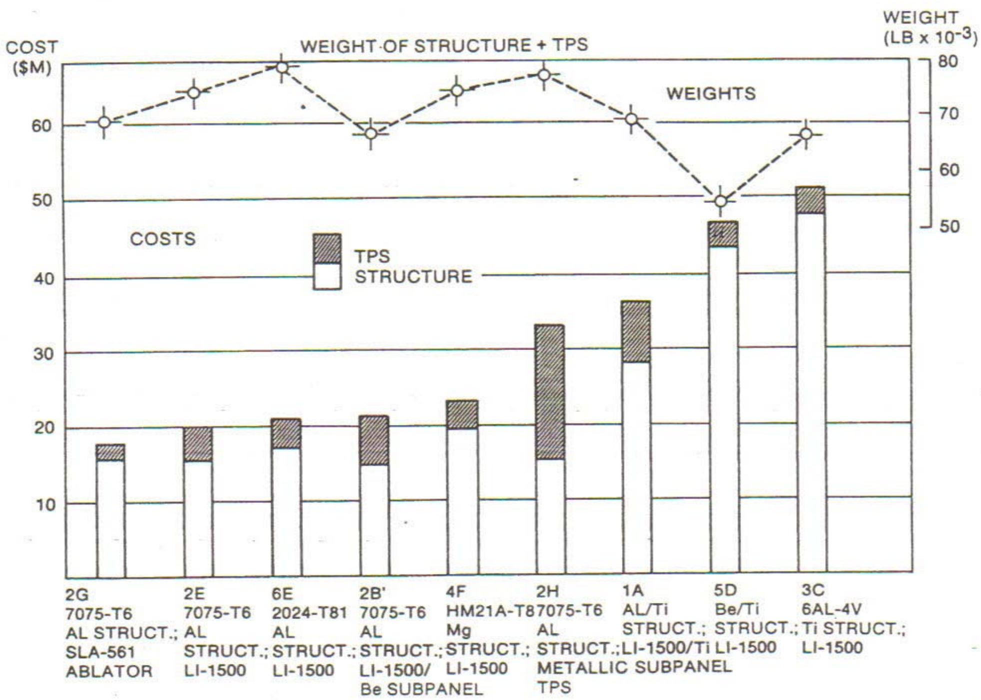
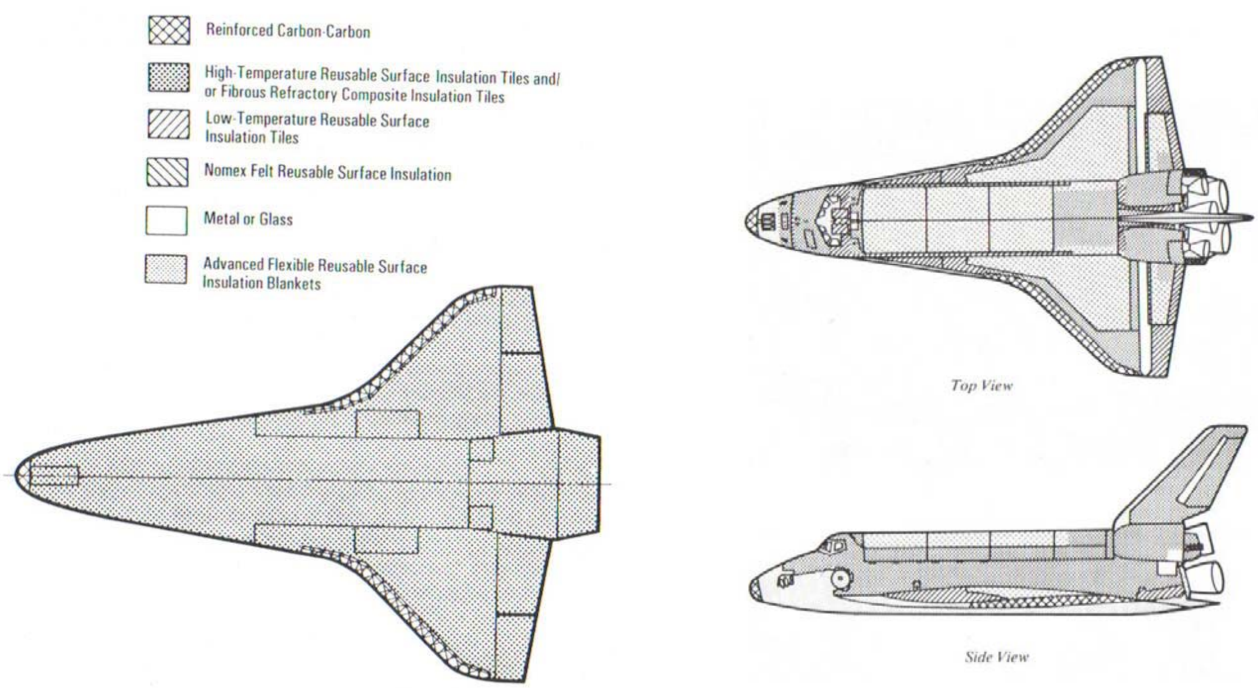


FIGURE 3.- ORBITER STRUCTURE/TPS FIRST UNIT COST COMPARISON

Acreage TPS Materials



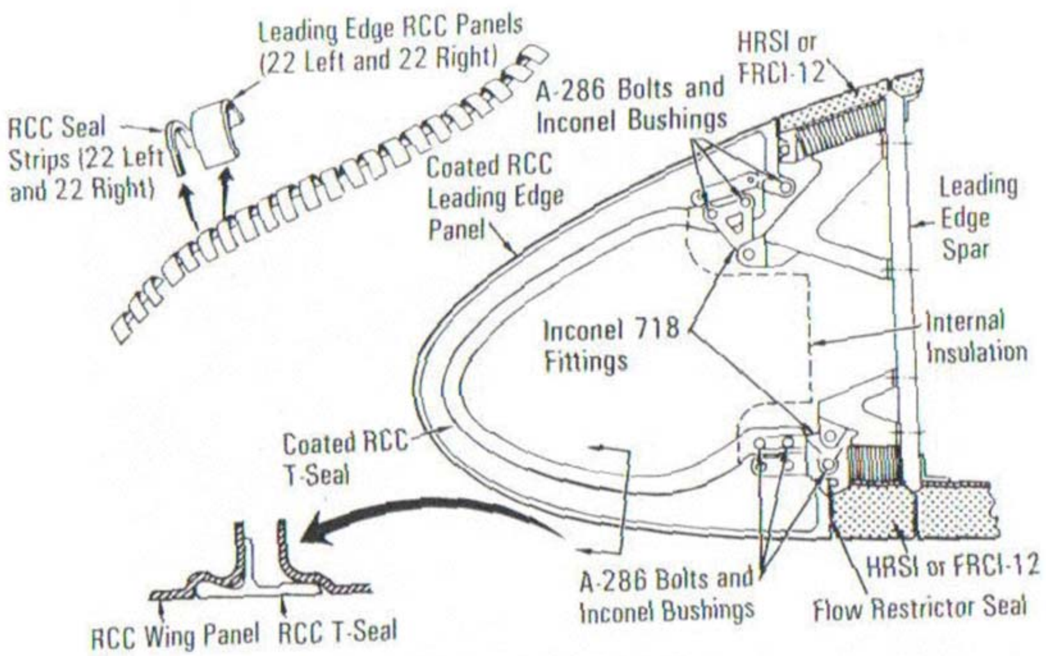
30,000 TPS Articles

	Approximate Number of Tiles or Blankets
High-temperature reusable surface insulation tiles	
22-pound tiles	501
9-pound tiles	20,047
Fibrous refractory composite insulation tiles	
12-pound tiles	2,945
Low-temperature reusable surface insulation tiles	
9-pound tiles	699
Advanced flexible reusable surface insulation blankets	2,277
Flexible reusable surface insulation	977**
	27,446*

*Columbia (OV-102) will have a slight variation in the number of tiles because of the Shuttle infrared leeside temperature sensing pod atop the vertical stabilizer. There will also be a slight variation in the number of tiles per vehicle.

**The FRSI sheets will vary slightly in number for each orbiter.

Leading Edge TPS



RCC Wing Leading Edge

Tile Design

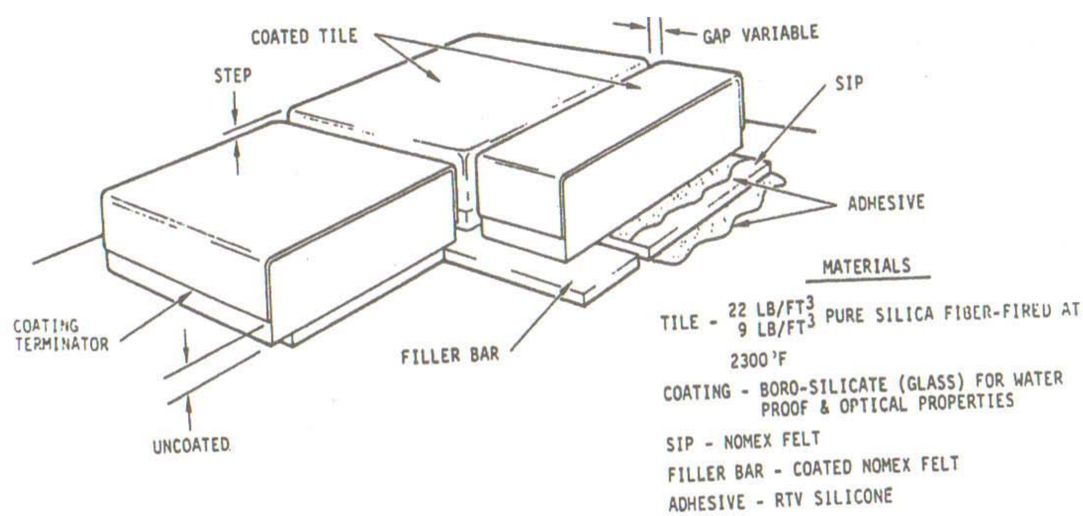


Figure 7.- Tile design.

Detailed Design

(Completing the design and establishing flight certification plans)

Challenges

- Tile material (silica) deformation at high temperature
  - Solution: Control purity of material
- Assuring strength integrity of 25,000 (low strength) Tiles for complex combined loads
- Inadequate bond line strength of LI-900 Tiles
- Certification Tests
- Assuring the integrity of installed tiles.

Combined Designed Loads

	PRE LIFT-OFF		LIFT-OFF	ASCENT		ENTRY / TAEM		LANDING
MIS-MATCH/WARPAGE	X	X	X	X	X	X	X	X
IGNITION OVERPRESSURE								
- SSME	X							
- SRB		X						
AIRLOAD								
- GRADIENT				X	X	X	X	
- SHOCK				X		X		
- VENT LAG				X	X	X	X	
- SKIN FRICTION				X	X	X	X	
VIBROACOUSTICS			X		X		X	
OUT-OF-PLANE DEFLECTION			X	X	X	X	X	X

Fig. 8 Baseline load combinations.

Note the absence of debris impact

Structural Deformation and Pressure Induced Stress

Structural Deformation

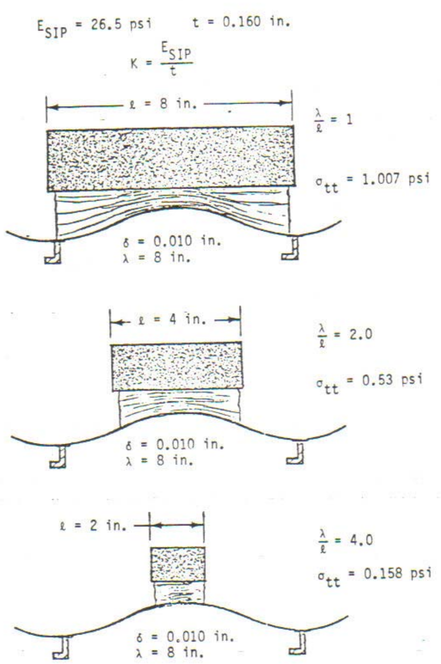


Fig. 6 Effects of substrate deflection.

Pressure Distribution

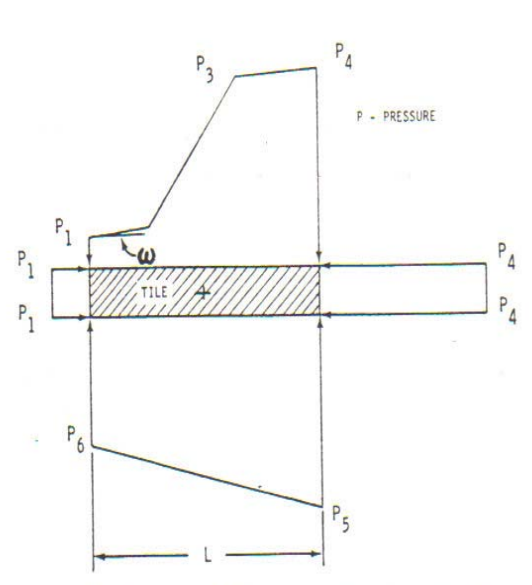


Fig. 7 Aeroshock freebody model for air loads.

Tile Stress Allowables

SIP Local Stiffness reduced effective Tile strength By 50%

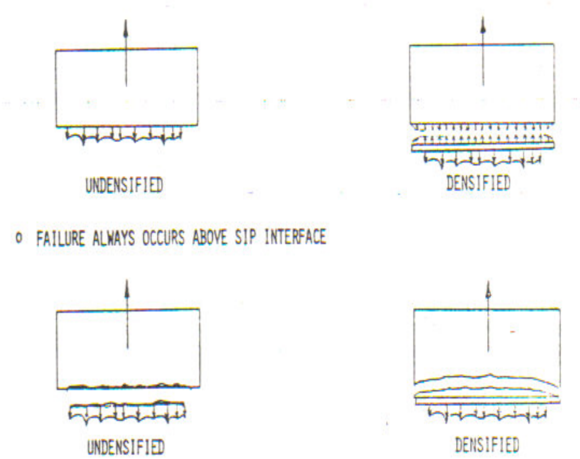


Fig. 4 Salient features of densified tiles.

Allowable Stress vs. Structural Deformation

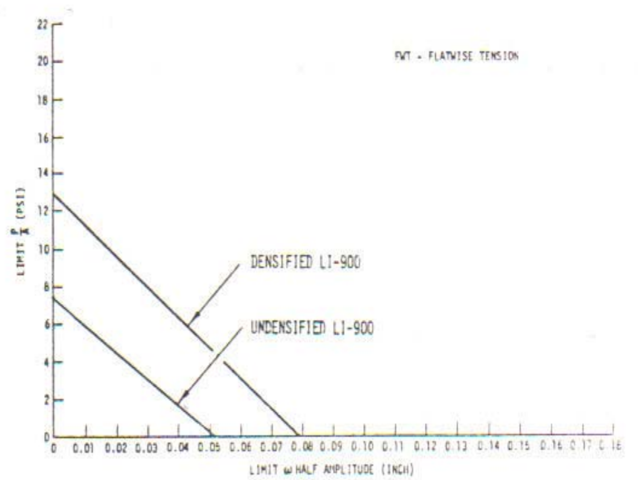


Fig. 5 Allowable FWT in presence of substrate deflection.

Analytical Tile Factors of Safety

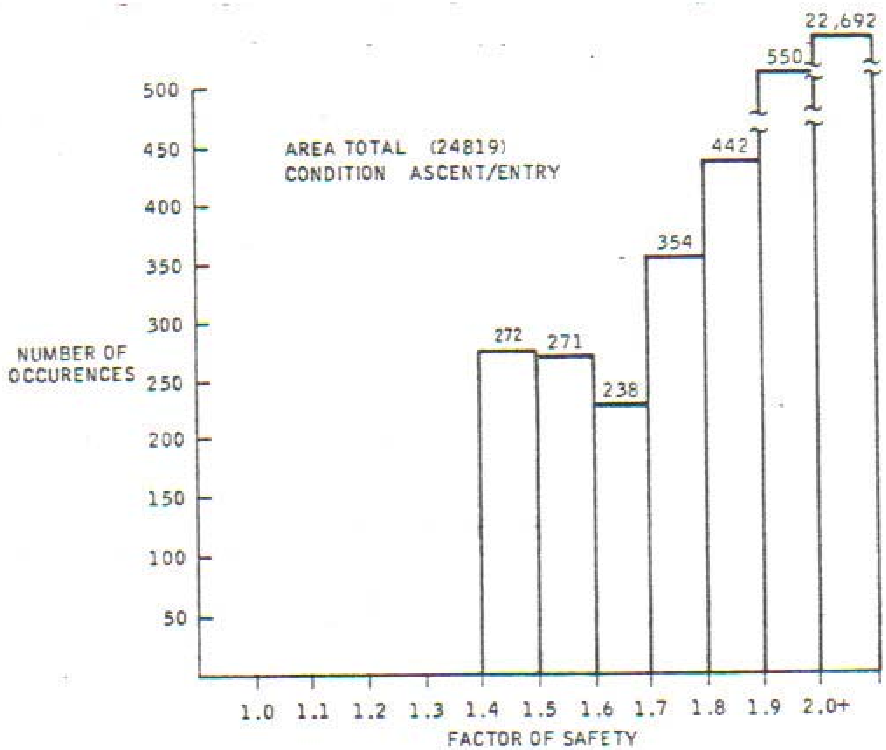


Fig. 9 Factor of safety histogram.

Verification of Flight Tiles

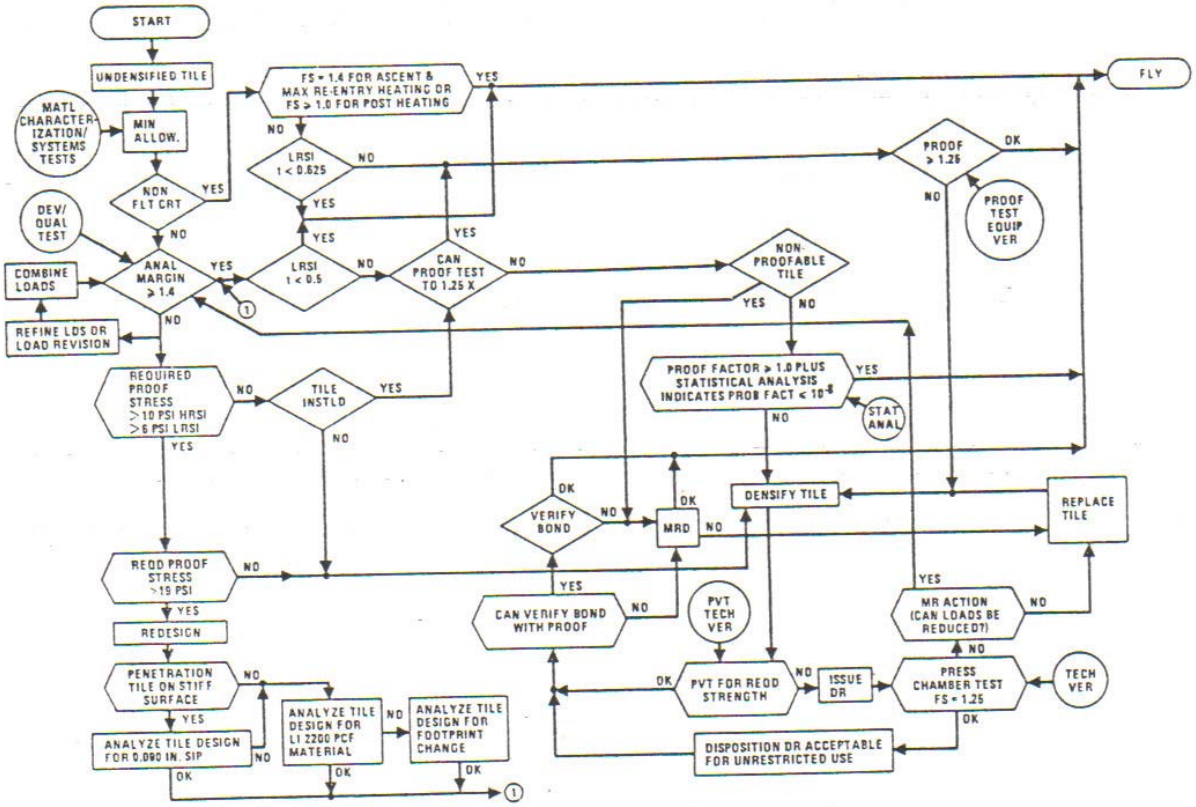
Issues:

- A large number of densified and undensified tiles installed, both critical and non-critical tiles (loss of one catastrophic), and some fail-safe.
- Needed to quickly demonstrate the required strength integrity.

Solution:

- Proof load test each tile to 125% of flight load, or
- Demonstrate by other methods that adequate strength existed

Tile System Acceptance Logic



Operations

Flight Experience/Ops Modifications

- Rigorous and innovative engineering and testing enabled the Orbiter Structure and TPS to perform successfully for design-to flight environments (not including debris).
- Surprises on STS-1
  - Overpressure on the vehicle because hydrogen gas accumulation
  - Center of pressure on the wing was further outboard and aft than predicted (because of SRB plume effect on pressure distribution)
  - Tile damage from debris
- Operations Changes
  - Hydrogen accumulation was contained and burned prior to SSME ignition
  - Ascent profiles were tailored to stay within the wing structural allowables modifying ascent trajectories and SSME thrust. Later day-of-launch winds were used to predict wing loads and increase the probability of launch.
- Design Changes
  - The ET foam insulation process was modified

MIT System Engineering Challenges

Challenges for the MIT Systems Engineering Study

- What different evaluation parameters, criteria, and analytical tools would you use during each phase of development and operations?
- What are the analytical tools are available today that were not available then, and what is the significance? Especially consider a combine thermal and structural model. Thermal stress is important.
- Are there thermal protection systems that could withstand the same environment as the Shuttle but that would be more damage tolerant?
- Would you design a separate crew escape system? Would this be the most reliable system for crew safety, or would it better to make the entire system more reliable?
- How would you “fix” the ET Insulation debris/Orbiter TPS problem?
- How important is “political systems engineering” and should it be a consideration for an entire program or even for a crew escape system?