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Strutjet-Powered Reusable Launch Vehicles

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(text follows)

INTRODUCTION

Martin Marietta and Aerojet are co-investigating the feasibility and viability of reusable launch vehicle designs. We are assessing two vehicle concepts, each delivering 8000 lb to a geosynchronous transfer orbit (GTO). Both accomplish this task as a two-stage system. The major difference between the two concepts is staging. The first concept, the two-stage-to-orbit (TSTO) system, stages at about 16 kft/sec, allowing immediate return of the first stage to the launch site using its airbreathing propulsion system for a powered cruise flight. The second concept, the single-stage-to-orbit (SSTO) system, accomplishes stage separation in a stable low earth orbit (LEO). These concepts distinguish themselves from other presently investigated concepts in three major aspects:

- First, the strutjet, a combined cycle engine system, avoids the extreme approaches of either all-rocket or all-airbreathing propulsion systems by combining the beneficial features of both systems in a logical and practical fashion such that significant specific impulse (Isp) gains are obtained without excessive engine weight. Strutjet-achievable mission average specific impulses are predicted to be 585 sec for the SSTO and 750 sec for the first stage of the TSTO system. Installed engine thrust-to-weight ratio is estimated at around 22:1. Corresponding values for an SSTO type conventional rocket engine are roughly 435 sec and 60:1 and for an SSTO NASP type propulsion system 700 sec and 15:1.

- Second, due to excellent Isp performance of strutjet-based systems, required propellant mass fractions are only 78 and 84 percent for TSTO and SSTO, respectively, and are within the present state of the art. In contrast, all-rocket SSTO mass fraction requirements are at least 90 percent.

- Third, thermal management of these vehicles can also be accomplished within the current state of the art because high-speed atmospheric operation is limited to Mach 8. This Mach number avoids severe vehicle heating conditions, which impose serious engineering challenges on the NASP X-30 vehicle and are typical for hypersonic atmospheric flight in the regime above Mach 8.

The enabling propulsion technology underlying both concepts is the Aerojet strutjet. This propulsion system combines ducted rocket, ram/scramjet, and pure rocket engine cycles into one compact engine. A strutjet operates in essentially four modes:

- As a ducted rocket during start and low-speed flight
- As a ramjet over the flight regime from about Mach 2.5 to 5
- As a scramjet from Mach 5 to 8
- As a pure rocket thereafter.

The strut, which gives this novel propulsion system its name, is the key element providing multiple operational functions such as compression of incoming air, inlet/combustor isolation, ram/scram fuel distribution and injection, and rocket thruster integration. Isp of this integrated engine is characteristic of airbreathing engines without the mass fraction penalty of having separate propulsion systems for different flight conditions.

SYSTEM BENEFITS OF THE STRUTJET PROPULSION

As Figure 1 illustrates, increases in specific impulse decrease the requirement for high propellant mass fraction, which is total propellant mass divided by takeoff mass of the vehicle without payload. Conventional chemical rocket-based SSTO systems require high mass fraction, about 90 percent, and, thus, depend on using cutting-edge materials and manufacturing processes. A propulsion system that offers higher specific impulse significantly reduces the need for such materials because lower mass fractions can still achieve viable solutions.
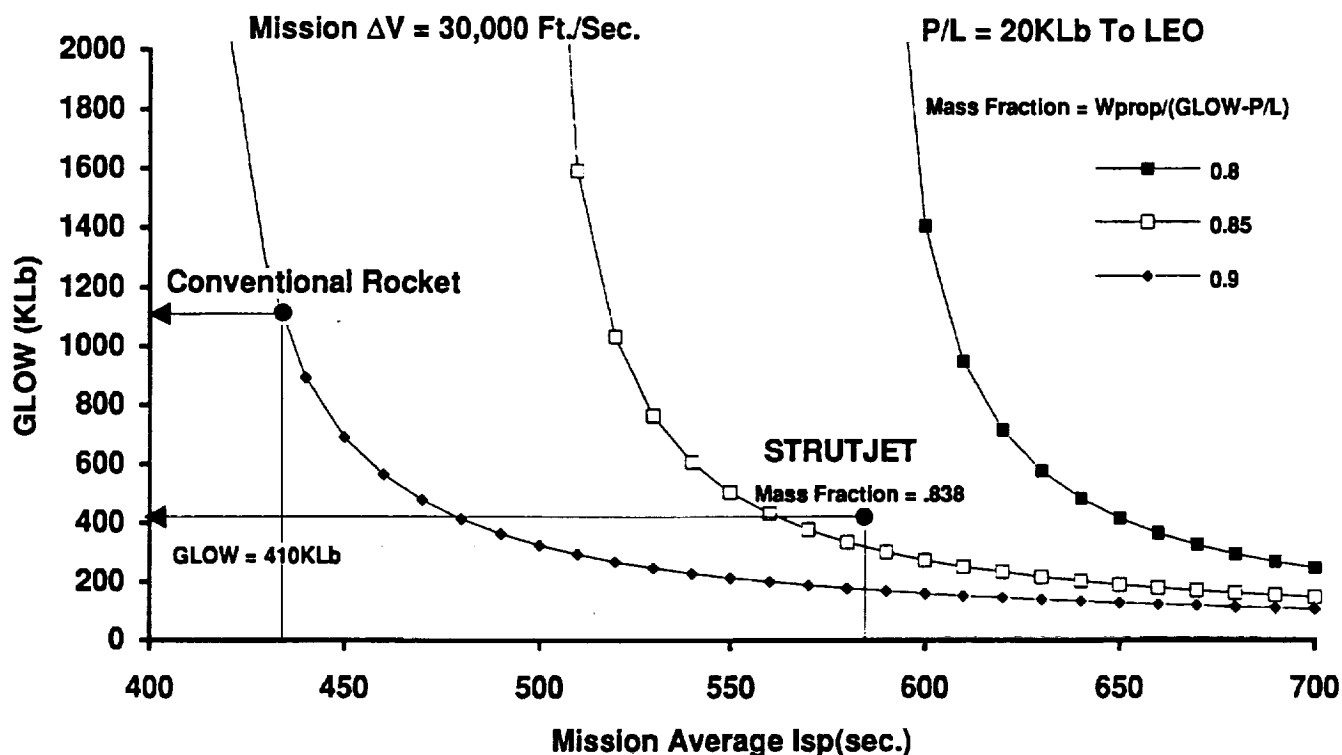

Figure 1.   Preferred Solution for SSTO: Strutjet

Figure 1 also shows that the strutjet SSTO Isp/gross lift-off weight (GLOW) point lies to the right of the "knee" of the 85 percent mass fraction curve, whereas corresponding points for all conventional rocket SSTOs lie directly on the "knee" or on the steep portion of the 90 percent mass fraction line. This advantage is even more pronounced for the TSTO vehicle. Thus, suborbital separation of the second stage raises first-stage average mission Isp from 585 to 750 seconds. The locus of this vehicle on the corresponding Isp/GLOW plot is on the gentle

slope portion below the 80 percent mass fraction line. Being on the steep portion, at or above the "knee" of a critical system parameter curve, is not sound engineering practice because it indicates a risky design. A small loss in Isp causes a sharp rise in vehicle GLOW, which makes the concept or the mission unfeasible.

In contrast, loci of the strutjet-based vehicles on the Isp/GLOW chart indicate a large potential for future mass fraction improvement and afford a rather large degree of Isp insensitivity. Whereas strutjet vehicle GLOW is about one-third that of a conventional chemical rocket vehicle, its dry weight is about half. These drastically reduced weights and corresponding sizes benefit ground operation turnaround times and cost. Furthermore, the ability to use state-of-the-art materials and manufacturing processes can reduce development risk and cost of a strutjet-based launch vehicle.

Strutjet propulsion offers versatility to overall vehicle design. For vehicles studied to date, takeoff is configured vertically. A horizontal takeoff, however, with its relatively low takeoff weight, may be even more attractive because it reduces engine takeoff thrust substantially. This reduces the strutjet's rocket to ram/scramjet thrust ratio, which results in some small Isp gains and engine weight reductions. The biggest benefit, however, is that horizontal takeoff facilitates ground operations like payload integration and launch preparation. The strutjet is configured as a modular engine concept in which the number of modules used in a particular vehicle design can be varied to accommodate most payload and orbit requirements. The strutjet inlet is based on the well characterized strut compression inlet first introduced by NASA Langley Research Center.

The most significant benefit derived from this inlet is geometric contraction and isolation in a shorter length than conventional inlets. This leads to an engine that is easier to integrate into the vehicle, is lighter weight, has less drag, and absorbs less heat. The strutjet uses an aft-expanding nozzle concept, which has the advantage of altitude compensation and high expansion ratio. The pure airbreathing mode of the strutjet also enables the vehicle to cruise in the atmosphere like an airplane. This allows launching from a single launch site to accomplish orbit inclinations ranging from equatorial to polar. It also permits returning to launch site after second-stage separation. The former benefit opens up the possibility of eventually closing down one of the coastal launch sites, saving substantial recurring resources.

STRUTJET PROPULSION SYSTEM

The strutjet-combined cycle engine promises to revolutionize payload launch into space. This engine synergistically combines the best attributes of the high-performance oxygen/hydrogen rocket with the ram/scramjet engine. These integrated propulsion elements are contained within a single engine using common propellant feeds, cooling systems, and controls. The rocket provides the bulk of the thrust for takeoff and acceleration to ramjet takeover speed. The rockets

are contained in compact struts placed within the ramjet duct shown in Figure 2. The air drawn into the engine by the ejector effect at subsonic speeds and rammed in at higher speeds provides significant thrust augmentation during boost. The strut inlet uses efficient forebody
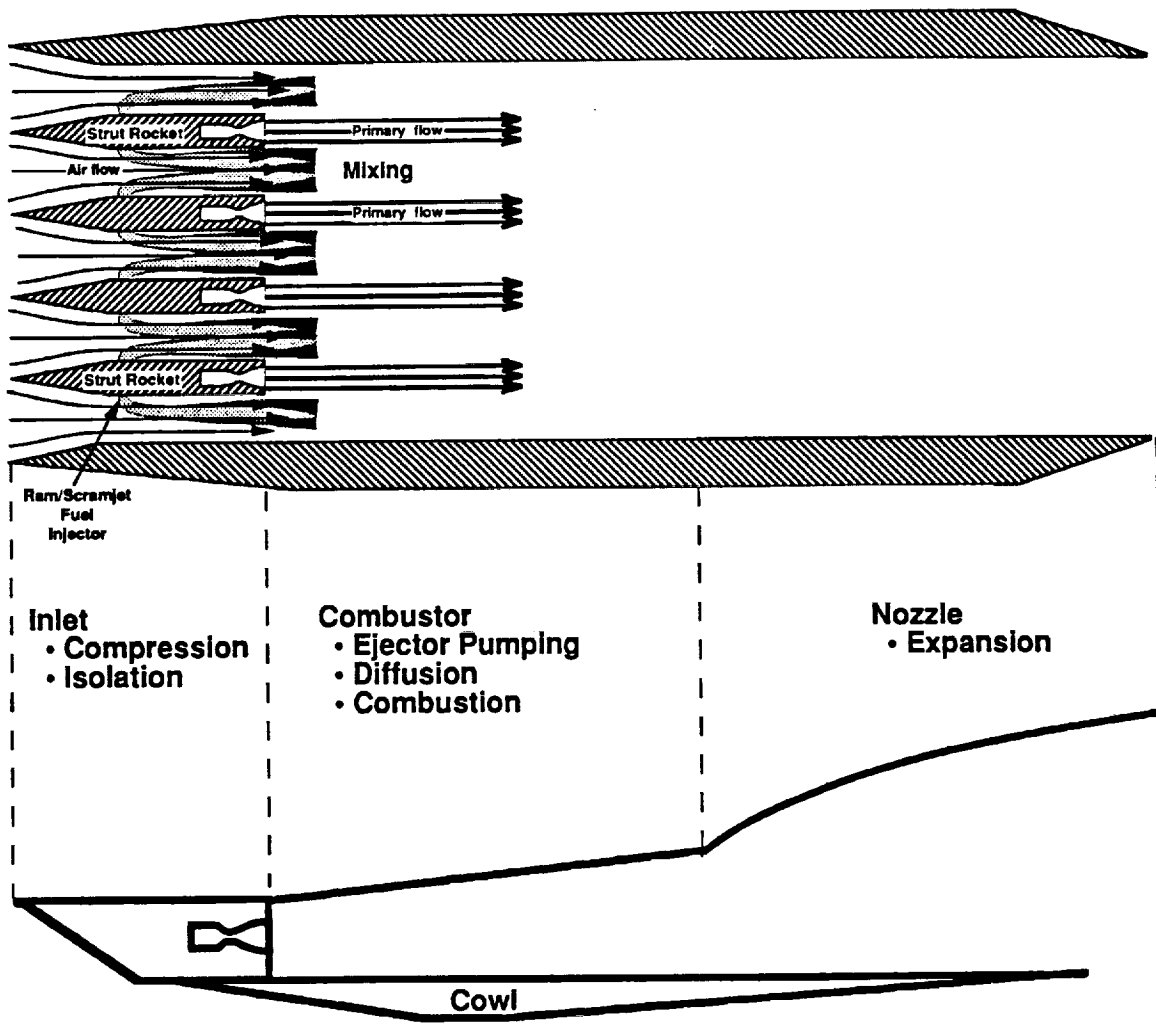

Figure 2. Strutjet Combines the Best of Rocket and Ramjet Engines

precompression together with strut compression, which is characterized by soft start, low spill drag, and good capture and recovery efficiencies. Initially, the fuel-rich rocket exhaust is sufficient to fuel air drawn into the engine. As the air mass flow increases with increasing speed, supplemental fuel is injected through ramjet injectors to maximize engine performance. Ramjet contribution occurs gradually starting at Mach 1 with full takeover at Mach 2.5. This transition provides the full benefit of the ramjet mode of operation with Isp approaching 3800 seconds.

Smooth transition from ram to scram mode has been demonstrated by Aerojet, as shown in Figure 3. Figure 4 shows the strutjet's Isp during a typical space launch mission. Aerojet's strutjet engine represents a significant departure from other airbreathing engine concepts, which
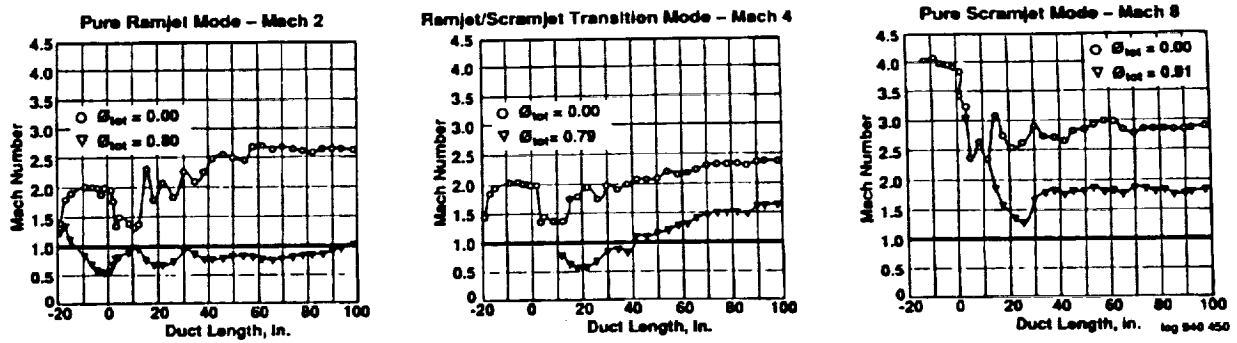
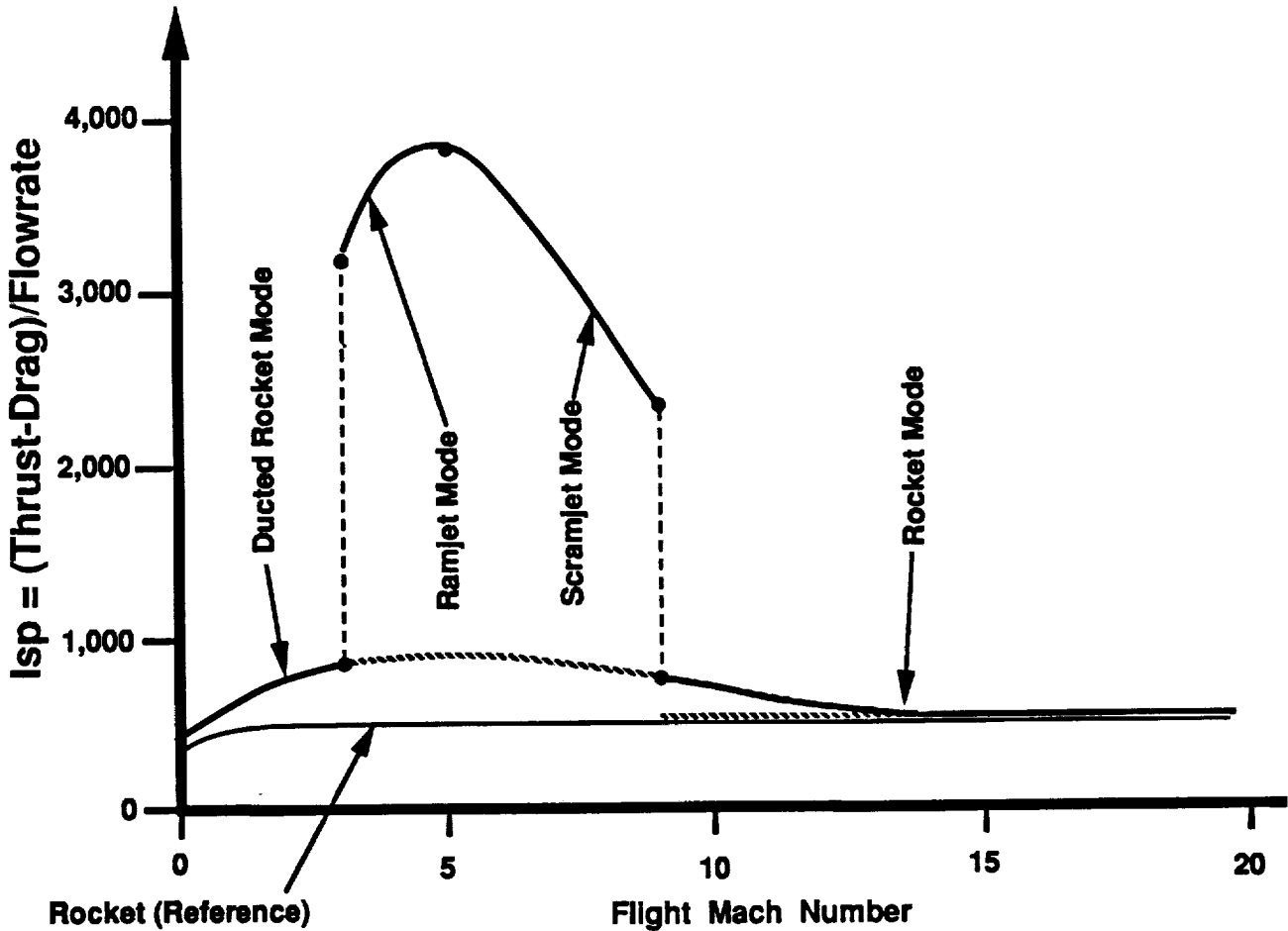Figure 3. Demonstrated Smooth Transition From Ramjet to Scramjet Operation

Figure 4. Strutjet Engine Performs Significantly Higher Than Conventional LOx/LH₂ Rocket Engine

are characterized by poor off-design inlet performance and heavy engine weight. The strut inlet operates well over a wide range of flight Mach numbers and contributes to a shorter, lighter engine. Figure 5 illustrates the strutjet inlet configuration. Struts also provide an ideal mounting place for ram/scram injectors. As shown in Figure 6, combustion efficiencies of 95 percent have
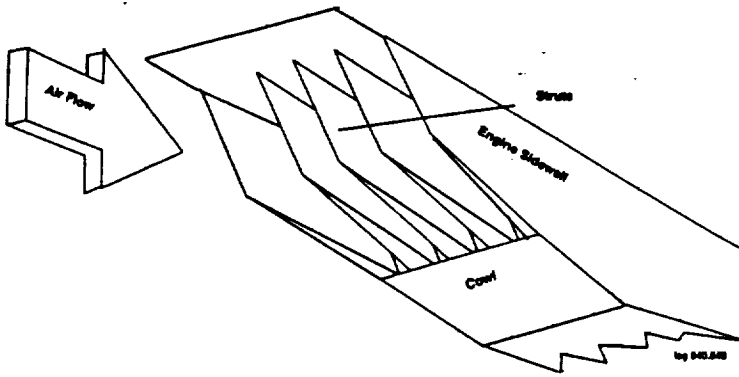
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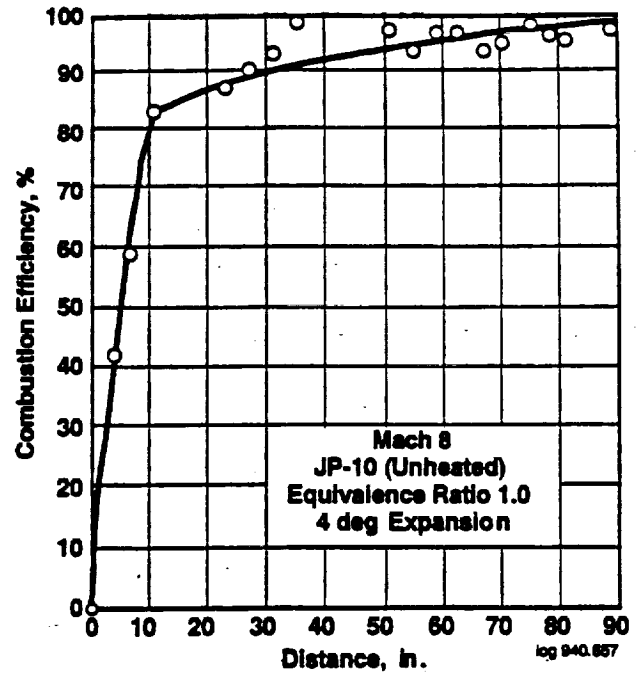Figure 5. Strut Compression Inlet Operates Over a
Wide Range of Mach Numbers

Figure 6. (Right) Ram/Scram Injection System Yields
90 Percent Combustion Efficiency In Only
30 Inches

Mach 8
JP-10 (Unheated)
Equivalence Ratio 1.0
4 deg Expansion

been demonstrated with hydrocarbon fuels at Mach 8 conditions at high fuel equivalency ratios, where it is most difficult to burn efficiently. Figure 7 illustrates how strut-mounted injectors reduce the "mixing gap," thus allowing a significant reduction in combustor length and weight. Achievable installed strutjet engine thrust-to-weight ratios are estimated to be as high as 30:1.

Mixing Gap G

Airflow

Products

Wall Injectors :7

Fuel

Combustion

Strutless Engine

Front View

Top View

Combustor Length = 60 G

Airflow

Mixing Gap g

Struts: 3
Injectors : 30

Products

· Shorter Combustor
· Less Viscous Losses
· Reduced Heat Load
· Higher Thrust
· Higher Isp

Strut Engine
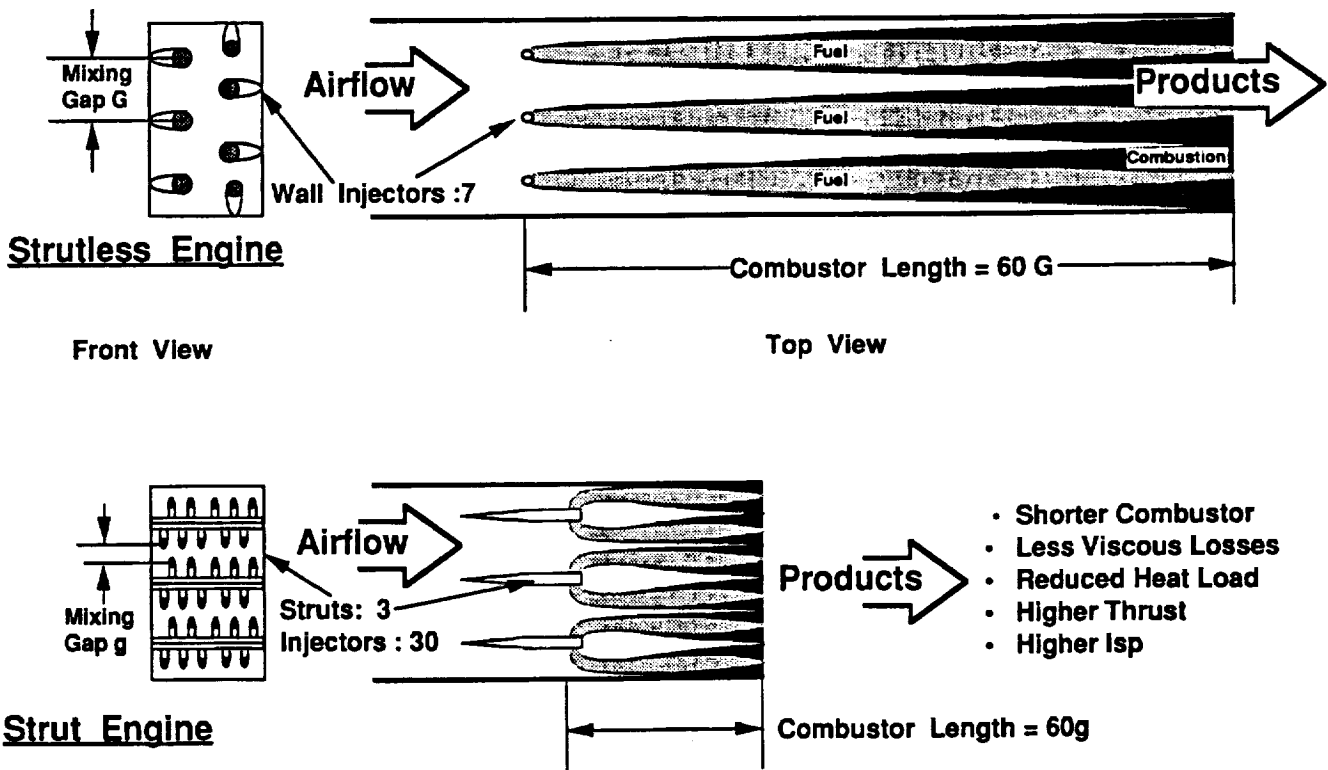
Combustor Length = 60g

Figure 7. Struts Enable Shorter and Higher Performing Engine

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TURBOMACHINERY

The turbomachinery, in particular the liquid hydrogen fuel pump, may be considered the Achilles heel of high-performance rocket engines. Unlike the conventional rocket engine, the strutjet provides high performance without relying on cutting edge turbomachinery technology, particularly advanced, high-stress, high-temperature materials. This in turn contributes significantly to increased reliability, extended life, and reduced cost of the strutjet engine.

The difference between the conventional rocket and the strutjet engines is manifested in the approach taken to achieve high performance. The mission average Isp of a conventional rocket-powered SSTO vehicle is strongly dependent on the vacuum Isp. Vacuum Isp is improved by using a high-area-ratio nozzle. If a fixed nozzle is used, the area ratio is the same at takeoff and during vacuum flight. Thus, the maximum fixed area ratio that can be used is determined by incipient nozzle flow separation at sea level. Nozzle flow separation occurs when nozzle exit pressure falls below 20 to 30 percent of the back pressure. High chamber pressures thus allow a higher area ratio without separation. Thus, conventional rocket engines typically operate at high chamber pressure, 3000 psi or more at takeoff, to permit an area ratio around 60:1. High chamber pressures place high demands on turbo pump discharge pressure and increase turbopump power level. This, in turn, produces unacceptable bleed losses if a gas generator cycle were used because overboard dump of the turbine drive gas would reduce mission average Isp more than the high area ratio would gain. Using the staged combustion cycle improves performance, but further increases required pump discharge pressure to provide the required pressure ratio across the turbine. This added cycle pressure can be partially mitigated by raising turbine inlet temperature. Fuel pump discharge pressures of 7000 to 8000 psi and turbine inlet temperatures on the order of 1700 °R are typically required for a staged combustion cycle engine with a 3000-psi chamber pressure.

In contrast, the strutjet can achieve high vacuum Isp at a chamber pressure of only 2000 psi because vacuum area ratio is determined by the large airbreathing nozzle exit, providing an area ratio of about 500:1. At takeoff, area ratio, which is set by the nozzle in the strut rocket, is typically on the order of 40:1. By definition, the strutjet engine has two distinct nozzle area ratios. Also, it can use a gas generator cycle that limits hydrogen pump discharge pressure to only about 3000 psi. The low required pumping power and available turbine pressure ratio allow low turbine inlet temperatures of about 1000 °R. Afterburning the fuel-rich turbine exhaust gases with the drawn-in or rammed-in air of the ducted rocket increases the Isp contribution of the exhaust gas from 200 sec for a conventional overboard dump to about 1000 seconds. In

summary, demands on the strutjet fuel turbopump are significantly reduced relative to the conventional rocket as shown below:

	Rocket	Strutjet	Reduction, %
Chamber Pressure, psi	3000	2000	33
Fuel Pump			
Discharge Pressure, psi	7000	3000	57
Turbine Inlet Temperature, °R	1700	1000	41
Turbine Tip Speed, rpm	2000	1700	15
Rotational Stress, %	100	72	28

As shown in Figure 4, during ascent from sea level to ramjet takeover and from scramjet cut-off to orbital insertion, the engine operates in the "ducted rocket" mode using drawn-in or rammed-in air to enhance thrust through mass flow increase and afterburning residual rocket fuel. During this mode, the engine's fuel side is powered by a fuel-rich gas generator exhausting into the ram/scram duct through dedicated injectors. The oxygen side is powered by an oxidizer-rich staged combustion cycle. In contrast to the hydrogen side, stage combustion on the oxygen side does not impose a technical challenge since oxygen, being a high density fluid, can be pumped to the required pressure levels with relative benign shaft speed. Full-flow oxygen-rich preburner technology has become available from Russia, providing the advantages of reduced turbine temperature and elimination of the interpropellant seals needed for fuel-rich gas-driven oxygen pumps. Figure 8 illustrates the engine cycle during the ducted rocket mode of operation. During pure airbreathing modes, the engine's entire oxygen feed system is inactive. As shown in
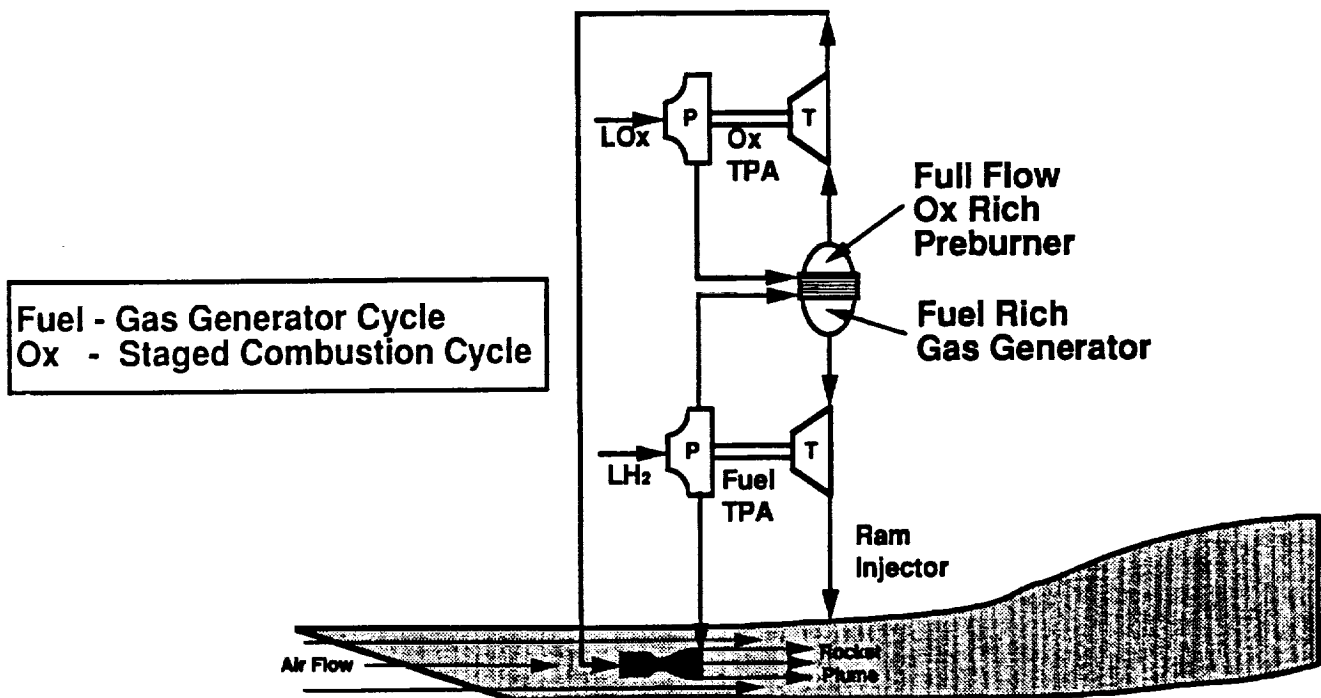

Figure 8.   Ducted Rocket Mode Provides High Thrust for Takeoff and Ascent

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Figure 9, the fuel side operates now in a benign expander cycle mode using heat available from required cooling of the engine structure. Figure 10 illustrates the location of these various operating modes on the fuel pump map.
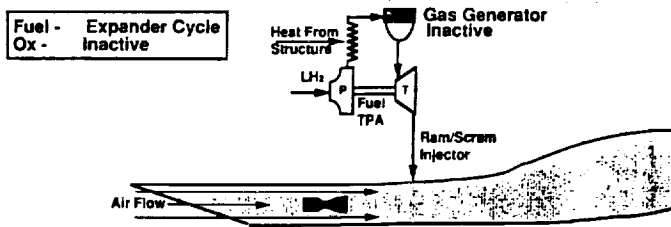

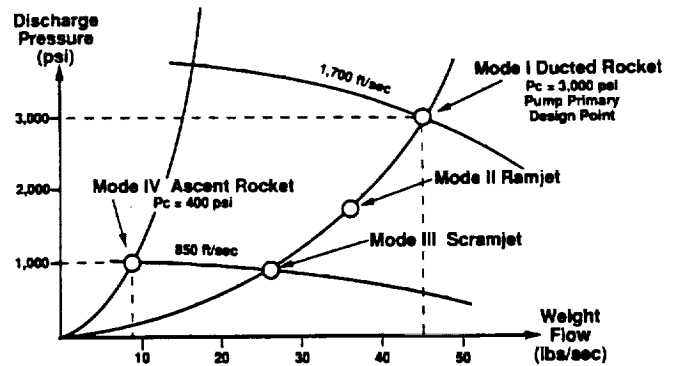Figure 9.   Ram/Scramjet Modes Provide High Isp for Acceleration From Mach 2.5 to 8

Figure 10.   Variable-Speed Hydrogen Turbopump Operates at Four Power Levels

ENGINE ARCHITECTURE

As will be shown later, a typical TSTO vehicle that delivers 8000 lb of payload to an LEO orbit has a GLOW of 340,000 pounds. Figure 11 shows the top-level architecture of the strutjet propulsion system for this application. Takeoff thrust at 512 klb provides a comfortable thrust-
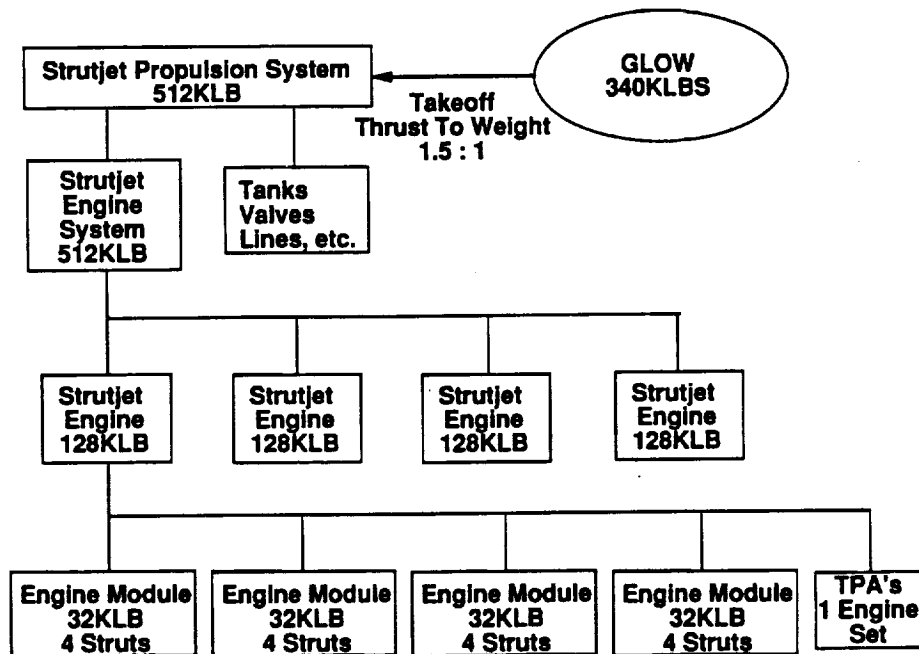

Figure 11.   Typical Strutjet Engine System Architecture

to-weight ratio of 1.5 for net vehicle acceleration and engine out capability. The overall engine system integrates four self-contained strutjet engines each consisting of four engine modules and one turbopump set. Each module is provided 32 klb of thrust and consists of four struts delivering 8 klb thrust.

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This concept is very flexible in terms of engine-vehicle integration and in flight operation. Also, it lends itself to a very logical and low-cost development approach. First, thrusters are being developed and packaged into one strut. Then, four struts are evaluated as a module. At this level, total thrust is only 32 klb, and ducted rocket and ram/scramjet performance, weight, and life requirements can be demonstrated. After completing these tests, four engine modules are integrated with one set of turbopumps and tested. This provides a complete engine at a thrust level of only 128 klb for demonstration. The modular approach (that is, the repeated application of like components) not only facilitates engine development and evaluation, it also lowers production hardware cost significantly.

STRUTJET VEHICLE CONCEPTS

In late 1993, Martin Marietta conducted an extensive analysis to determine which launch vehicle configurations have the highest potential for meeting requirements for a launch system delivering 8000 lb to GTO. Results of this analysis showed that two of the reusable candidates that best met the requirements were a single-stage-to-LEO launch vehicle (SSTO) with an upper stage to GTO and a two-stage-to-GTO launch vehicle (TSTO). Both concepts use a strutjet propulsion system on the reusable first stage of the vehicle and an expendable upper stage. Common to both vehicle configurations are the following attributes:

- Vertical takeoff/horizontal landing of reusable first stage
    - Good takeoff and low-speed acceleration provided by ducted rocket system
- Expendable second stage
    - SSTO concept : staged at LEO
    - TSTO concept : staged at 16 kft/sec; first stage returns to launch site
- Potential for single launch site for all inclinations
- High mission average specific impulse
    - SSTO : 585 sec
    - TSTO: 750 sec, both based on:

Ducted Rocket	400 to 675 sec
Ramjet	3200 to 3800 sec
Scramjet	3800 to 2400 sec
Pure Rocket	470 sec

- Lower takeoff and dry weights than conventional rocket vehicles
    - GLOW reduction-strutjet/chemical rocket: 410 klb/1100 klb ≈ 1/3
    - Dry weight reduction-strutjet/chemical rocket: 63 klb/110 klb ≈ 1/2

- Airbreathing operation to only Mach 8
  - Manageable aero heating environments
  - Testable with today's facility capabilities
- Available material technologies for engine and vehicle
- Large potential for future payload growth and cost reductions
  - Isp increase through airbreathing operation at higher than Mach 8
  - Mass fraction improvement through advanced materials
- Single propellant combination for all operational modes, LOX/LH$_2$.

Figure 12 illustrates the design of the SSTO concept. The TSTO vehicle concept, also shown, is similar in design with the first stage smaller and the second stage larger, requiring two RL-10A4 engines.

Mass Properties	SSTO	TSTO
Mass Fraction	.84	.78
1st Stage Weight - KLBS	390	261
2nd Stage Weight - KLBS	12	51
Payload To GTO	8	8
GLOW - KLBS	410	340
Landing Weight - KLBS	63	62

Operating Mode	
Takeoff	Vertical
Landing	Horizontal

Staging		
1st Stage	LEO 80x80NMI @28.5	Sub-Orbital @ 16Kft/sec
2nd Stage	LEO To GTO	From 16Kft/sec To GTO

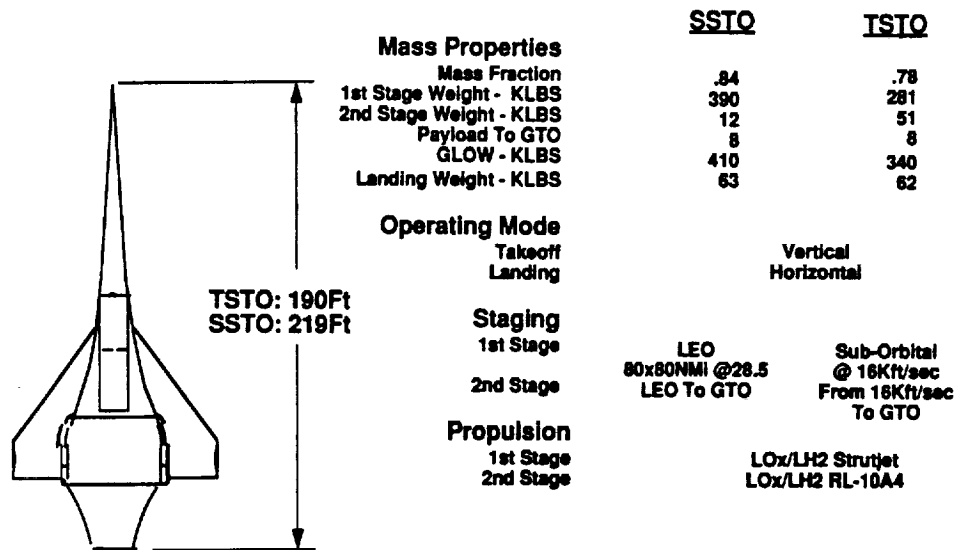| Propulsion	
1st Stage	LOx/LH2 Strutjet
2nd Stage	LOx/LH2 RL-10A4

TSTO: 190Ft
SSTO: 219Ft

Figure 12. Strutjet-Powered Vehicles for SSTO and TSTO

engines. The first stage of the TSTO vehicle includes fuel to return to the launch site. Trajectories for the reusable launch vehicles are shown in Figure 13 for SSTO and in Figure 14 for TSTO. Both trajectories, after a short rocket-powered vertical rise, execute a pitchover phase to enable airbreathing capability until Mach 8. When a flight speed of Mach 8 is achieved the airbreathing modes are terminated, and the vehicles pitch up into a steeper ascent trajectory under pure rocket power. As shown in Figure 13, orbit insertion of the SSTO vehicle occurs at a down range of about 1,000 nmi. In contrast, as shown in Figure 14, second stage deployment occurs at a downrange of about 400 nmi. The first stage then follows with a ballistic trajectory to an altitude of about 300,000 ft, descends and turns unpowered, restarts the ramjet at about 1400 nmi downrange, and cruises back to the launch site at an altitude of 100,000 ft and a flight speed of Mach 5.
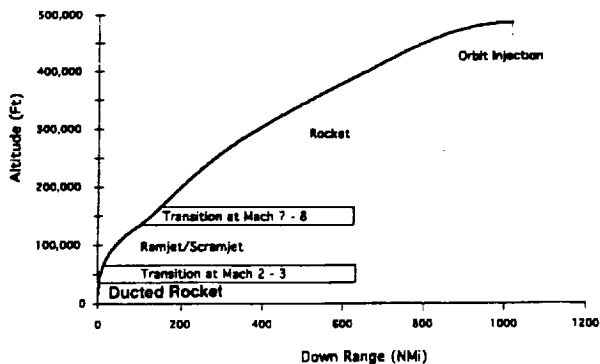
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Figure 13. SSTO: Trajectory of Reusable
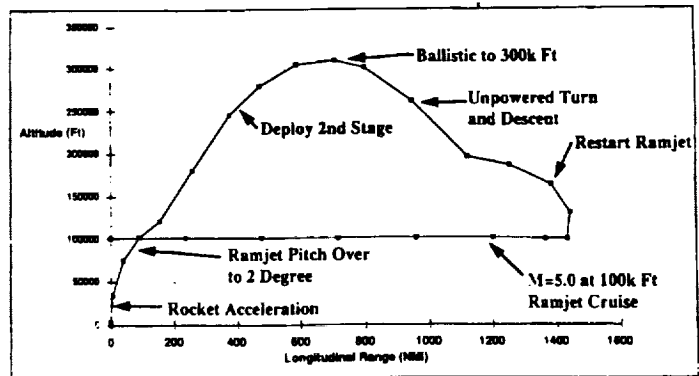Strutjet-Powered Vehicle

Figure 14. TSTO: Trajectory of Reusable
Strutjet-Powered First Stage

SUMMARY AND CONCLUSIONS

For the reference mission, delivery of 8000 lb to GTO, two vehicle concepts are defined: an
SSTO with an expendable second stage and a TSTO with stage separation at about 16 kft/second.
Both systems are significantly lighter in takeoff and dry weight, 67 and 50 percent respectively,
than their conventional rocket counterparts.

Design of an SSTO launch system is extremely sensitive to the performance of the propulsion
system. Using existing or upgraded conventional chemical rocket propulsion systems results in
vehicle designs that are not compatible with sound engineering practices due to their high
sensitivity to system Isp and inert weight growth. These sensitivities can be brought down to
levels that are consistent with today's practices if a combined cycle engine like Aerojet's strutjet
is used. The strutjet is a propulsion system that, due to its possible mission average Isp of 585 to
750 sec and a relatively high engine thrust-to-weight ratio of about 22, enables using state-of-art
material technology.

The strutjet is a rugged engine design using state-of-the-art materials and manufacturing
processes. Fundamental operating conditions of the engine, like ducted rocket performance and
ram-to-scramjet transition, have been demonstrated by test or can be derived reliably from
existing data. Test data are available for inlet aerodynamic performance and thermal
management of strut leading edges, rocket chambers, and ram duct engine sidewalls and panels.
Strut injectors have been proven successfully for hydrocarbon fuels; similar results for hydrogen
fuel are expected.

Next steps in developing this promising space launch concept center around additional
component design, fabrication and ground tests, an overall engine design, fabrication and free jet
test. Subsequent subscale flight tests will demonstrate the governing principals of this propulsion
concept and its scalability to a full operational engine and vehicle.

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