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Satellite Power System: Concept Development and Evaluation Program

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1.3 HLLV SINGLE STAGE TO ORBIT (HTO/SSTO)—HIGH TECHNOLOGY ALTERNATE

The HTO-SSTO is a most advanced concept and, consequently, a higher technology risk option. This concept adapts existing and advanced commercial and/or military air transport system concepts, operations methods, maintenance procedures, and cargo handling equipment. The principal operational objective is to provide economic, reliable transportation of large quantities of material between earth and LEO at high flight frequencies with routine logistics operations and minimal environmental impact. An associated operational objective is to reduce the number of operations required to transport material and equipment from their place of manufacture on earth to low earth orbit. (Since this study was conducted under company discretionary funds and existing computer programs, some of the units in tables and figures have not been converted to the metric system.)

Some of the key operational features are:

- Single orbit up/down from/to the same launch site (at any launch azimuth subject to payload/launch azimuth match)
- Capable of obtaining equatorial orbit
- Takeoff and land on standard commercial or military runways
- Simultaneous multiple launch capability
- Total system recovery
- Self-ferry capability from manufacturing site to launch site
- Amenable to alternate launch/landing sites
- Incorporates Air Force (C-5A Galaxy) and commercial (747 cargo) payload handling, including rail, truck, and cargo-ship containerization concepts, modified to meet space environment requirements
- Swing-nose loading/unloading, permitting standard aircraft loading concepts
- Systems servicing with existing support equipment on runway aprons or service hangars

The HTO-SSTO utilizes a tri-delta flying wing concept, consisting of a multi-cell pressure vessel. The *Whitcomb airfoil section offers an efficient* aerodynamic shape for obtaining a high propellant volumetric efficiency. LH_2 and LO_2 tanks are located in each wing near the vehicle c.g., and extend from the root rib to the wing tip, Figure 1.3-1. In the aft end of the vehicle, three LOX/LH_2 high P_c rocket engines are attached with a double-cone thrust structure to a two-cell LH_2 tank.

Most of the cargo bay side walls are provided by the root-rib bulkhead of the LH_2 wing tank. The cargo bay floor is designed similar to the C-5A military transport aircraft. The top of the cargo bay is a mold-line extension of the wing upper contours, wherein the frame inner caps are arched to resist pressure. The forward end of the cargo bay provides a circular seal/locking mechanism to the forebody. Cargo is deployed in orbit by swinging the forebody to 90 or more degrees about a vertical axis and transferring cargo from the bay on telescoping rails.

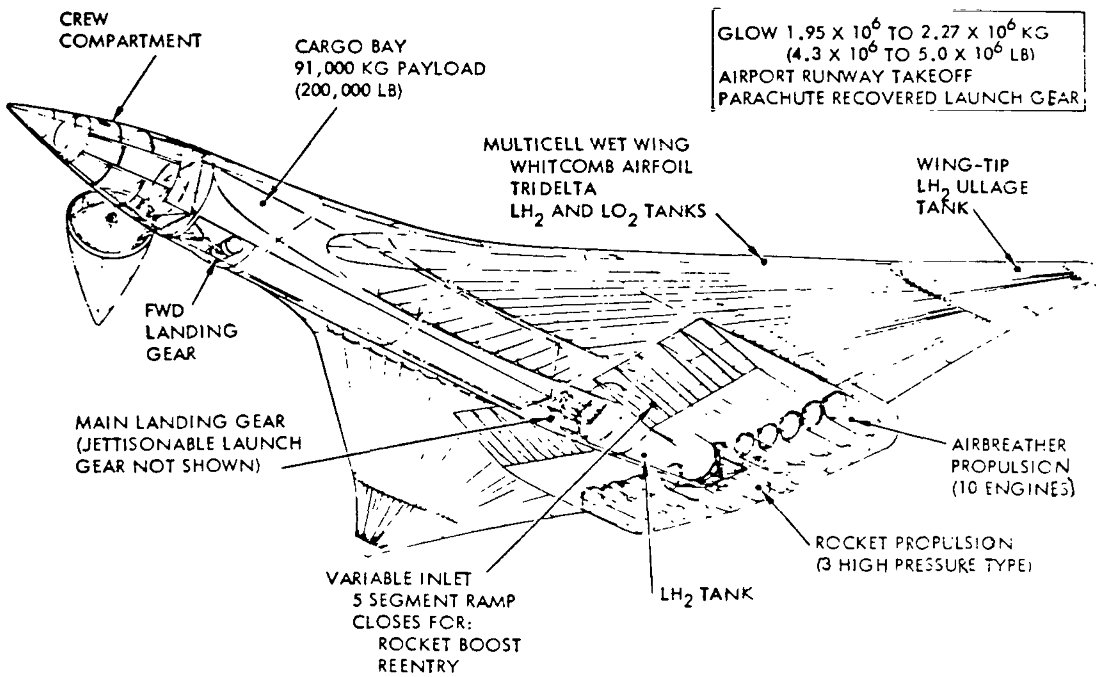


Figure 1.3-1. HTO-SSTO Design Features

The forebody is an ogive of revolution with an aft dome closure. The ogive is divided horizontally into two levels. The upper level provides seating for crew and passengers, as well as the flight deck. The lower compartment contains electronic, life support, power, and other subsystems including spare life support and emergency recovery equipment.

Ten high-bypass, supersonic-turbofan/airturbo-exchanger/ramjet engines with a combined static thrust of 6.68 MN are mounted under the wing. The inlets are variable area retractable ramps that also close and fair the bottom into a smooth surface during rocket-powered flight and for high angle-of-attack ballistic reentry. Figure 1.3-2 is an inboard profile of the vehicle, illustrating some of the details of vehicle construction.

Figure 1.3-3 presents details of the multi-cell structure of the wing. The upper figure illustrates the application of Shuttle-type RSI tile thermal protection system (TPS). The lower figure shows a potential utilization of a "metallic" TPS.

The wing is an integrated structural system consisting of an inner multicell pressure vessel, a foam-filled structural core, an inner facing sheet, a perforated structural honeycomb core, and an outer facing sheet. The inner

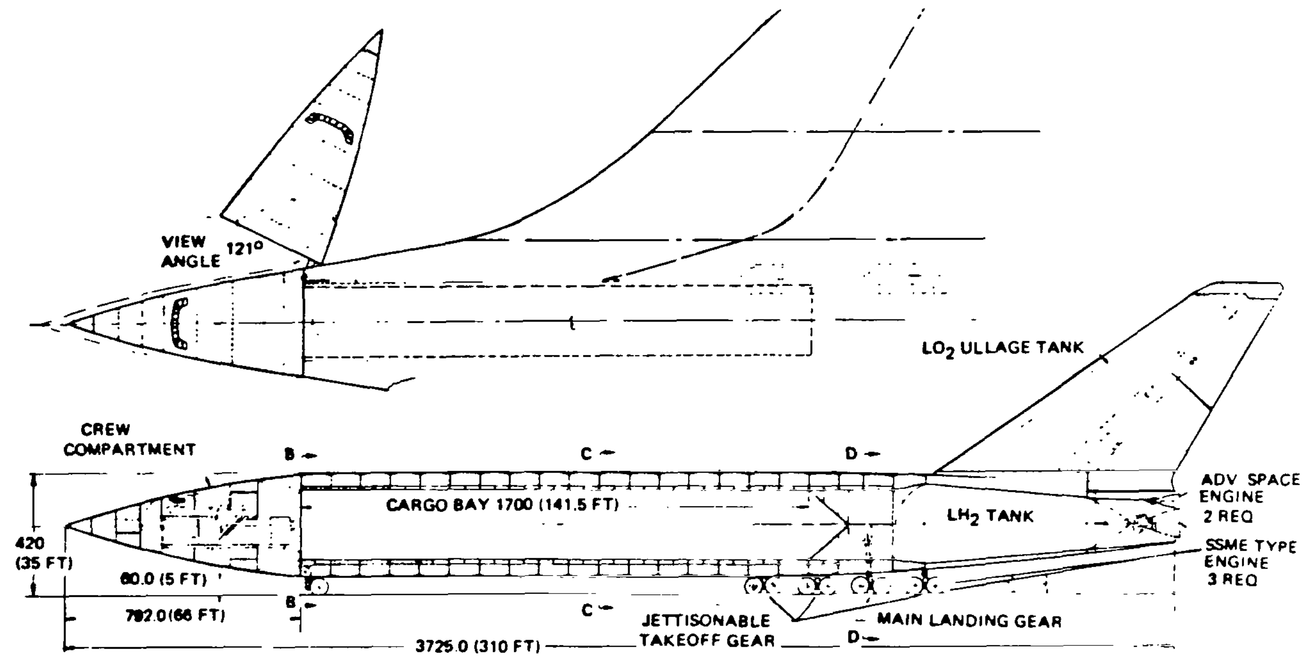


Figure 1.3-2. HTO-SSTO Inboard Profile

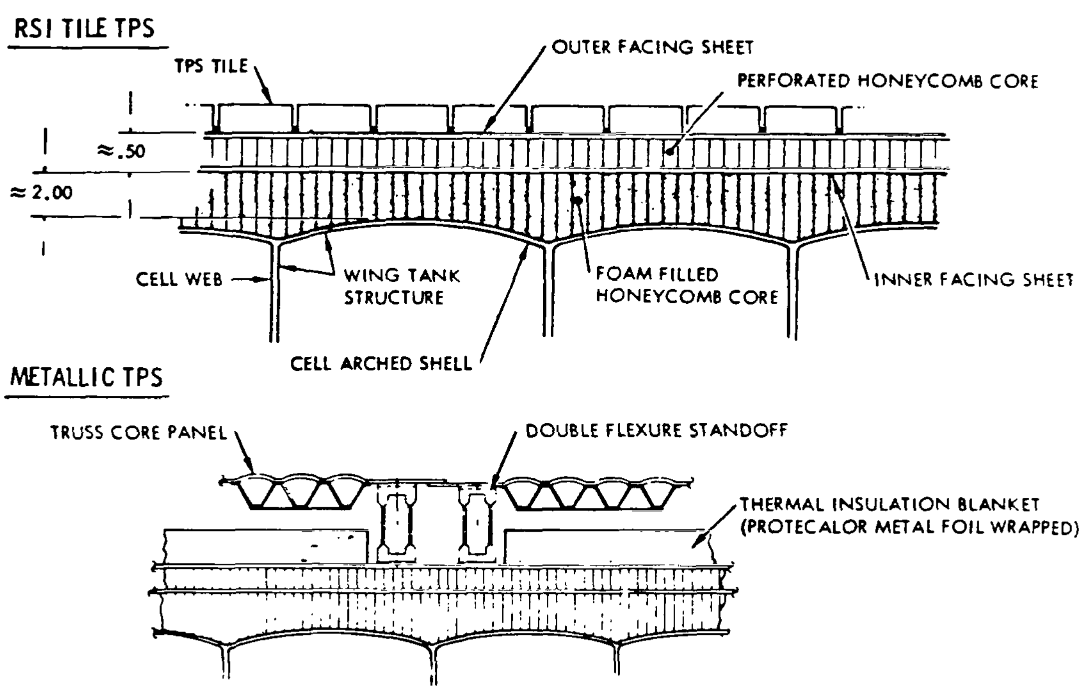


Figure 1.3-3. Wing Construction Detail with Candidate TPS Configurations

multi-cell pressure vessel arched shell and webs are configured to resist pressure. The pressure vessel and the two facing sheets, which are structurally interconnected with phenolic-impregnated glass fiber, honeycomb core, resist wing spanwise and chordwise bending moments. Cell webs react winglift shear forces. Torsion is reacted by the pressure vessel and the two facing sheets as a multi-box wing structure.

The outer honeycomb core is perforated and partitioned to provide a controlled passage, purge, and gas-leak detection system in addition to the function of structural interconnect of the inner and outer facing sheets.

The proposed multi-cycle airbreathing engine system, Figure 1.3-4, is derived from the General Electric CJ805 aircraft engine, the Pratt and Whitney SWAT-201 supersonic wraparound turbofan/ramjet engine, the Aerojet Air Turborocket, Marquardt variable plug-nozzle, ramjet engine technology, and Rocketdyne tubular-cooled, high-P_c rocket engine technology. The development of a multicycle engine of this type would require a most ambitious technology advancement program.

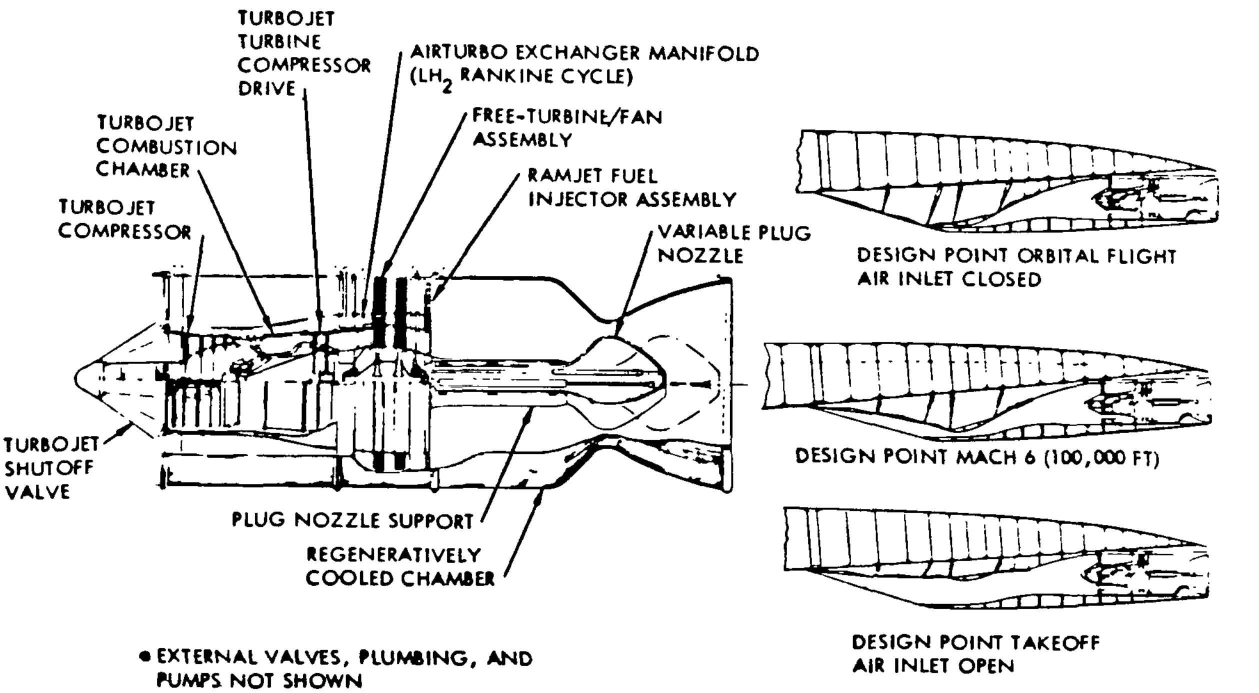
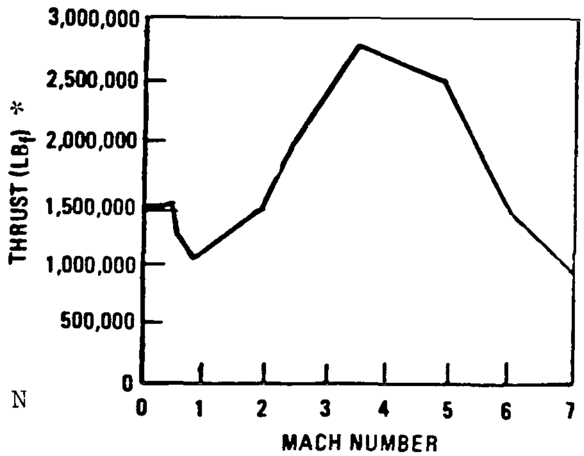


Figure 1.3-4. Multi-Cycle Airbreathing Engine and Inlet, Turbofan/Air-Turboexchanger/Ramjet

The multi-mode power cycles include: an aft-fan turbofan cycle, an LH_2 regenerative Rankine air-turboexchanger cycle; and a ramjet cycle that can also be used as a full-flow (turbojet core and fan bypass flow) thrust-augmented turbofan cycle. These four thermal cycles may receive fuel in any combination permitting high engine performance over a flight profile from sea-level takeoff to Mach 6 at 30-km altitude.

The engine air inlet and duct system is based on a five-ramp variable inlet system with actuators to provide ramp movement from fully closed (upper RH figure) for rocket-powered and reentry flight, to fully open (lower RH figure) for takeoff and low altitude/Mach number operation.

The inlet area was determined by the engine airflow required at the Mach 6 design point. The configuration required 6.68 MN thrust at the Mach 6 condition, and at least 5.8 MN for takeoff. This resulted in an inlet area of approximtely 10.5 m^2 for a 10-engine configuration. In order to provide pressure recovery with minimum spillage drag over the wide range of Mach numbers, the variable multi-ramp inlet is required. Estimated engine thrust (total of 10 engines) vs. velocity is given in Figure 1.3-5 in pounds.



*1 lb = 4.45 N

Figure 1.3-5. Airbreather Thrust Vs. Mach Number

Estimated aerodynamic coefficients and maximum lift/drag, lift coefficients, and angle-of-attack data are presented in Figures 1.3-6 and 1.3-7.

The SSTO uses aircraft-type flight from airport takeoff to approximately Mach 6, with a parallel burn transition of airbreather and rocket engines from Mach 6 to 7.2, and rocket-only burn from Mach 7.2 to orbit. Figure 1.3-8 illustrates a typical trajectory from KSC to an equatorial earth orbit. The prime elements of the trajectory are described below:

- Runway takeoff under high-bypass turbofan/airturbo exchanger (ATE)/ramjet power
- Jettison and parachute recovery of launch gear
- Climb to cruise altitude with turbofan power
- Cruise at optimum altitude, Mach number, and direction vector to earth's equatorial plane, using turbofan power
- Execute a large-radius turn into the equatorial plane still under turbofan power

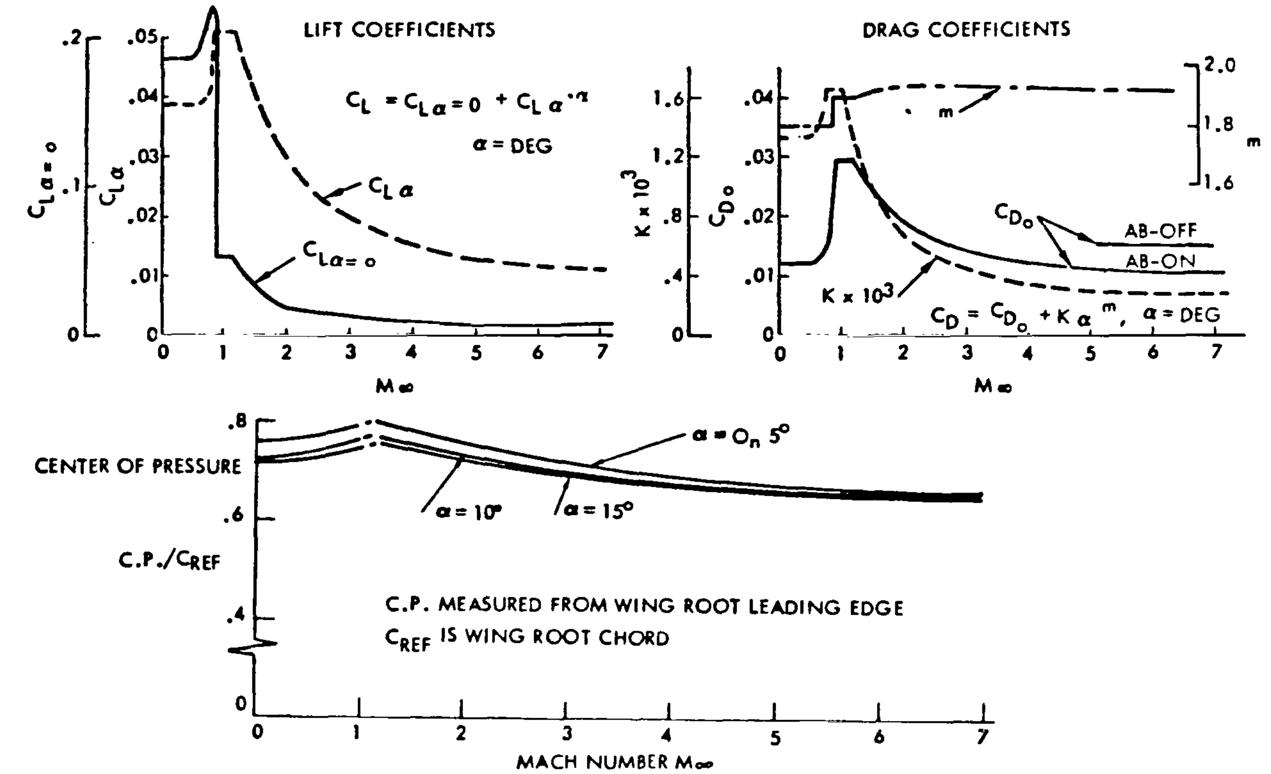


Figure 1.3-6. Aerodynamic Coefficients

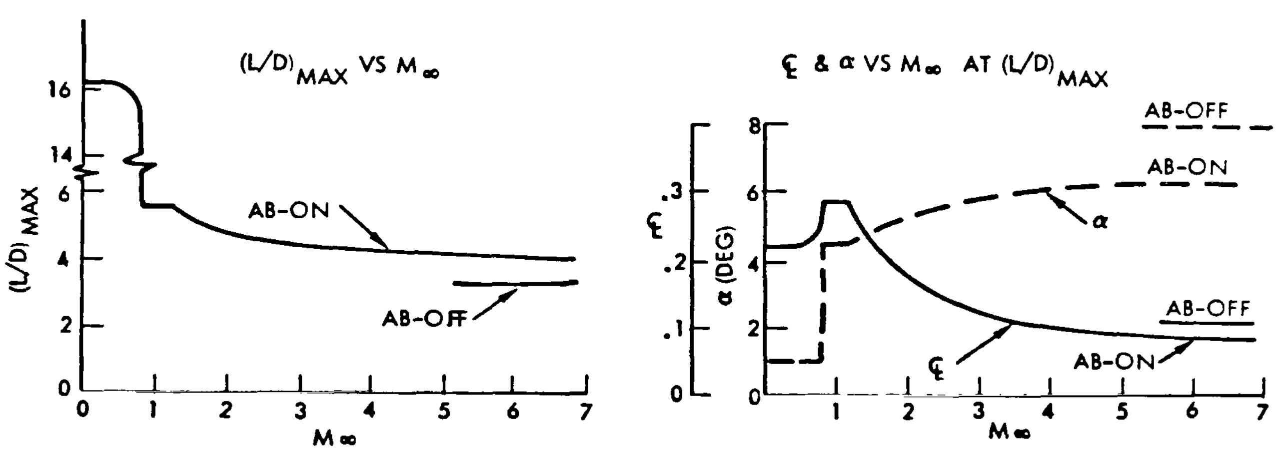


Figure 1.3-7. Maximum Lift/Drag

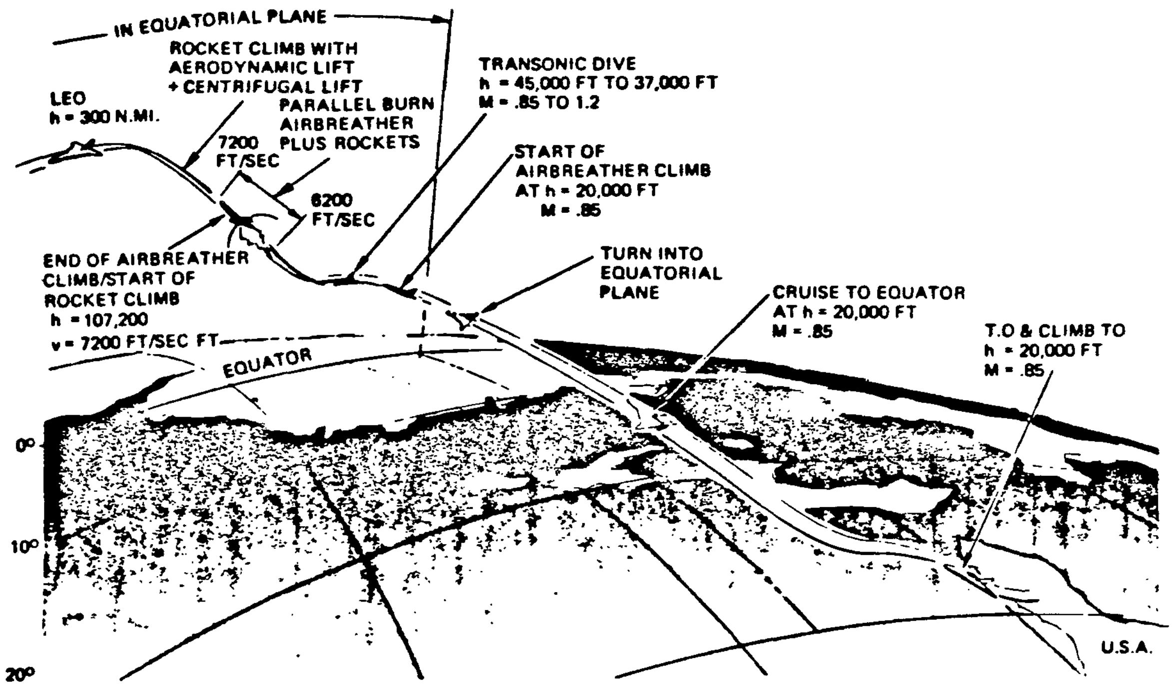


Figure 1.3-8. SSTO Trajectory

- Climb subsonically at optimum climb angle and velocity to an optimum altitude, using high bypass turbofan/ATE/ramjet power
- Perform pitchover into a nearly constant-energy (shallow γ-angle) dive and accelerate through the transonic region to approximately Mach 1.2, using torbofan/ramjet power
- Execute a long-radius pitch-up to an optimum supersonic climb flight path, using turbofan/ATE/ramjet power
- Climb to approximately 29 km (95 Kft) altitude and 1900 m/s (6200 fps) velocity, at optimum flight path angle and velocity, using proportional fuel-flow throttling from turbofan/ATE/ramjet, or full ramjet, as required to maximize total energy acquired per unit mass of fuel consumed as function of velocity and altitude
- Ignite rocket engines to full required thrust level at 1900 mps and parallel burn to 2200 mps
- Shut down airbreather engines while closing airbreather inlet ramps
- Continue rocket power at full thrust
- Insert into an equatorial elliptical orbit 91×556 km (50×300 nmi)
- Shut down rocket engines and execute a Hohmann transfer to 556 km (300 nmi)
- Circularize Hohmann transfer

The reentry trajectory is characterized by low γ (flight path angle), high α (angle of attack) similar to Shuttle. The main reentry elements are:

- Perform delta velocity maneuver and insert into an equatorial elliptical orbit
- Perform a low-γ, high-α deceleration to approximately Mach 6.0
- Reduce α to maximum lift/drag for high-velocity glide and cross-range maneuvers to subsonic velocity (approximately Mach 0.85)
- Open inlets and start airbreather engines
- Perform powered flight to landing field, land, and taxi to dock

Ascent and descent trajectories of the SSTO and Space Shuttle missions are compared in Figure 1.3-9. Because the performance of airbreathing engines and the aerodynamic lift of the winged vehicle depend on a high dynamic pressure, the SSTO flies at much lower altitude during the powered climb than the vertical ascent trajectory of the Space Shuttle for a given flight velocity. Light wing loading of the SSTO contributes to the rapid deceleration during deorbit.

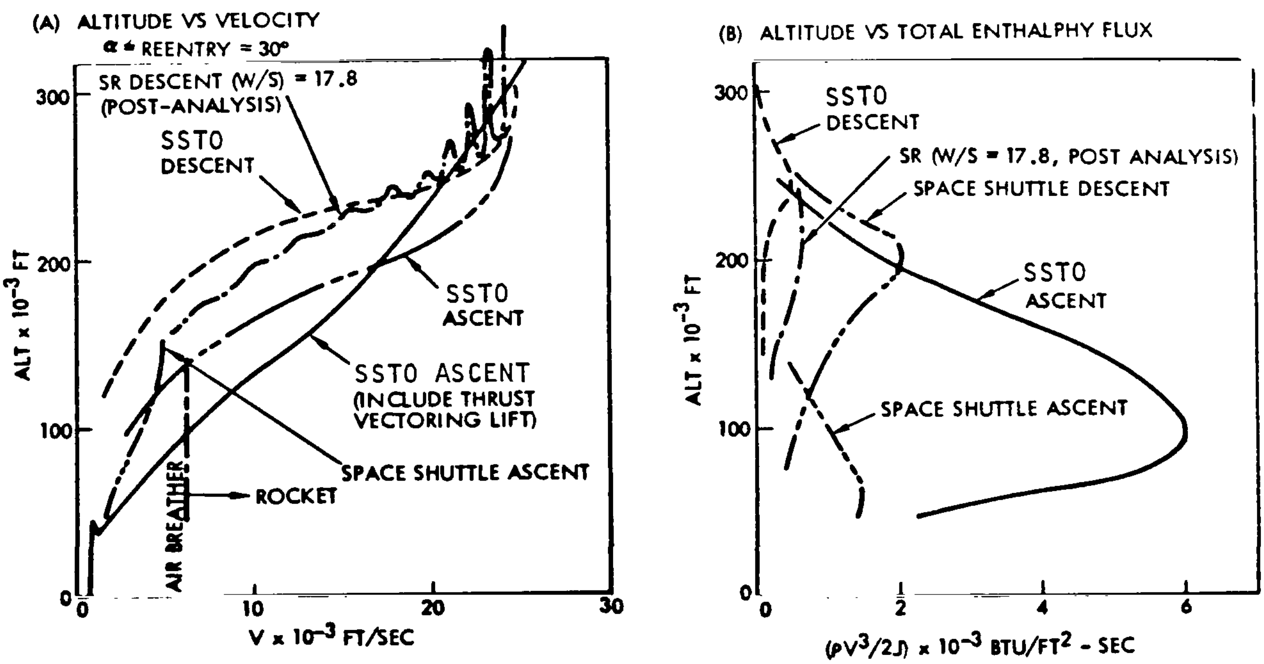


Figure 1.3-9. Ascent and Descent Trajectory Comparisons

The total enthalpy flux histories which indicate the severity of expected aerodynamic heating are also shown in Figure 1.3-9. As expected, the aerodynamic heating of ascent trajectory may design the SSTO TPS requirement. The maximum total enthalpy flux is estimated near the end of airbreather power climb trajectory. Except in the vicinity of vehicle nose, wing leading edge, or structural protuberances, where interference heating may exist, most of the ascent heating is from the frictional flow heating on the relatively smooth flat surface.

The descent heating is mainly produced by the compressive flow on the vehicle windward surface during the high angle-of-attack reentry, and is expected to be lower than the Space Shuttle reentry heating.

For the wing lower surfaces, heating rates were computed including the chordwise variation of local flow properties. Effects of leading edge shock and angle of attack were included in the local flow property evaluation. Leading edge stagnation heating rates were based on the flow conditions normal to the leading edge, neglecting cross-flow effects. All computations were performed using ideal gas thermodynamic properties.

Wing upper-surface heating rates were computed using free-stream flow properties, i.e., neglecting chordwise variations of flow properties. Heating rates were computed for several prescribed wall temperatures as well as the reradiation equilibrium wall temperature condition. Transition from laminar to turbulent flow was taken into account in the computations. Wing/body and inlet interference heating effects were not included in this preliminary analysis. The analysis was limited to the ascent trajectory, since the descent trajectory is thermodynamically less severe.

Isotherms of the peak surface temperatures for upper and lower surfaces (excluding engine inlet interference effects) for the SSTO and the STS orbiter are shown in Figure 1.3-10. Leading edge and upper-wing surface temperatures have similar profiles. The SSTO lower-surface temperatures are from 400°F to 600°F lower than the orbiter due to lower reentry wing loading (23 vs. 67 psf).

Preliminary data indicate that the titanium aluminide system (Figure 1.3-3) may be lighter than the RSI tile for the SSTO TPS system due to the lower average temperature (1000°F to 1600°F) profiles occurring over 80% of the vehicle exterior surface. The metallic truss core sandwich structure is similar to that developed for the B-1 bomber. The radiative surface panel consists of a truss core sandwich structure fabricated by superplastic/diffusion bonding. For temperatures up to 1500/1600°F, the concept utilizes an alloy based on the titanium-aluminum systems which show promise for high-temperature applications currently under development. For temperatures higher than 1500/1600°F, it is anticipated that the dispersion-strengthened superalloys currently being developed for use in gas turbine engines may be applicable. Flexible supports are designed to accommodate longitudinal thermal expansion while retaining sufficient stiffness to transmit surface pressure loads to the primary structure. Also prominent are expansion joints which must absorb longitudinal thermal growth of the radiative surface, and simultaneously prevent the ingress of hot boundary layer gases to the panel interior. The insulation consists of flexible thermal blankets, often encapsulated in foil material to prevent moisture absorption. The insulation protects the primary load-carrying structure from the high external temperature.

Unit masses of the SSTO TPS concept are compared with the unit mass of the STS orbiter RSI in Figure 1.3-11. The unit mass of the RSI includes the tiles,

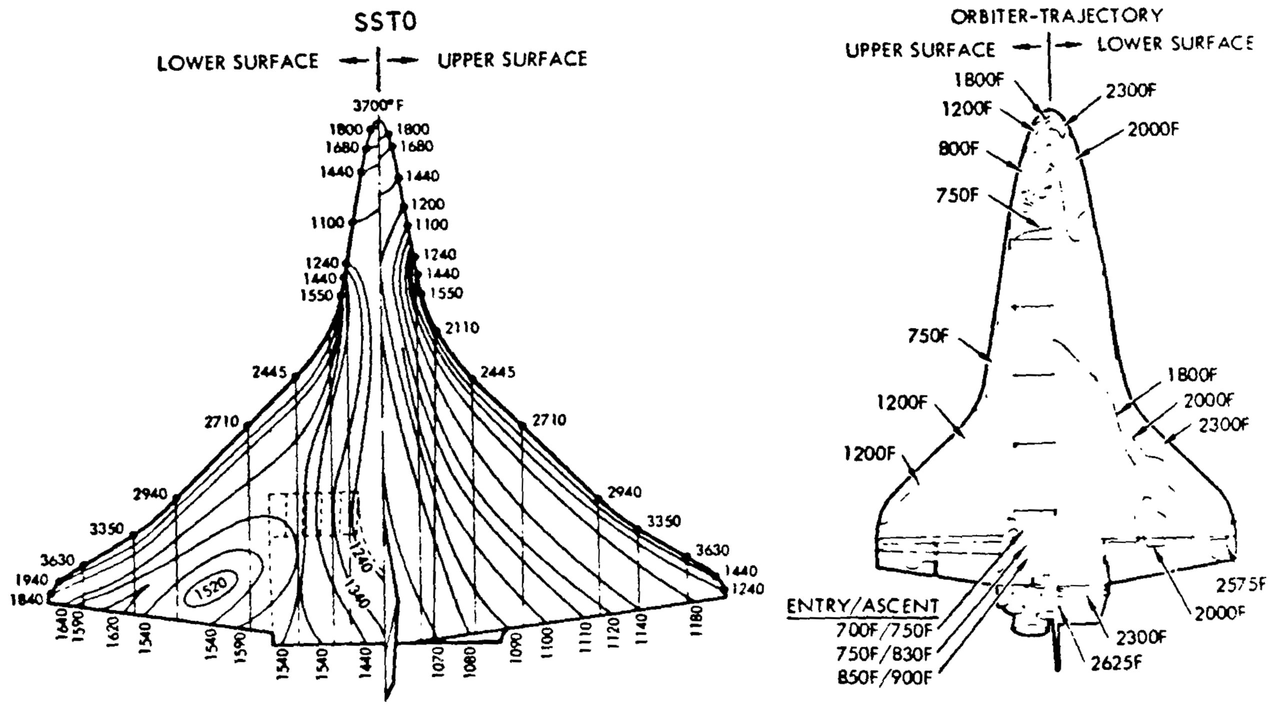


Figure 1.3-10. Isotherms of Peak Surface Temperature During Ascent

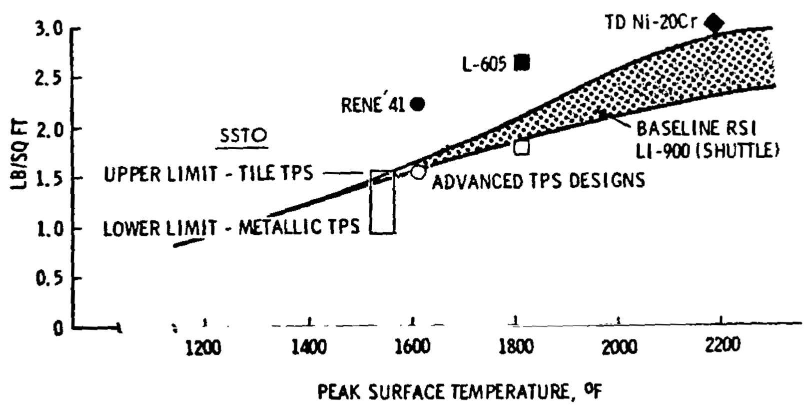


Figure 1.3-11. Unit Mass of TPS Designs

the strain isolator pad, and bonding material. The hatched region shown for the RSI mass is indicative of insulation thickness variations necessary to maintain mold line over the bottom surface of the STS orbiter. The RSI is required to prevent the primary structure temperature from exceeding 350°F. The unit masses of the metallic TPS are plotted at their corresponding maximum use temperatures. The advanced designs are seen to be competitive with the directly bonded RSI.

SSTO mass properties are dominated by the tri-delta wing structure, the thermal protection system, and the airbreather and rocket propulsion system. Estimated vehicle weights data are presented in Table 1.3-1.

Table 1.3-1. SSTO Weight Summary

Item Description	Weight (10^3 kg)
Airframe, aerosurfaces, tanks and TPS	167.8
Landing gear	12.3
Rocket propulsion	32.5
Airbreather propulsion	63.5
RCS propulsion	4.5
OMS propulsion	2.3
Other systems	17.2
Subtotal	300.4
Growth (10%)	30.0
Total inert weight (dry)	330.4
Useful load (fluid, reserves, etc.)	21.5
Inert weight and useful load	351.9
Payload weight	89.2
Orbital insertion weight	441.1
Propellant ascent	1826.9
GLOW (post-jett. launch gear)	2268.0

Again, it is emphasized that the SSTO concept represents a most advanced technology option and considerable further analyses are required to demonstrate viability of concept and definition of a much advanced technology program.

1.4 SMALL VTO/HL HLLV CONCEPTS (PREFERRED ALTERNATE CONCEPTS)

The primary driver in establishing HLLV requirements is the timely delivery of construction material to LEO; thus the payload magnitude becomes a major design parameter. The present-day use of the term "heavy lift" connotates a launch system with a payload capability substantially greater than the 30 metric tons of the Space Shuttle. A "small" heavy-lift system is a large vehicle; the term "small" is comparative to the very large SPS reference system. While reduced HLLV size would permit use of the already developed SSME with appropriate modifications to provide longer life, this in turn incurs an increased number of flights to deliver an equivalent mass to orbit. In addition, VTO/HL vehicle